Using similar mathematical modelling with both single module IV curve measurements and array Inverter data

Juergen Sutterlueti[1] and Steve Ransome[2]

[1]Gantner Instruments, Austria J.Sutterlueti@gantner-instruments.com

[2]Steve Ransome Consulting Ltd, U.K. steve@steveransome.com

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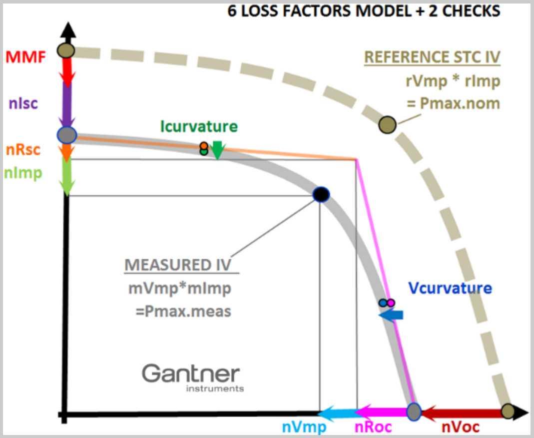
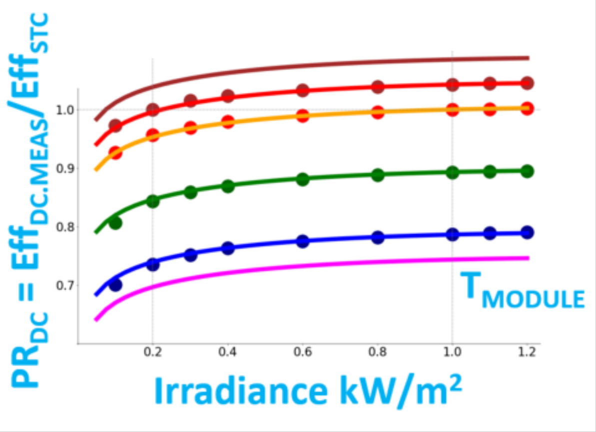
Overview of measurement types and models at different levels

Levels	DC, AC	Performance Measurements	Variability, losses	Models
Modules - Strings	DC	Can be full IV curves, indoor or outdoor	Minimal with single modules, mismatch in strings	1-diode, SAPM, LFM etc.
Inverter	DC → AC	V_{MPP} tracking, Efficiency vs Pin, Thermal cut out, clipping, downtime etc.		
Large Arrays	DC side or AC side	Usually just P_{MAX}, sometimes I_{MAX} and V_{MAX}	Module mismatch, Soiling, T_{MOD}, Wiring losses Cloud variability across array	Empirical e.g PVUSA, scaled module + inverter model, MPM etc.

Gantner Instruments (GI) OTF in Tempe, AZ

GI powerplant in the UK

Model Introduced	DC, AC	Parameters	Pros and Cons	
LFM Loss Factors Model (2011 26th Hamburg PVSEC)	DC	Derives 6 normalised IV curve parameters and 2 curvature checks	☑ Optimised model for good IV traces. ☒ Cannot derive R_{SC}, R_{OC} from poor IV curves	
MPM Mechanistic Performance Model (2017 7th PVPMC Canobbio)	DC side or AC side	Derives 5 normalised PR_{DC} parameters	☑ Optimised model for PR_{DC} for indoor matrix, outdoor data ☒ Only derives PR_{DC}	

Comparison of two different models used by GI/SRCL

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Model introduced	DC, AC	Parameters	Pros and Cons	Enhancements
LFM Loss Factors Model (2011 26th Hamburg PVSEC)	DC	Derives 6 normalised IV curve parameters and 2 curvature checks	☑ Optimised model for good IV traces. ☒ ~~Cannot derive R_{SC}, R_{OC} from poor IV curves~~	Simplify LFM parameters to work with lower quality IV curves and also just Imp and Vmp values
				☑ Overlap !
MPM Mechanistic Performance Model (2017 7th PVPMC Canobbio)	DC side or AC side	Derives 5 normalised PR_{DC} parameters	☑ Optimised model for PR_{DC} for indoor matrix, outdoor data ☒ ~~Only derives PR_{DC}~~	Generalise MPM equations to work with LFM like parameters e.g. nI_{SC}, nR_{SC}, … nV_{OC}

Are Coefficients …	☑ LFM and MPM	☒ Empirical models
Meaningful **(depend on physical effects)**	**Yes** e.g. • $P_{ACTUAL}/P_{NAMEPLATE}$ = **P Tolerance** • 1/P * dP/dT_{MODULE} = **Temp Coeff γ** • **nV_{OC}** = $measV_{OC}/refV_{OC}$ etc.	**No** not dependent on real behaviour e.g. X1, X2 T_{MOD} * $T_{AMBIENT}$ T_{MOD} * $LOG(G_I)^2$
Orthogonal **(independent of each other)**	**Yes** Allow for a unique fit.	**No** Unique fits aren't possible.
Robust **(can fit data with noise)**	**Yes** Fits sensibly without being perturbed	**No** non realistic predictions e.g. spikes and/or non linearity
Normalised **(divide by reference values)**	**Yes** parameters can be compared and validated more easily e.g. $nV_{OC} = V_{OC.MEAS}/V_{OC.NOMINAL}$ may be 95% module → string	**No** hard to see what is good behaviour at different levels e.g. V_{OC}=30V module, V_{OC}=600V string What about MPPT limits?

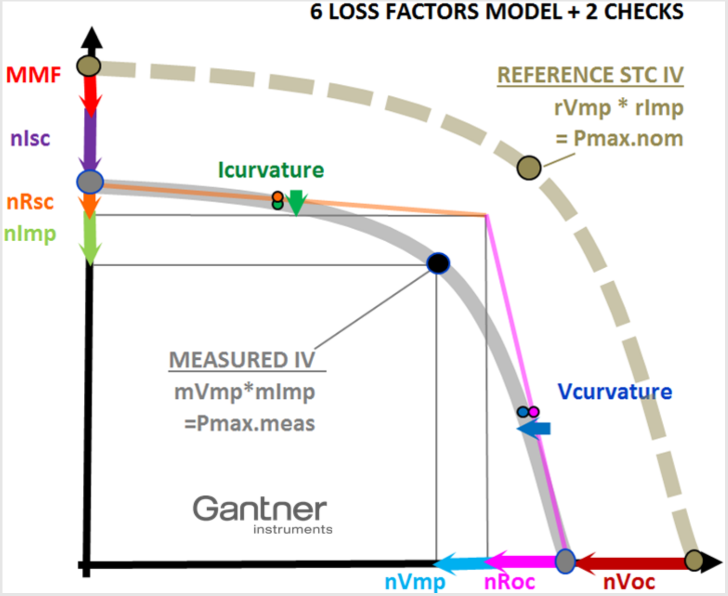
E.g [Stein et al 28th PVSEC Paris 2013] for comparison with 1-diode and SAPM

- The **Loss Factors Model "LFM"** provides a powerful analysis of indoor or outdoor IV curves

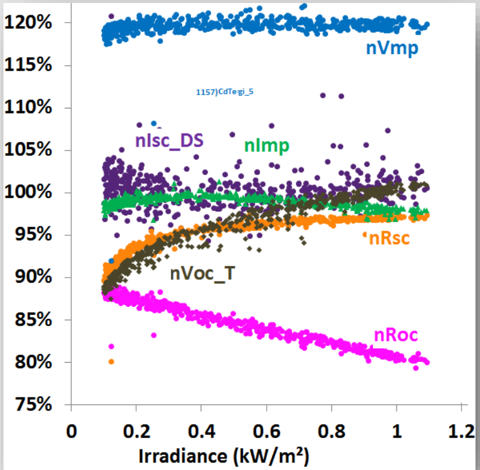
$$PR_{DC} = nI_{SC} * nR_{SC} * nI_{MP} * nV_{MP} * nR_{OC} * nV_{OC}$$

- Two other parameters nI_C and nV_C show the deviation from expected $I@V_{MP}/2$ and $V@I_{MP}/2$ and give measured values indicating amounts of cell current mismatch and roll over respectively

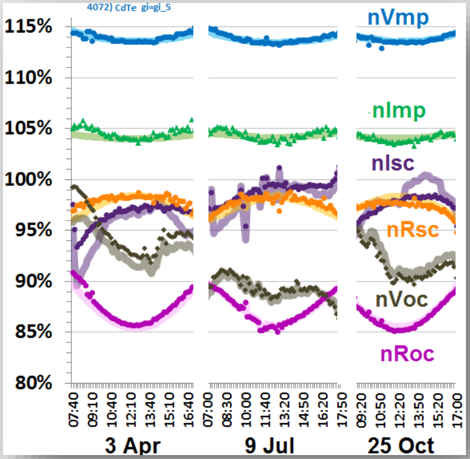
LFM



Characterise a module vs. G_I, Tmod etc.



Predict performance vs. time and weather



LFM can easily find any discrepancies, degradation, poor measurements etc

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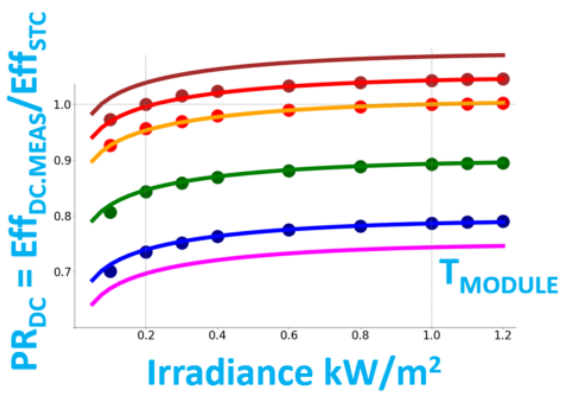
1. $I_{MAX} \propto G_I$ — Module STC rating actual/nominal W
2. $P_{MAX} \propto (1+\gamma*(T_{MOD}-25))$ — Power temperature coefficient "γ"
3. $V_{MAX} \propto \log(G_I)$ — From diode equation
4. $\Delta P_{MAX} \propto I_{MAX}^2 * R_{SERIES}$ — $I^2.R_S$ loss
5. $T_{MOD} \sim T_{AMB}$ – fn(Windspeed) — NMOT Thermal rise
6. ~~R_{SHUNT} vs. GI~~ — (depends on technology) – behaves like 3.V_{MAX}

Mechanistic Performance Model only uses these dependencies !

