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Quantifying Long Term PV Performance and Degradation under Real Outdoor and IEC 61853 Test Conditions Using High Quality Module IV Measurements

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INTRODUCTION

- **Many PV performance degradation studies only report changes of P_{MAX} (corrected to STC) with time**
- **The type of degradation (e.g. R_{SHUNT}, R_{SERIES}) can cause differences in "P_{MAX} vs. instantaneous conditions" and also "Energy Yield vs. site"**

Degradation type	P_{MAX} vs. irradiance G_I	Energy Yield vs. insolation site Y_R
Rshunt ↓	Bigger fall at low irradiance	Worst at low insolation sites
Rseries ↑	Falls more at high irradiance	Largest drop high insolation sites
Isc ↓	Similar	Similar

- **A new approach is given which can :**
  - **identify 12 different causes of underperformance or instability**
  - **quantify degradation rates vs. time**
  - **calculate power degradation vs. weather or energy yield degradation by climate**

Example graphs are shown for 9 years of data Modules #11 Thin film (slightly degrading), #12 c-Si (stable) and #15 Thin Film (catastrophic failure)

EXPLANATION OF LFM COEFFICIENTS

	Previous LFM 6	More Detailed LFM 12	Loss is Related to	When do worst losses usually occur ?
1		Soiling	Time since rain; dusty sites	After long, dry periods
2		Spectral Response	EQE vs. Spectral distribution (SF)	Thin Film – Redder ; MJ – when not matched
3		Reflectivity	Reflectivity vs. AOI and Beam Fraction (BF)	Clear sky, off Axis; no ARC
4	I_{SC}	I_{SC}	Browning, Delamination	
5	R_{SC}	R_{SC}	R_{SHUNT}	Low light levels
6		Curvature I_{SC} to I_{MP}	Mismatch from cell cracking or shading	Low light levels
7	I_{MP}	FF_I	Fill factor (I and V separate) independent R_{SHUNT}, R_{SERIES}	
8	V_{MP}	FF_V		
9		Curvature V_{MP} to V_{OC}	If non ohmic back contact, roll over	High light levels
10	R_{OC}	R_{OC}	Related to ~ R_{SERIES} (+exponential component)	High Light levels
11	V_{OC}	V_{OC}	Varies as ~Log irradiance	Low light levels
12		Tempe-rature	Gamma (P_{MAX} but can be separated components)	High Temperatures, cSi

IV CURVE ANALYSIS vs. G_I and T_{MOD}

A 1-diode model (e.g. de Soto) can't fit IV curves well with

☒ cell mismatch or shading (steps between I_{SC} and I_{MP})
☒ rollover (non ohmic back contact glitches ~ V_{OC})
☒ other "imperfections" in measurements

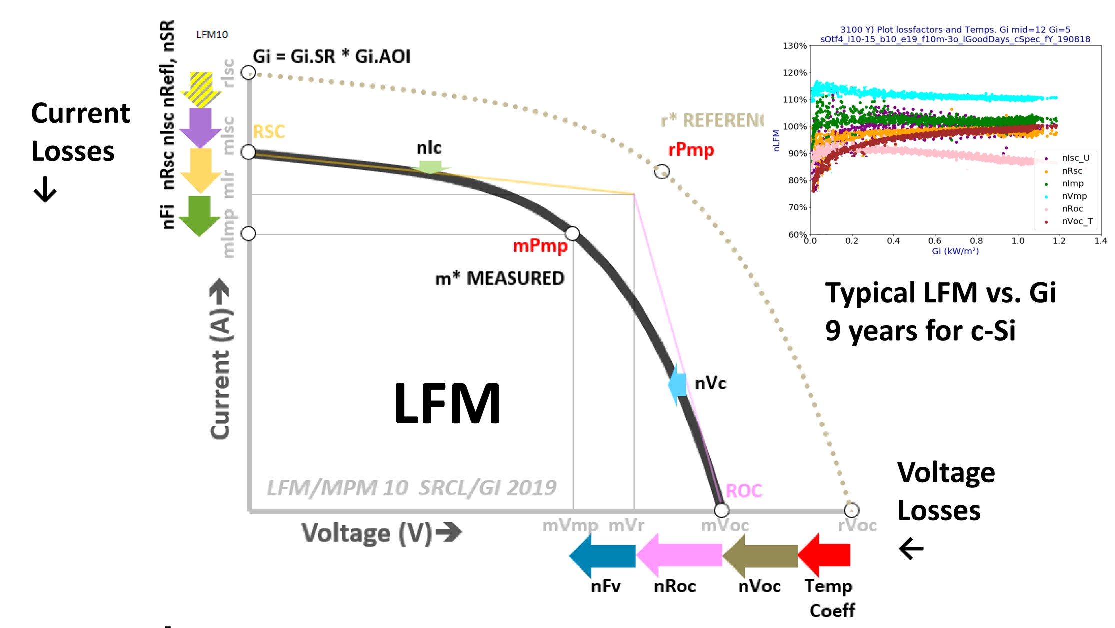
Irradiance and Temperature corrections to STC (e.g. using IEC 60891) rely on linear behaviour and exact factors being known

An updated **"Loss factors Model"** (with 12 detailed parameters) has been developed to avoid these limitations

☑ fits <u>any</u> IV curves (even imperfect traces)
☑ qualifies/quantifies "faults" such as shading or mismatch
☑ performs spectral and reflectivity/aoi corrections

LFM parameters are

☑ technology agnostic
☑ area independent
☑ normalised
☑ meaningful e.g. "% power loss due to R_{SERIES}"



$$PR_{DC} = \frac{1}{rFF} * [nI_{SC} \times nR_{SC} \times nF_I] \times [nF_V \times nR_{OC} \times nV_{OC}]$$

Corrections for reflectivity and spectral response

$$nI_{SC_{T,AOI}} = nI_{SC_T} \times ((1 - BF \times cAOI \times (1/\cos(AOI)) - 1)) + cBF \times BF$$

$$nI_{SC_{T,SPEC}} = nI_{SC_T} \times fn(SF) = nI_{SC_T} \times (1 + cSF_M \times (SF - cSF))$$

$$SF = \sum G_{350...650nm} / \sum G_{350...1050nm}$$

MATRIX METHOD PR_{DC} vs. G_I and T_{MOD}

PV performance can also be measured at a matrix of irradiances and module temperatures e.g. "PR_{DC} @100-1100W/m²;10-85C"

IEC 61853-3:2018 specifies a bilinear interpolation fit but this

☒ extrapolates non-linear functions inaccurately
☒ is affected by missing data
☒ has poor accuracy if there are random scatter errors

The **"Mechanistic Performance Model"** (MPM) is used here as it

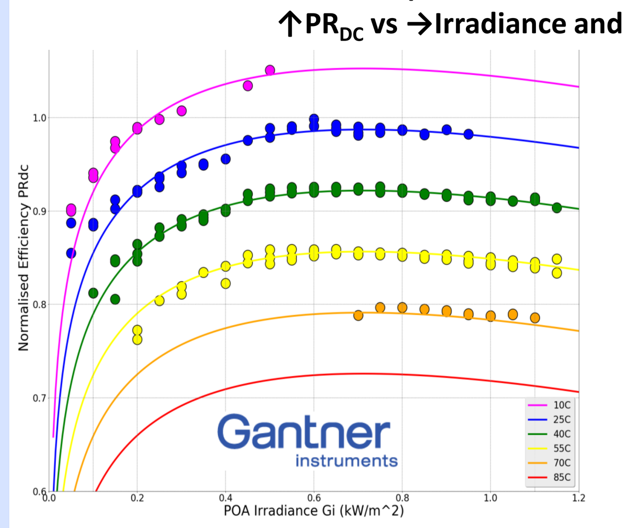
☑ optimally fits any matrix data (PR_{DC}, nI_{SC}, nV_{OC}, nR_{SC} etc.).
☑ has been verified against data from 10+ top institutes
☑ used successfully since 2017

MPM : $PR_{DC} = C_1 + C_2 \times dT_{MOD} + C_3 \times Log_{10}(G_I) + C_4 \times G_I + C_5 \times WS$

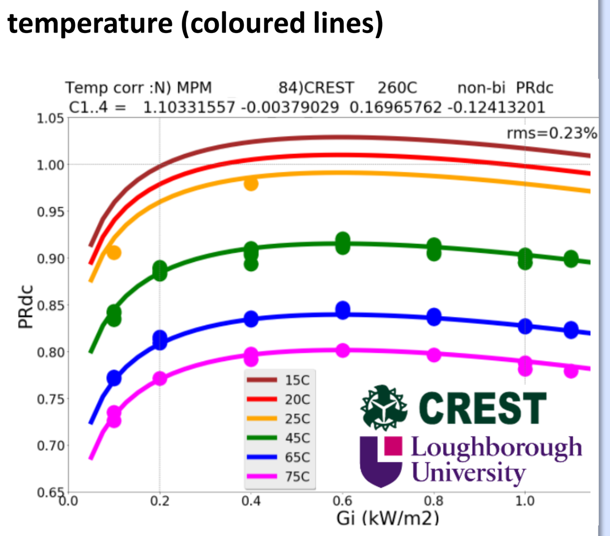
Tolerance | Temperature coeff | Low light ~V_{OC}, R_{SHUNT} | High light R_{SERIES} | Wind