$$PR_{DC} = C_1 + C_2*(T_{MOD}-25) + C_3*Log_{10}(G_I)+ C_4*G_I + C_5*WS$$

P_{ACTUAL} Temperature Voc R_{SERIES} NOCT

- $dT_{MOD} = (T_{MOD} - 25)$
- G_I = plane of array irradiance (kW/m²)
- WS = wind speed (ms^{-1})



[7th PVPMC Mar 2017 Canobbio CH][44th PVSC Jun 2017 Washington DC US],[PVSEC-27 Nov 2017 Shiga JAP]

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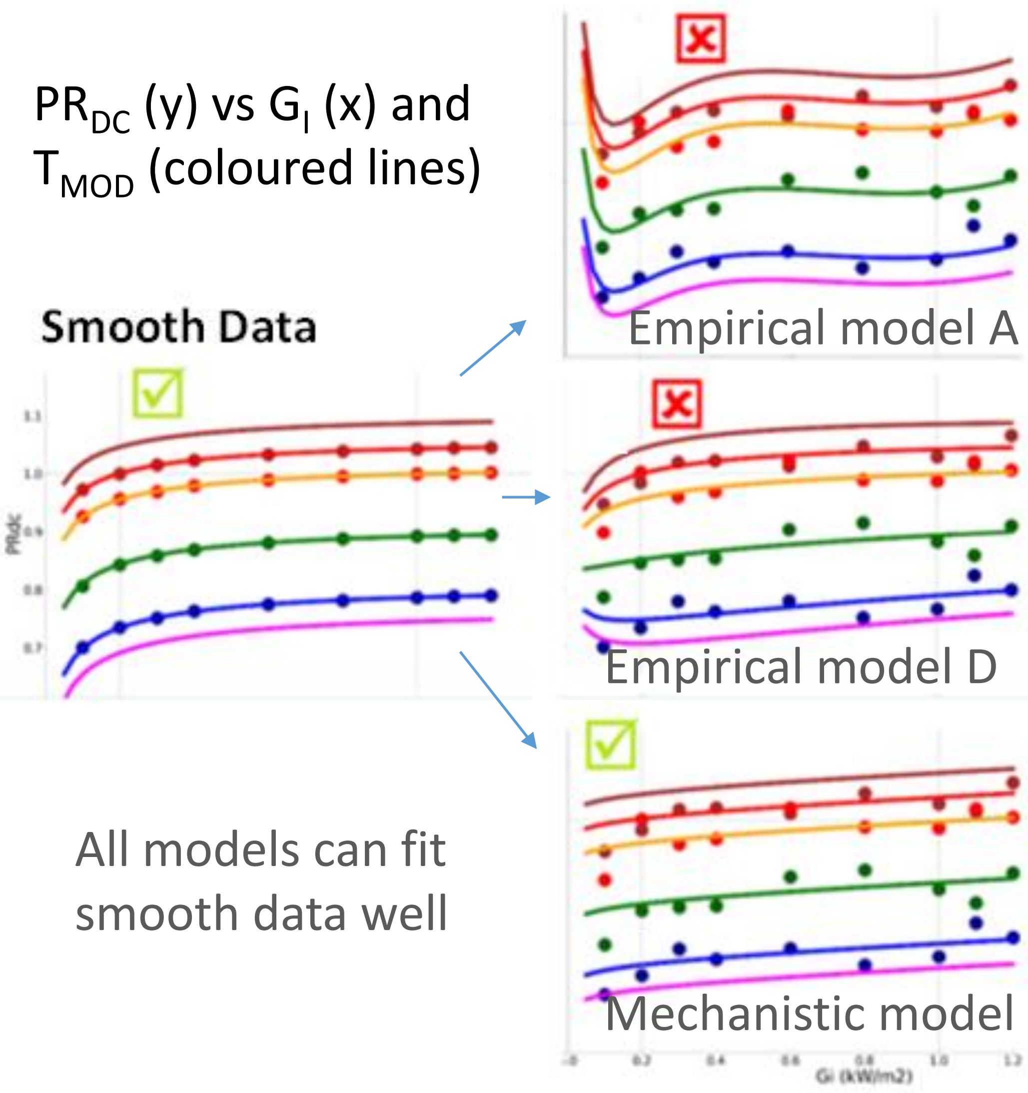
PR_{DC} (y) vs G_I (x) and T_{MOD} (coloured lines)



All models can fit smooth data well

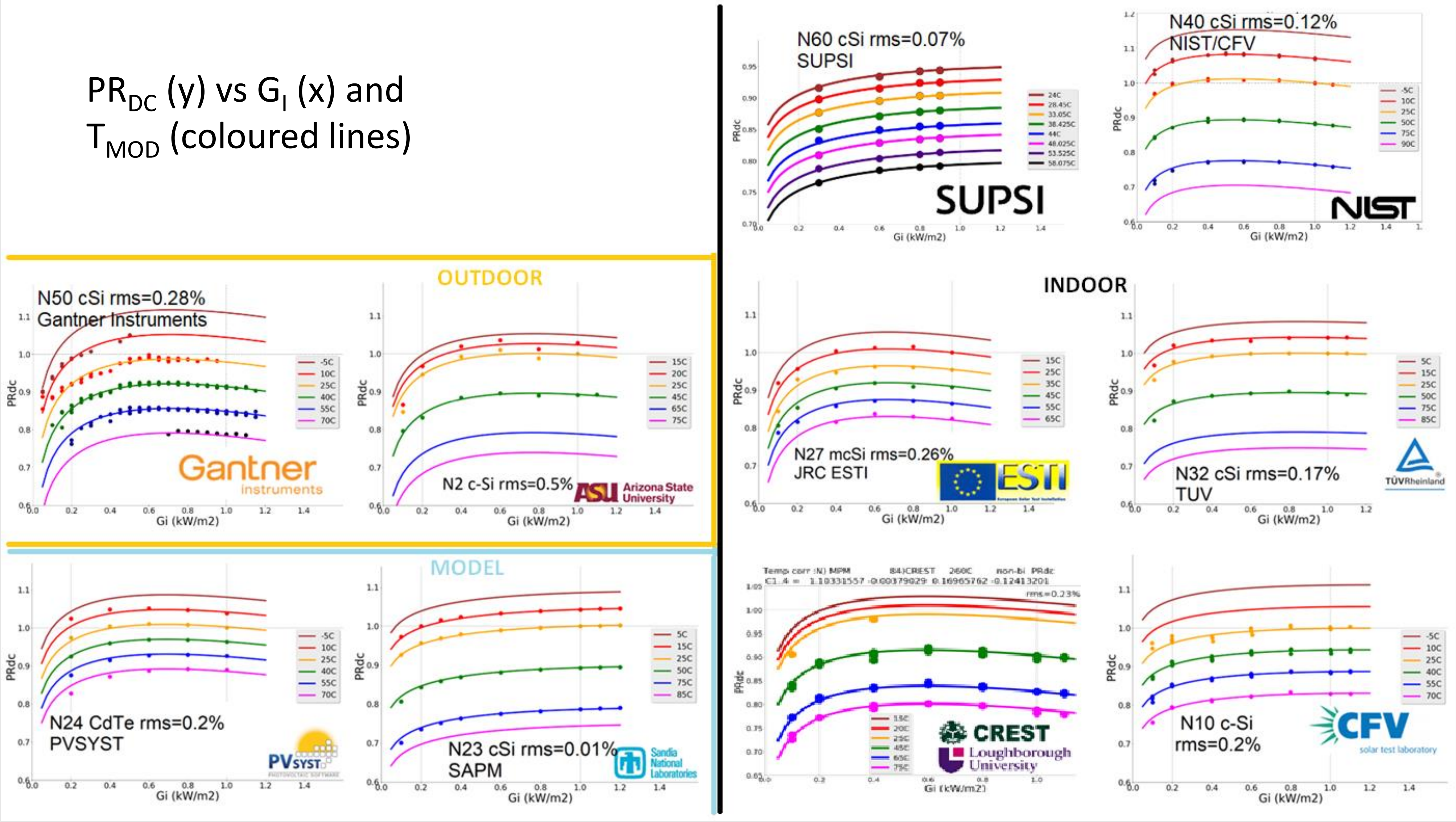
Added noise to mimic real measurements and test robustness

☒ Empirical models can be affected by random scattered points and give non physical fits

☑ Mechanistic models can be unaffected by random scattered points and still gives physical fit

Mechanistic Performance Model fits IEC 61853 Matrices well from all data sources tested

(Please send us any more for confidential comparisons or to be included here !)



Why mechanistic model coefficient values are more useful than from empirical models

Compare fits vs. technology cSi aSi CdTe **[SUPSI data]**

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Technology	ID	C_1	C_2	C_3	C_4	C_5	rms
c-Si	60)	-42.3	53.9	-10.7	-32.9	-8.0	0.22%
c-Si	62)	-127.2	159.8	-31.7	-97.8	-23.9	0.22%
c-Si	64)	-71.5	90.5	-18.0	-55.3	-13.5	0.09%
c-Si	66)	-93.4	117.6	-23.4	-72.0	-17.6	1.84%
c-Si	67)	100.2	-123.8	24.6	75.6	18.4	0.24%
c-Si	68)	-69.5	87.9	-17.5	-53.8	-13.1	0.16%
c-Si	70)	-37.3	131.4	-98.7	21.9	23.5	0.10%
c-Si	71)	6.4	-6.8	1.4	4.1	0.9	0.07%
c-Si	72)	60.7	-132.5	76.7	10.1	-10.2	0.59%
c-Si	73)	53.8	-68.9	16.3	38.4	8.7	0.09%
TF a-Si	65)	0.2	1.1	-0.3	-0.5	-0.1	0.94%
TF a-Si	74)	90.8	-121.1	31.9	62.8	13.2	0.32%
TF CdTe	63)	-0.6	2.2	-0.6	-1.2	-0.3	0.27%

Technology	ID	C_1	C_2	C_3	C_4	C_5	rms
c-Si	60)	96.2%	-0.45%	8.3%	-2.1%	0.0%	0.07%
c-Si	62)	109.6%	-0.42%	20.5%	-10.0%	0.0%	0.09%
c-Si	64)	106.4%	-0.45%	8.5%	-6.4%	0.0%	0.09%
c-Si	66)	107.7%	-0.48%	11.9%	-7.7%	0.0%	0.08%
c-Si	67)	115.2%	-0.48%	18.2%	-15.4%	0.0%	0.11%
c-Si	68)	107.6%	-0.47%	10.4%	-7.5%	0.0%	0.09%
c-Si	70)	103.7%	-0.46%	3.9%	-4.3%	0.0%	0.08%
c-Si	71)	113.7%	-0.46%	24.4%	-12.4%	0.0%	0.08%
c-Si	72)	99.6%	-0.44%	0.7%	1.2%	0.0%	0.20%
c-Si	73)	109.4%	-0.45%	17.1%	-9.2%	0.0%	0.09%
TF a-Si	65)	112.2%	-0.11%	31.6%	-11.9%	0.0%	0.21%
TF a-Si	74)	122.7%	-0.22%	39.5%	-23.1%	0.0%	0.33%
TF CdTe	63)	12[illegible].3%	-0.[illegible]3%	19.6%	-20.2%	0.0%	0.16%

$C_1 = P_{MAX}$ tolerance

C_2 = Realistic P_{MAX} Temperature coefficient (TF < c-Si)

Empirical model with 5 parameters

- no meaningful pattern to coefficients
- large variability
- self compensation (e.g. C_1 vs. C_2)

MPM Mechanistic model with 4 parameters

- Meaningful values of all coefficients = more robust fitting
- Better average rms fit

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With "normalised Resistance vs. Voltage" (nRV) curves shown on log scale

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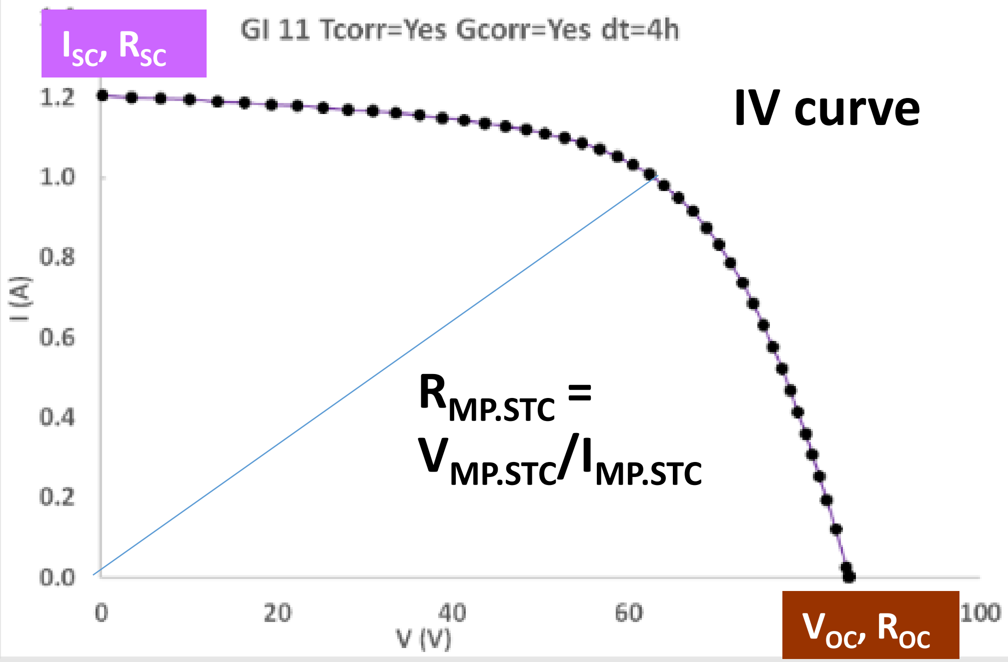
Smooth IV data is needed to extract precise values particularly for R_{SC}.

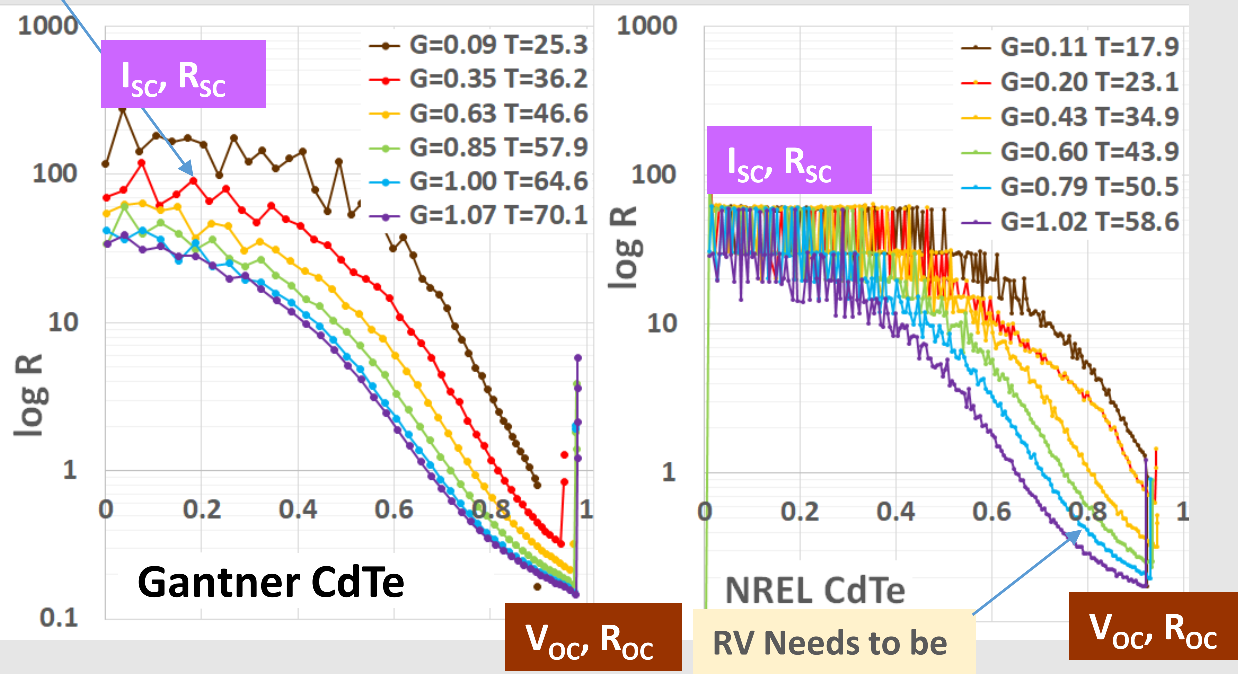
$$nR_n = -\Delta V/\Delta I \,/\, (R_{MP.STC})$$



Analysing nRV data can show if limited precision, errors, drift, scatter exist

nRV Needs to be smooth near V=0 for Isc,Rsc

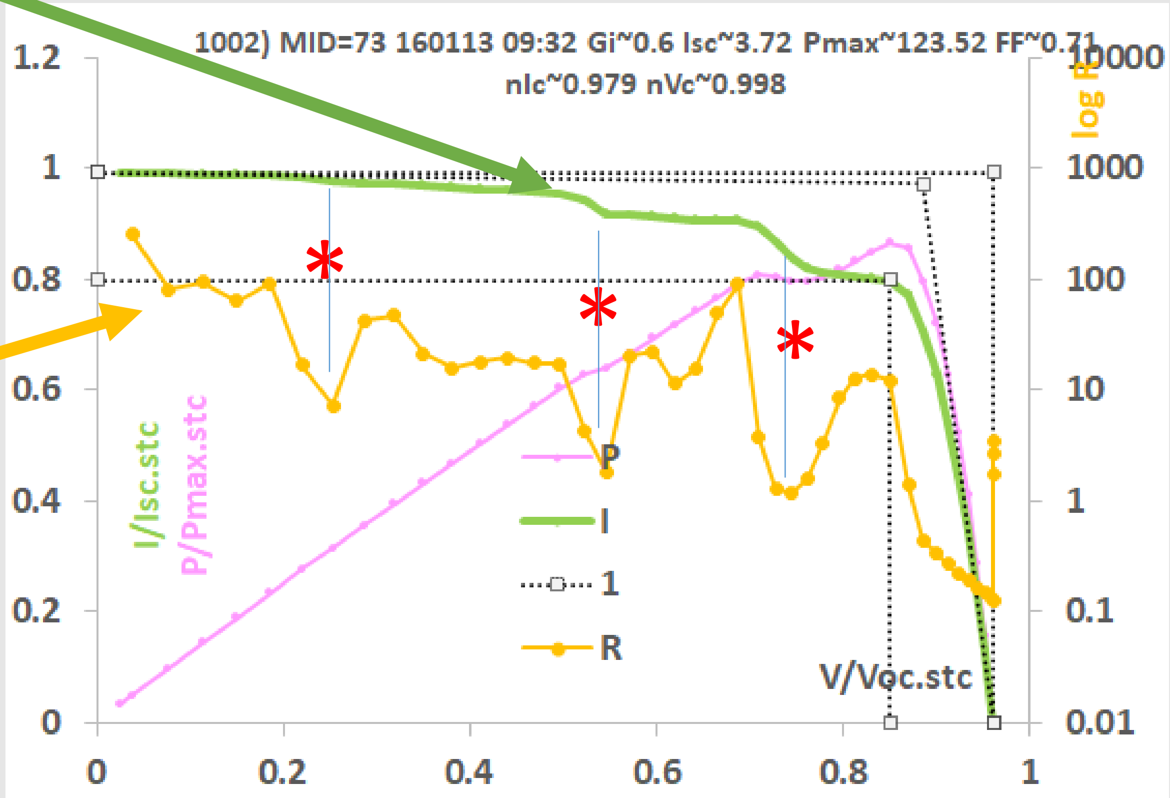
Log (nR_n) vs. V and (G,Tmod), CdTe modules



RV Needs to be smooth only when V<Voc

Gantner(L) much smoother I_{SC} than NREL Daystar (R)