Where $dT_{MOD} = (T_{MOD}-25)C$; G_I = kW/m²; WS = ms⁻¹

Example Matrix measurements and MPM fits: ↑PR_{DC} vs →Irradiance and temperature (coloured lines)



Typical MPM fit lines to outdoor data 4000 data points, binned, 1year at OTF

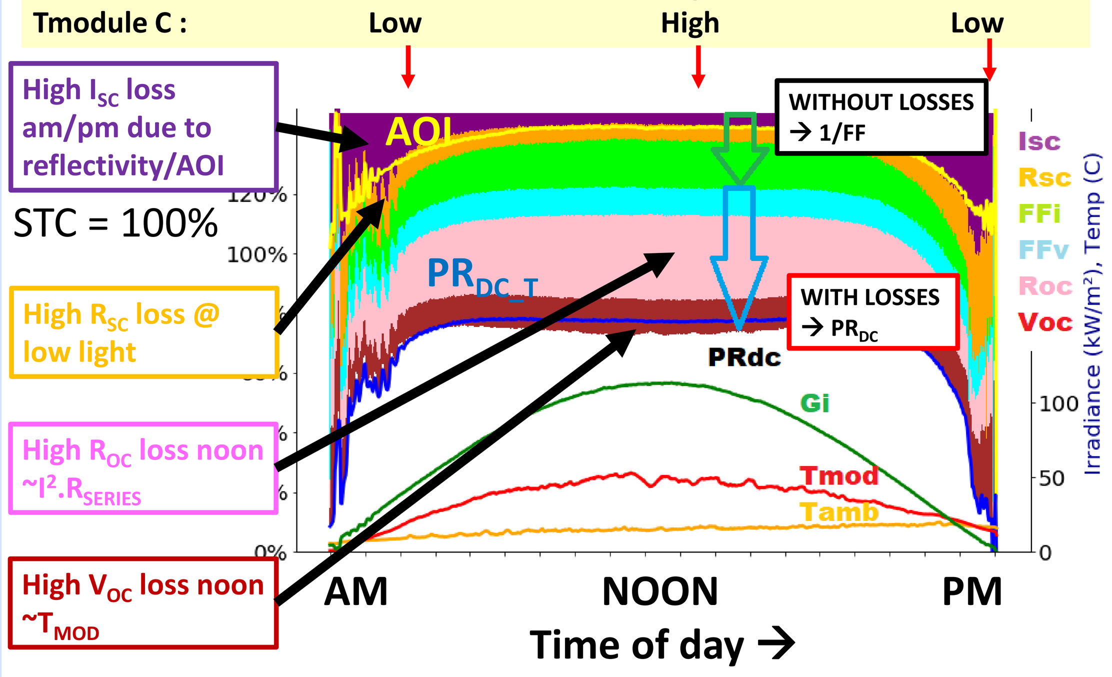


Typical MPM fit lines to indoor data 1-3 measurements at ~23 points

☑ The MPM has "**normalised, orthogonal, robust and meaningful**" coefficients C_1 to C_5
☑ C_1-C_5 magnitudes give <u>normalised losses</u>
☑ Changes C_1-C_5 with time give <u>normalised degradation rates</u> and imply cause