- **Normalised IV curve** ($I_{MEAS}/I_{SC.STC}/G_I$ vs. $V_{MEAS}/V_{OC.STC}$) shows steps (*) between I_{SC} and I_{MP} indicative of cell current mismatch due to broken cells, variability or shading
- Derivation of **nRV curves** quantify and qualify the three steps (minima in nRV curve)
- Steps are also apparent in **PV curve**
- As nRV is normalised value should be ~1 at I_{MP} on a perfect (stepless) curve



cSi and Thin Film normalised IV curves Imeas/Isc.stc vs. Vmeas/Voc.stc

MORNING 09:32
MID IRRADIANCE 0.6kW/m^2

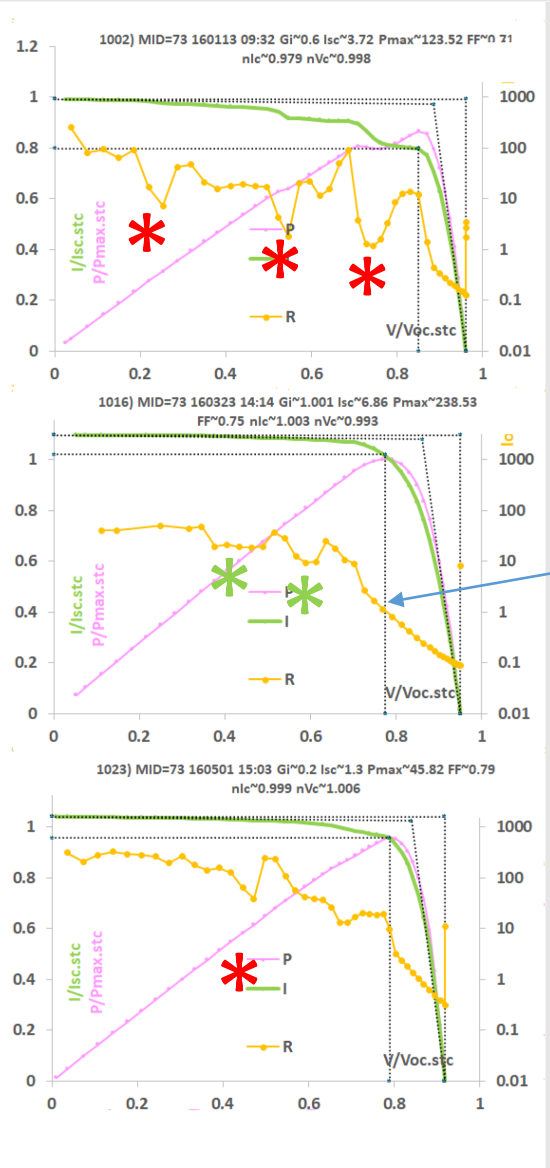
FF : Lower c-Si
nRv : 3 Steps low<10

MID DAY 14:14
HIGH IRRADIANCE 1.0kW/m^2

FF : High
nRv : Smooth low>10

MID DAY 15:03
LOW IRRADIANCE 0.2kW/m^2

FF : High
nRv : Smooth low>10



$nR_n = -\Delta V/\Delta I$ * Rmp.stc (should be 1 at Vmp for a "perfect" IV curve)

- Accurate IV data such as GI's can be used to determine steps from shading and mismatch
- Each step has its own dip
- Rule of thumb: if a dip is below 10 it is noticeable

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cSi Thin Film

cSi and Thin Film normalised IV curves Imeas/Isc.stc vs. Vmeas/Voc.stc

nR_n = -ΔV/ΔI * rVmp/rImp (should be 1 at Vmp for a "perfect" device as top)

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MORNING 09:32
MID IRRADIANCE 0.6kW/m²

FF : Lower c-Si
nRv : 3 Steps low<10

MID DAY 14:14
HIGH IRRADIANCE 1.0kW/m²

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LOW IRRADIANCE 0.2kW/m²

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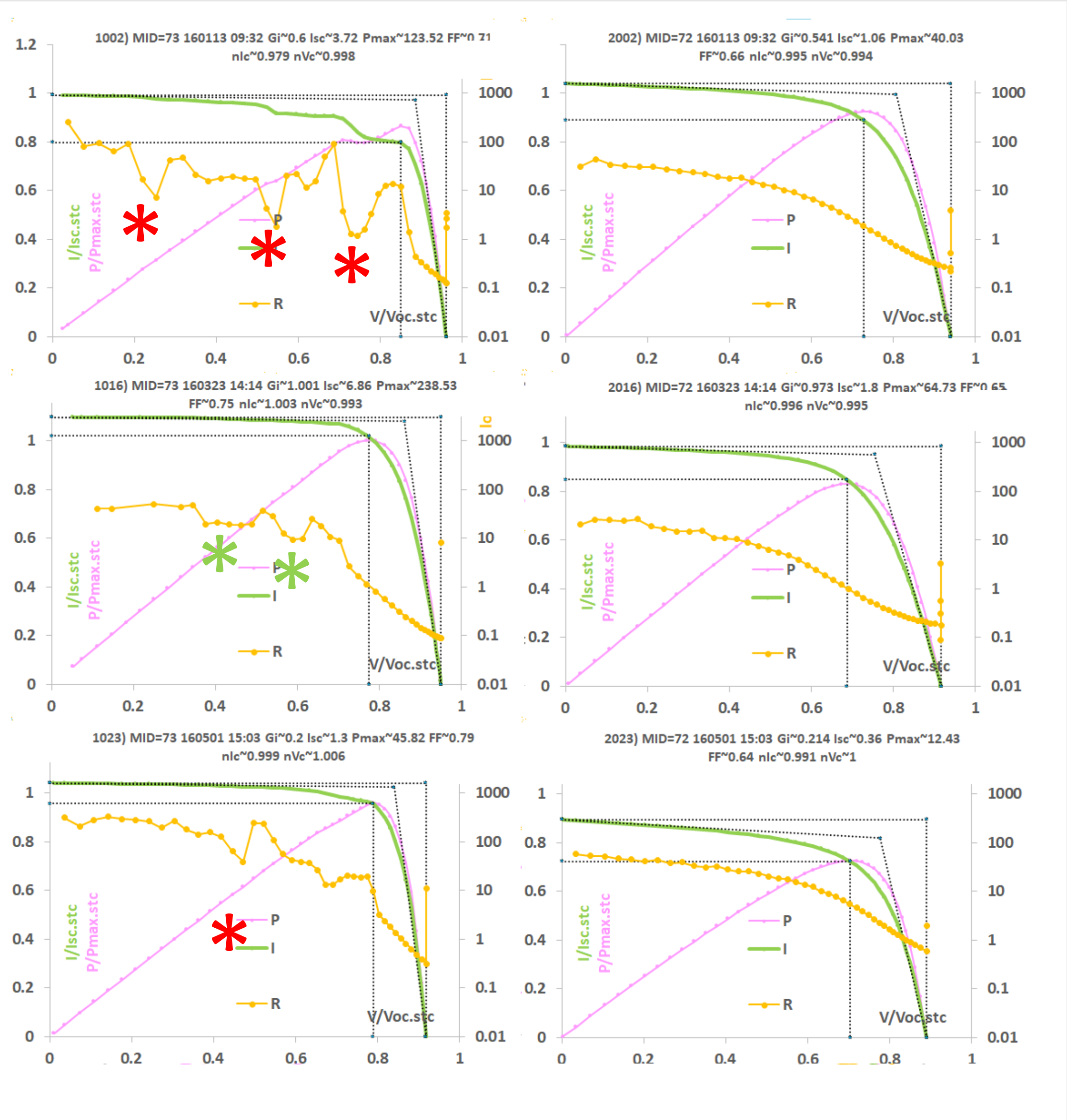

cSi　　Thin Film

- Accurate IV data such as GI's can be used to determine steps from shading and mismatch
- Each step has its own dip
- Rule of thumb:
  if a dip is below 10 it is noticeable

Thin Film generally has lower FF than c-Si so doesn't show any large curvature effects

(Generalise naming : previous LFM had 6 parameters and is called LFM6)

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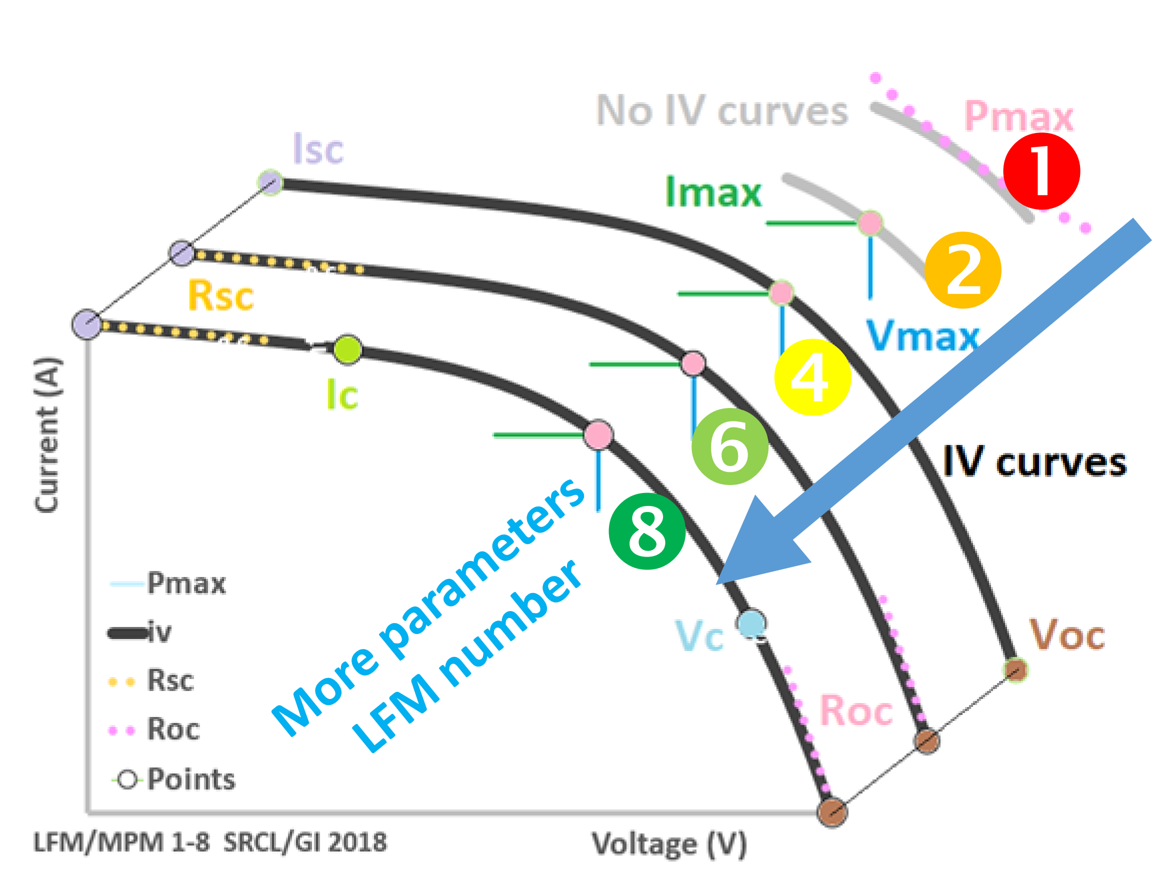
LFM#	Parameters available and description (New)			
❶		Pmax		(no IV curve, tangent)
❷		Imax, Vmax		(no IV curve, 2 points)
❹	Isc,	Imax, Vmax	and Voc	
❻	Isc, Rsc,	Imax, Vmax,	Roc and Voc	
❽	Isc, Rsc, Ic, Imax, Vmax, Vc, Roc and Voc			

Where

Ic = Icurvature (measured vs. expected) at Vmp/2 due to cell mismatch, shading, non linear Rshunt

Vc = Vcurvature (measured vs. expected) at Imp/2 due to roll over or other non ideal behaviour



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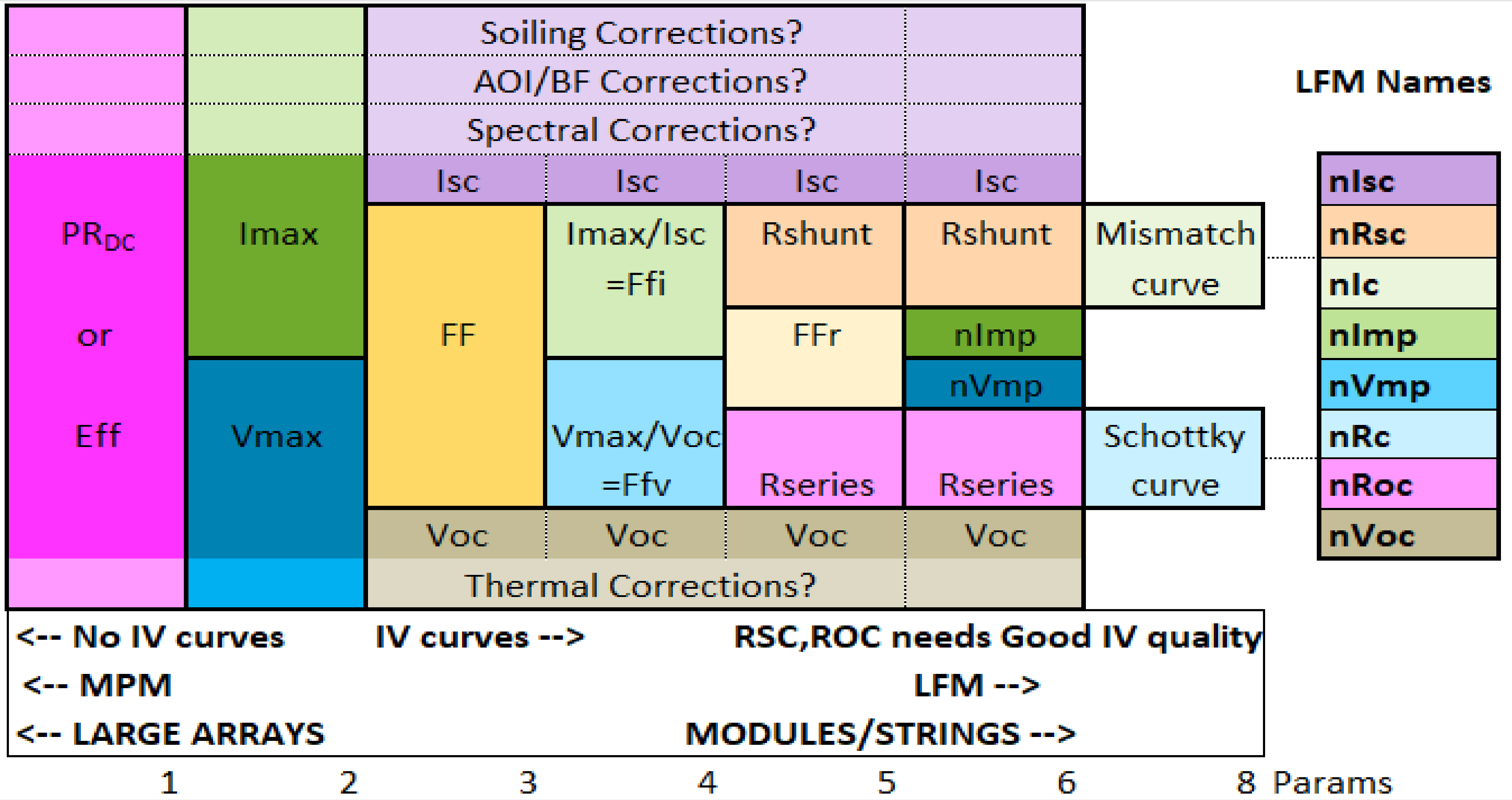
PR_{DC} can be viewed as the product of a number of parameters

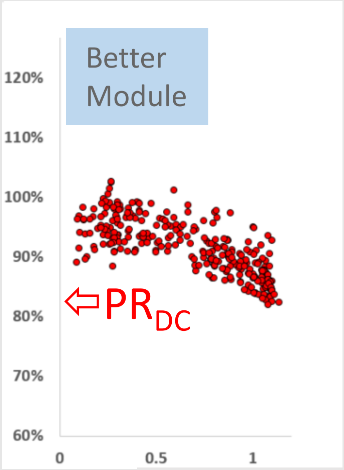


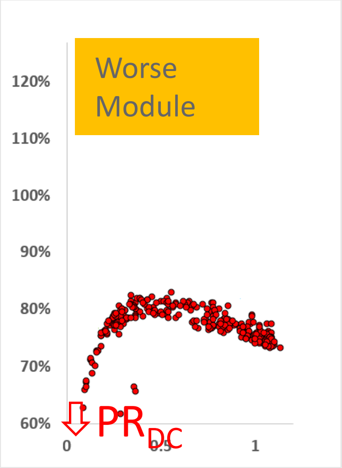
PV Performance can be understood better with more parameters to identify the real cause of changes and underperformance

Model and #parameters = LFM1

Which parameters make these modules differ?

➊ **PR$_{DC}$** at all irradiances and especially at low light





Irradiance kW/m^2

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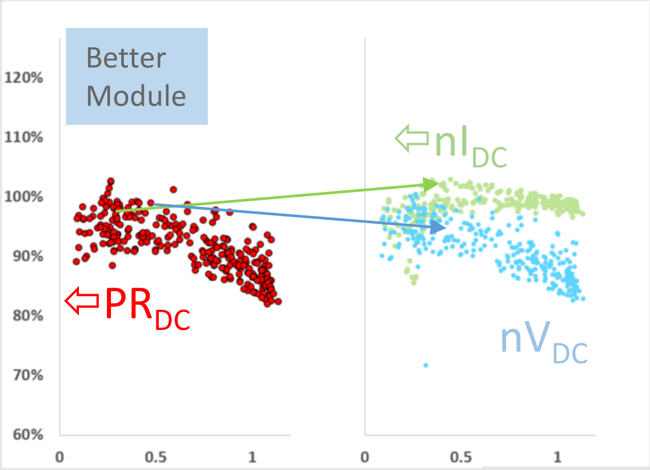
PV Performance can be understood better with more parameters to identify the real cause of changes and underperformance

Model and #parameters = LFM1 LFM2

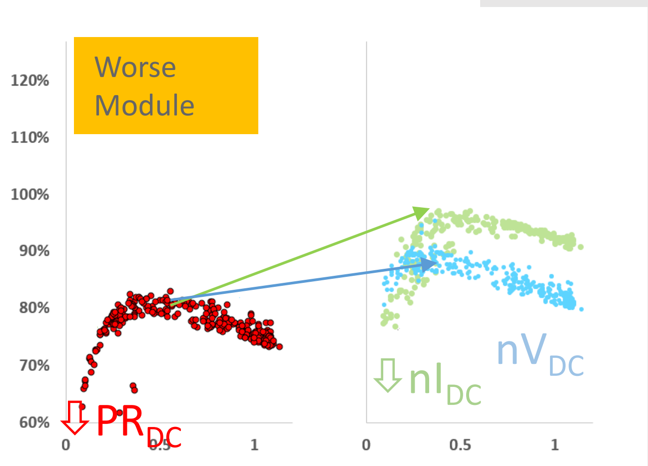
Which parameters make these modules differ?

➊ PR_{DC} at all irradiances and especially at low light

➋ low light nI_{DC}



$PR_{DC} \rightarrow nI_{DC} * nV_{DC}$



Irradiance kW/m²

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PV Performance can be understood better with more parameters to identify the real cause of changes and underperformance

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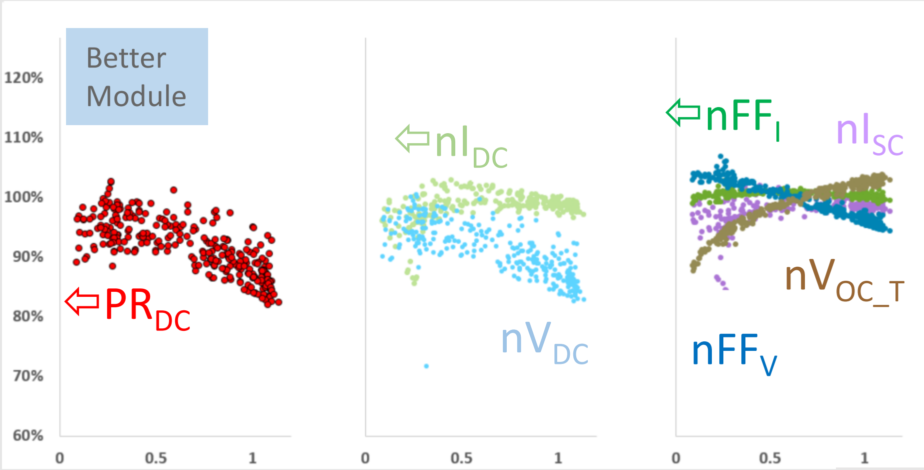
Model and #parameters = LFM1 LFM2 LFM4

Which parameters make these modules differ?

❶ PR_{DC} at all irradiances and especially at low light

❷ low light nI_{DC}

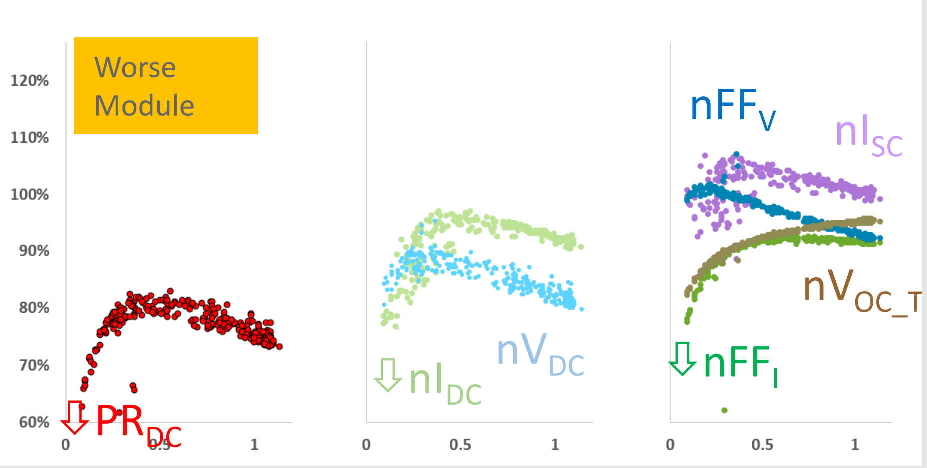
❹ low light nFF_I



$PR_{DC} \rightarrow nI_{DC} * nV_{DC}$

$nI_{DC} \rightarrow nI_{SC} * nFF_I$

$nV_{DC} \rightarrow nV_{OC} * nFF_V$



Irradiance kW/m²

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PV Performance can be understood better with more parameters to identify the real cause of changes and underperformance

Model and #parameters = LFM1 LFM2 LFM4 LFM6

Which parameters make these modules differ?

❶ PR_{DC} at all irradiances and especially at low light

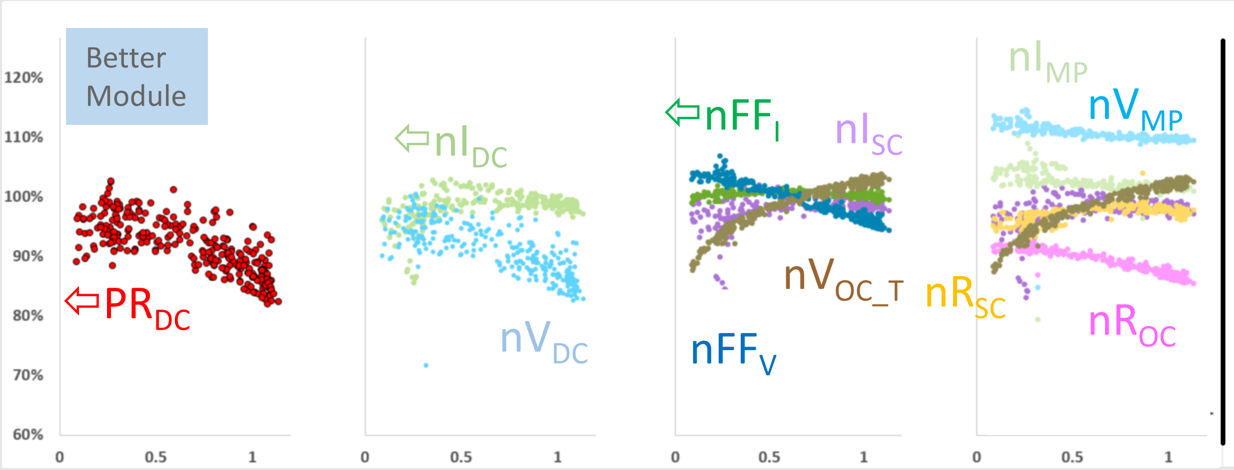
❷ low light nI_{DC}

❹ low light nFF_I

Analysing Resistance parameters needs good quality IV curves

❻ low light nR_{SC} (better R_{SHUNT})

high light nR_{OC} (lower R_{SERIES})



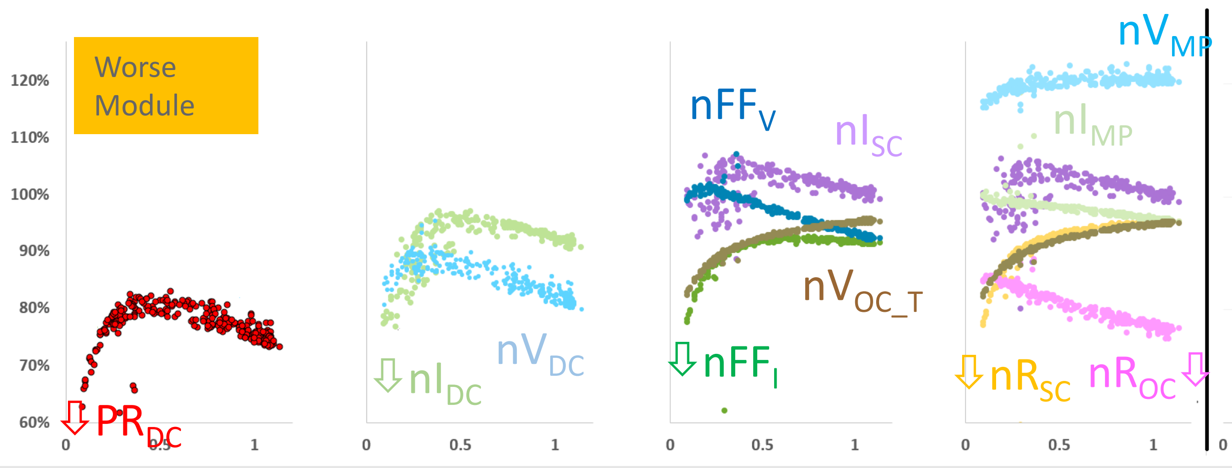
$PR_{DC} \rightarrow nI_{DC} * nV_{DC}$

$nI_{DC} \rightarrow nI_{SC} * nFF_I$

$nV_{DC} \rightarrow nV_{OC} * nFF_V$

$nFF_I \rightarrow nR_{SC} * nI_{MP}$

$nFF_V \rightarrow nR_{OC} * nV_{MP}$



Irradiance kW/m²

LFM6,8 Only possible with highest quality measurements

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PV Performance can be understood better with more parameters to identify the real cause of changes and underperformance

Model and #parameters = LFM1 LFM2 LFM4 LFM6 LFM8

Which parameters make these modules differ?

❶ PR_{DC} at all irradiances and especially at low light

❷ low light nI_{DC}

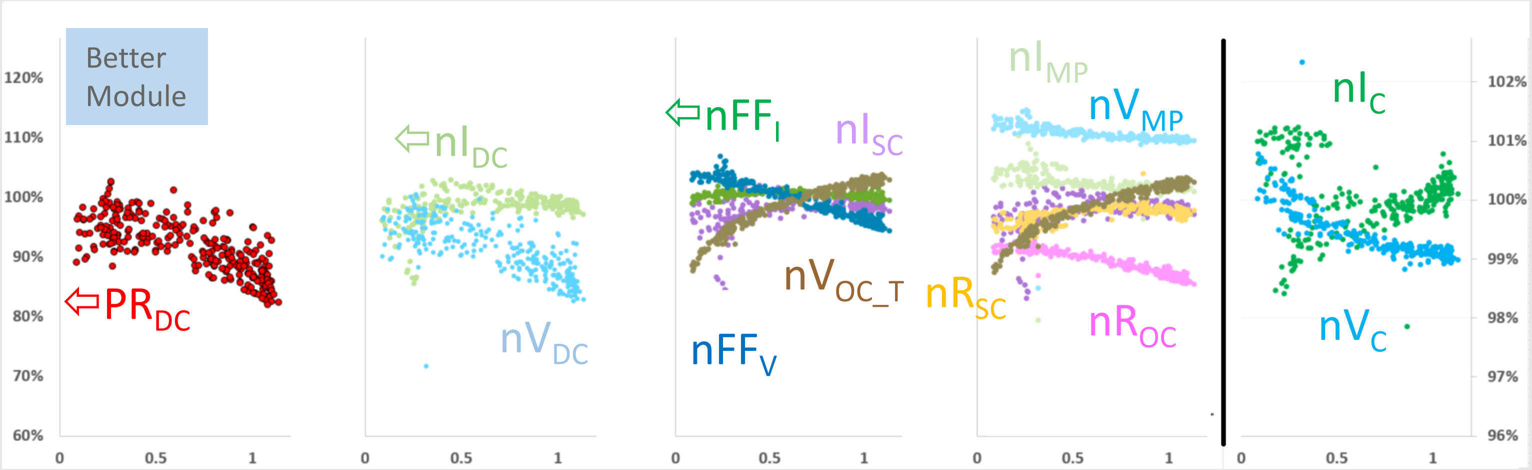
❹ low light nFF_I

Analysing Resistance parameters needs good quality IV curves

❻ low light nR_{SC} (better R_{SHUNT})

high light nR_{OC} (lower R_{SERIES})

❽ Curvature parameters show more nIc scatter in good module particularly at low light (cell mismatch and/or shading), poor module has lower FF so is less affected



$PR_{DC} \rightarrow nI_{DC} * nV_{DC}$

$nI_{DC} \rightarrow nI_{SC} * nFF_I$

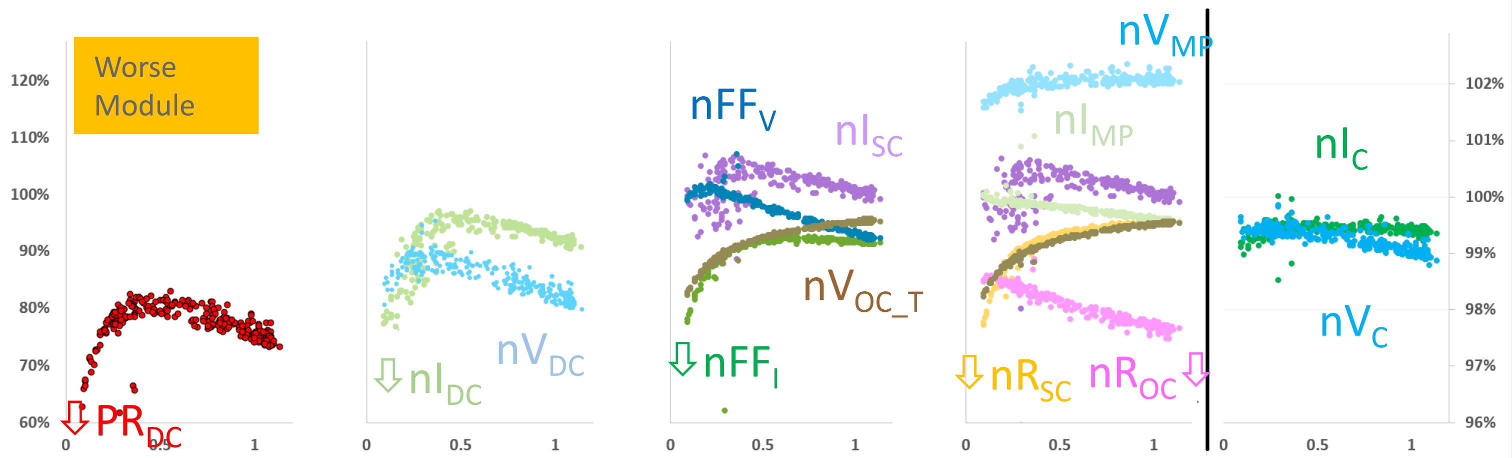
$nV_{DC} \rightarrow nV_{OC} * nFF_V$

$nFF_I \rightarrow nR_{SC} * nI_{MP}$

$nFF_V \rightarrow nR_{OC} * nV_{MP}$

nI_C~cell mismatch

nV_C~Voc rollover



Irradiance kW/m²

LFM6,8 Only possible with highest quality measurements

Using yearly matrix averages to determine outdoor performance

3 LFM parameters vs. G_I and T_{MOD} (coloured dots) for two technologies (GI, 2014)

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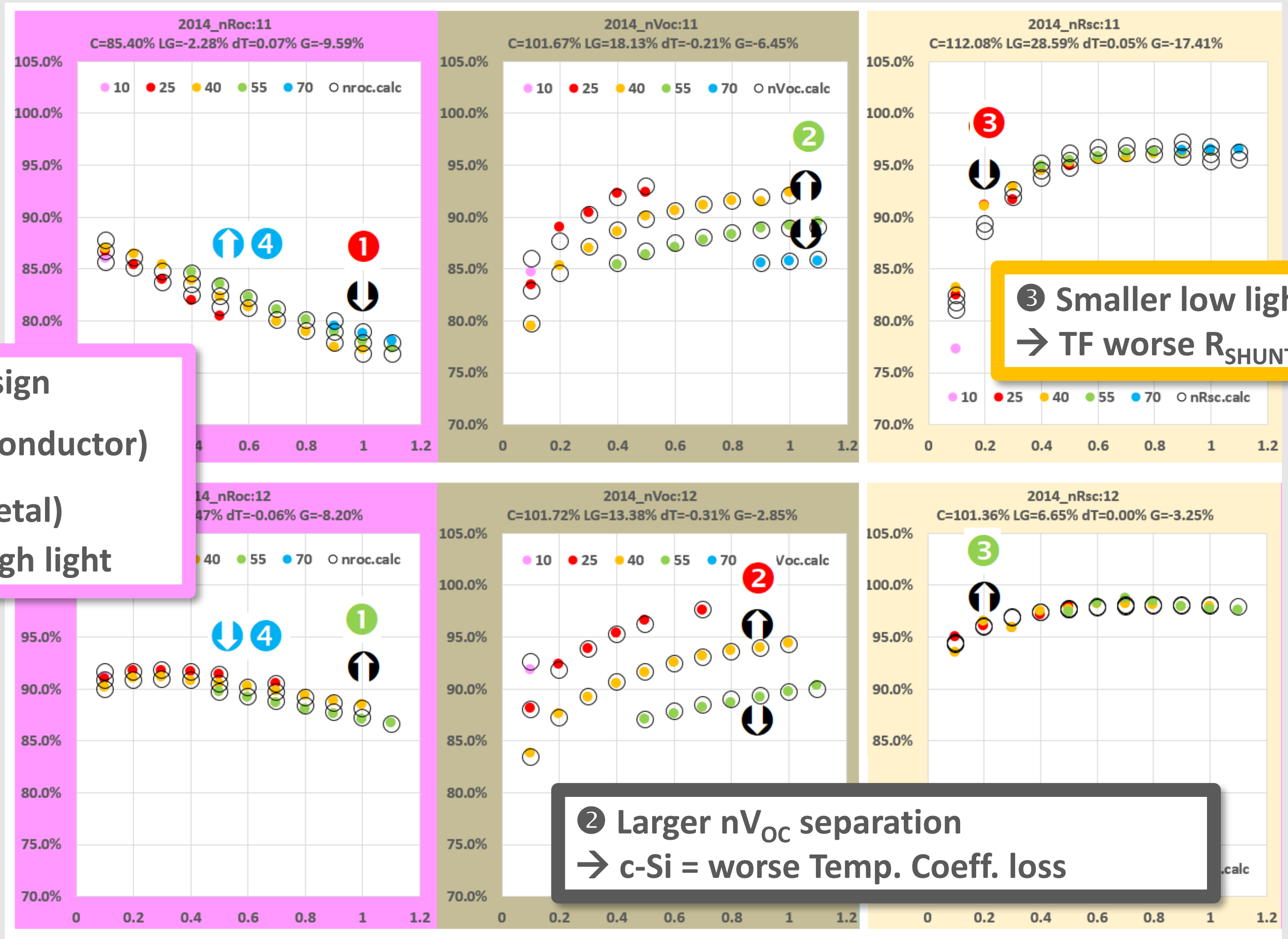
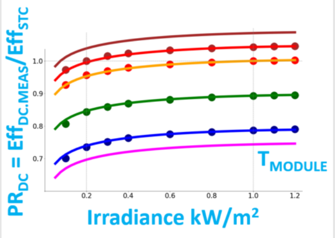
LFM parameter: nR_{OC} (~R_{SERIES}) nV_{OC} (~V_{OC}) nR_{SC} (~ R_{SHUNT})

Degrading thin film #11

Stable c-Si #12





Similar to to PRDC

❹ R_{SERIES} Temp. Coeff. sign

TF +0.07%/K (TCO semiconductor)

c-Si -0.06%/K (tabbing metal)

❶ Thin film worse at high light

❸ Smaller low light nR_{SC}
→ TF worse R_{SHUNT} Loss

❷ Larger nV_{OC} separation
→ c-Si = worse Temp. Coeff. loss

T_{MODULE} (C)

- 10
- 25
- 40
- 55
- 70

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nR_{SC} vs. Gi : Finding the cause and rate of drop of a degrading module 2013-16 (GI)

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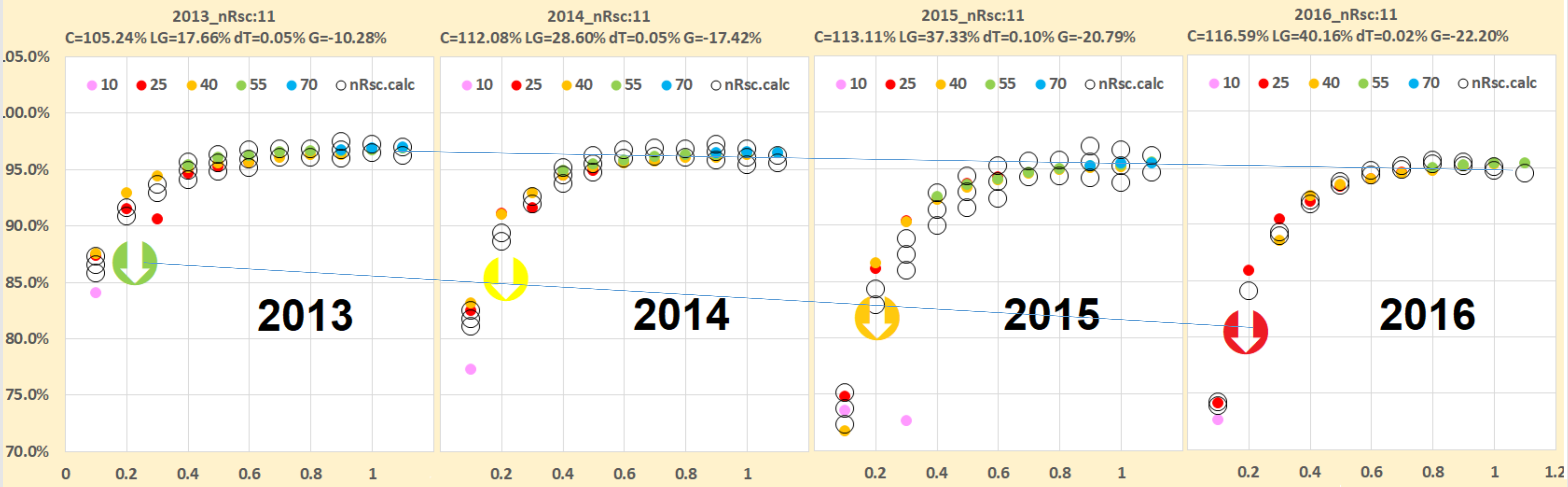

7% Performance fall at low light in 3 years is caused by degrading R_{SHUNT} causing nR_{SC} to reduce but at high light remains similar (GI data)

As PR_{DC} is the product of six coefficients –
<u>any</u> drop or change has a direct influence on PR_{DC} and therefore energy yield.

T_{MODULE} (C)
- 10
- 25
- 40
- 55
- 70

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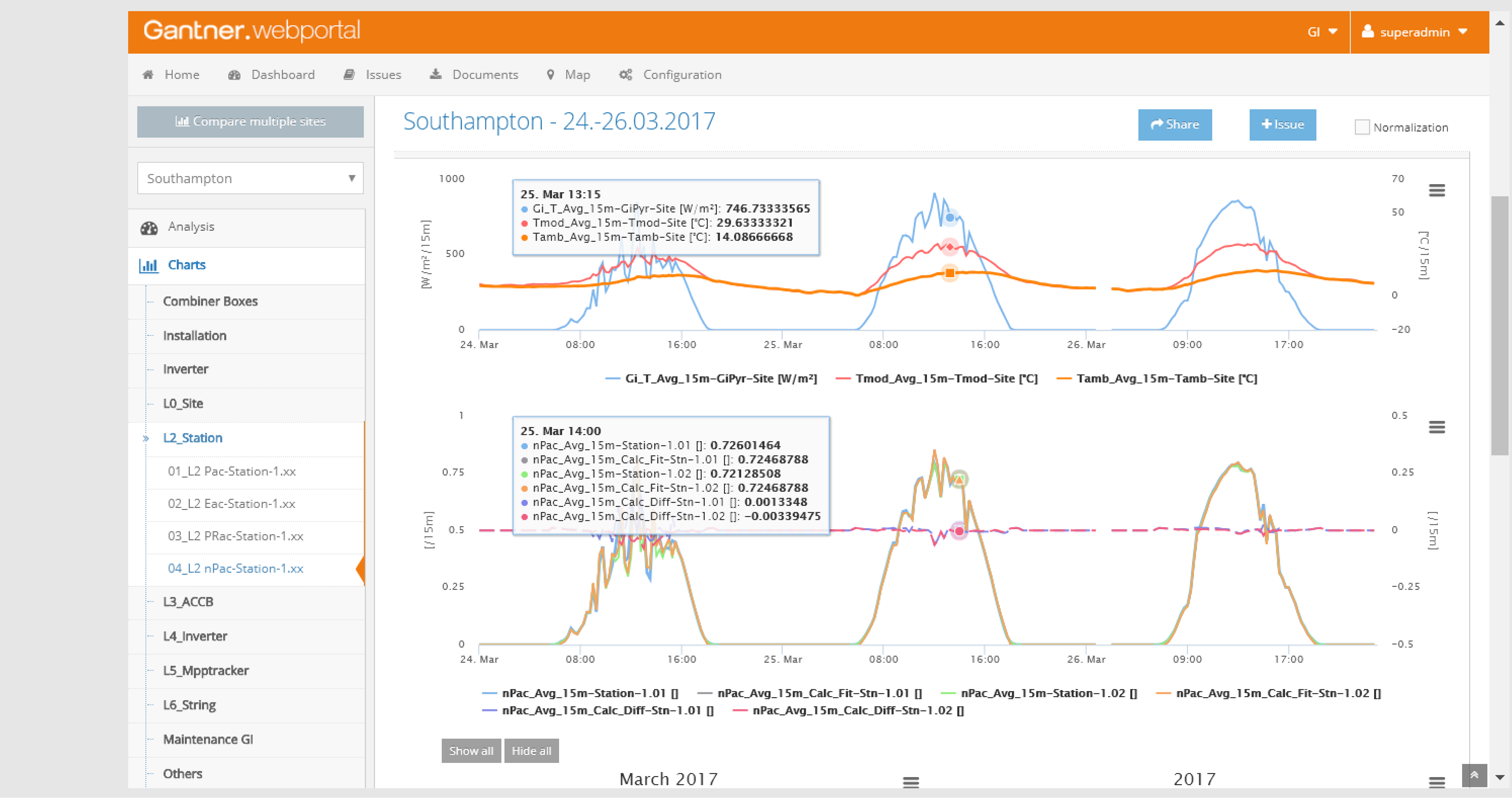
Large array UK variable weather day LFM 2 (I_{DC} and V_{DC}) predicted performance (real time)



IPERMON - Joint project with UCY to merge approaches

(as seen with Marios Theristis talk yesterday)

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FOSS Research Centre for Sustainable Energy

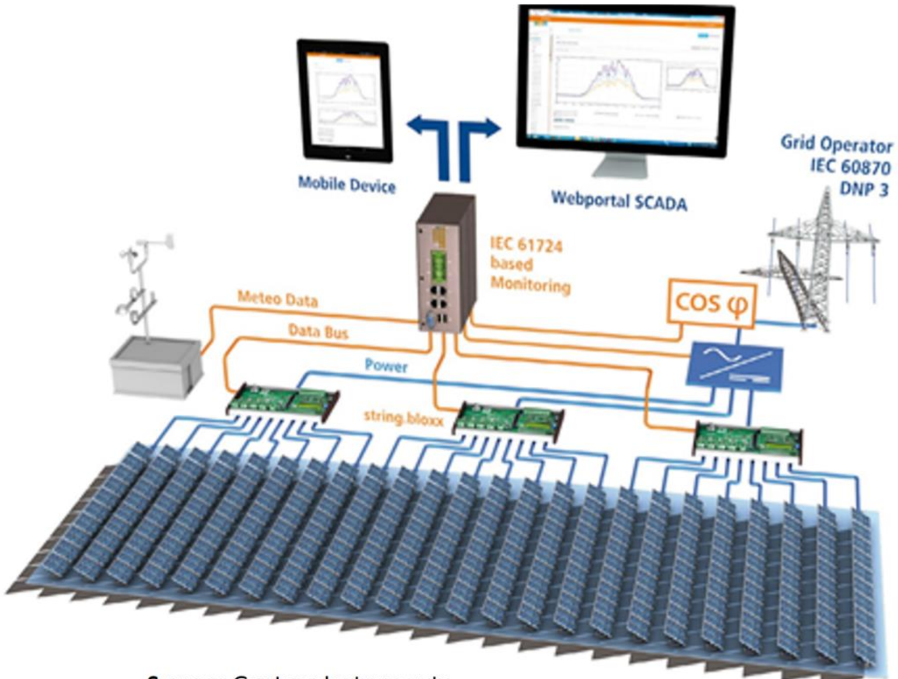
Gantner instruments — University of Cyprus PV Technology

Ipermon SOLAR-ERA.NET

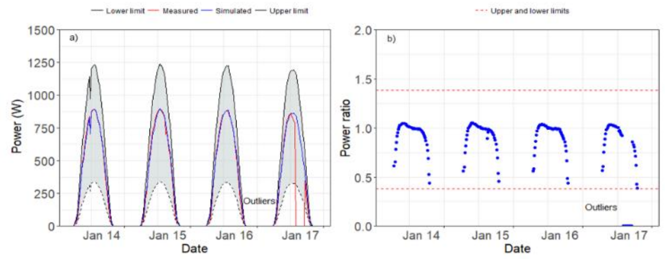
IPERMON

Partners: Gantner Isntruments and University of Cyprus
Project: IPERMON [Solar-ERA.net project]
Budget: €400,000
Duration: 36 Months
Weblink: http://www.pvtechnology.ucy.ac.cy/projects/ipermon/

Development of innovative condition monitoring platform (algorithms and devices to quantify performance loss, diagnose faults and estimate degradation from acquired data).



Source: Gantner Instruments



30/04/2018

5

Conclusions

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- **Sophisticated modelling and analysis can be performed using the combined MPM/LFM method**
- **The normalised RV method shows data quality and also analyses steps from cell mismatch or shading**
- **If IV curves are not available (e.g. large arrays) then a good understanding of PV performance can be derived.**
- **With good IV curves (as from Gantner) the causes of any underperformance and rates of any PV degradation (e.g. ”R_{SHUNT} at low light”) can easily be found using these methods**
- **Scalable fault detection and analytics are available on the Gantner webportal available serving industry requirements**

Thank you for your attention

[1] Ransome et al, 44th PVSC 2017 Washington DC "How to Choose the best Empirical Model for Optimum Energy Yield Predictions"
[2] Shiga “ 7TuPo "QUANTIFYING AND ANALYSING THE VARIABILITY OF PV MODULE RESISTANCES RSC AND ROC TO UNDERSTAND AND OPTIMISE KWH/KWP MODELLING"
[3] Shiga “7MoO.5.4 "OPTIMISED FITTING OF INDOOR (E.G. IEC 61853 MATRIX) AND OUTDOOR PV MEASUREMENTS FOR DIAGNOSTICS AND ENERGY YIELD PREDICTIONS"
[4] http://www.gantner-webportal.com
[5] Optimized PV Performance using State of the Art Monitoring for Increased Asset Value PVPMC8 2017

Gantner instruments

Spare slides

SRCL
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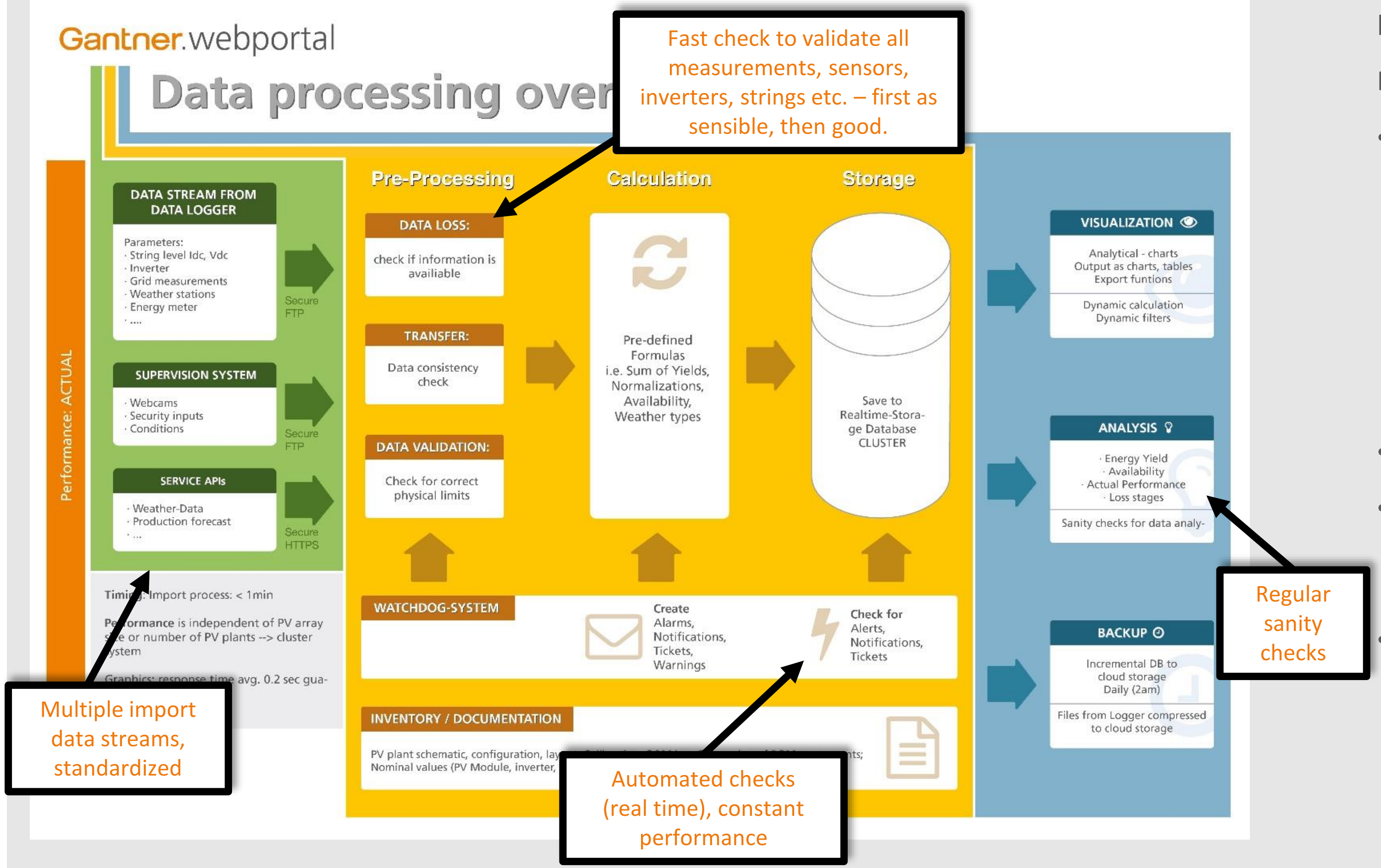

Data processing - real time

Multiple sources need harmonized data concept

- Naming convention:
  - For fast and easy use
  - Structure: {Parameter}_{Modifier}-{Component}-{ID}

    Example:
    Pdc -Inv-1.1.1-1,
    Pdc_T-Inv-1.1.1-1
    Gi-GiPyr-1.1
    Idc-Mpp-1.01.01.03.1
- Color code & Unit convention
- Filters/Limits:
  - Run all data sets with standardized filters
- Converter for 3rd party