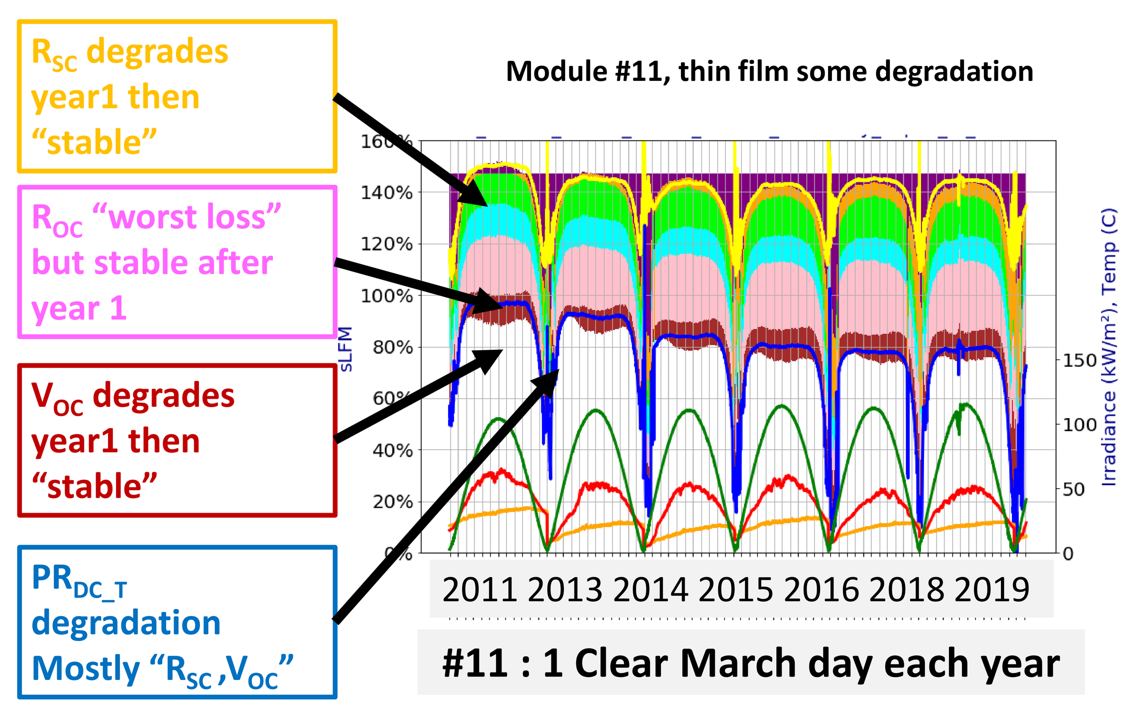
PV PERFORMANCE vs. LOSS TYPES (1 day)

AOI deg :	High	Low	High
Spectrum AM :	Redder	Bluer	Redder
Irradiance kW/m² :	Low	High	Low
Tmodule C :	Low	High	Low



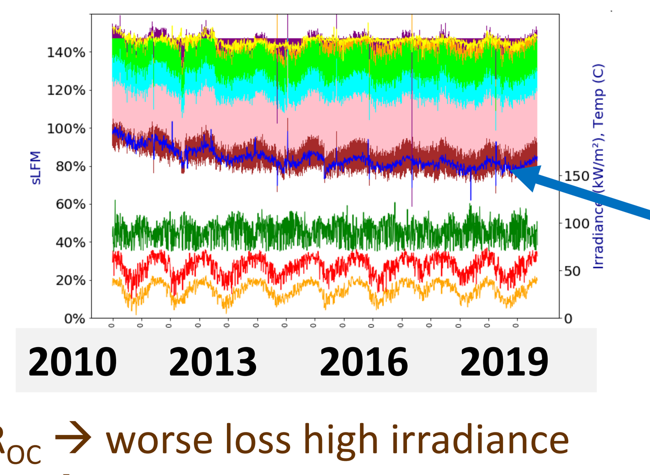
Tallest stripes → biggest cause(s) of performance loss

DEGRADATION vs. LOSS TYPE and TIME



- "Smooth height increase vs. time" give degradation rate
- "Sudden changes" mean performance glitch e.g. breakage

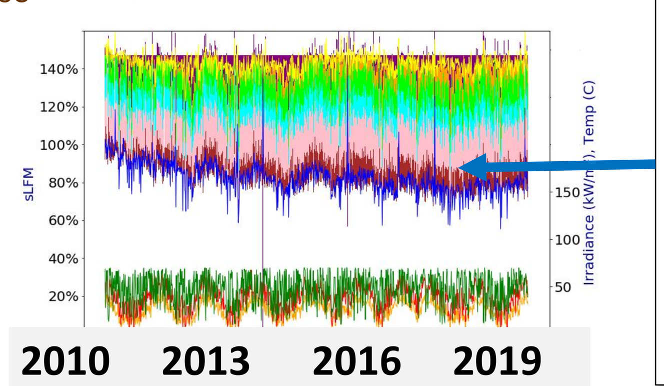
DEGRADATION vs. LOSS TYPE, IRRADIANCE



#11 HIGH Gi>0.7kW/m²

Loss	2010	2019
R_{SC}	3%	6%
R_{OC}	22%	26%
V_{OC}	11%	15%
PR		
PR_{DC_T}	92%	77%

R_{OC} → worse loss high irradiance
R_{SC} → higher loss at low irradiance



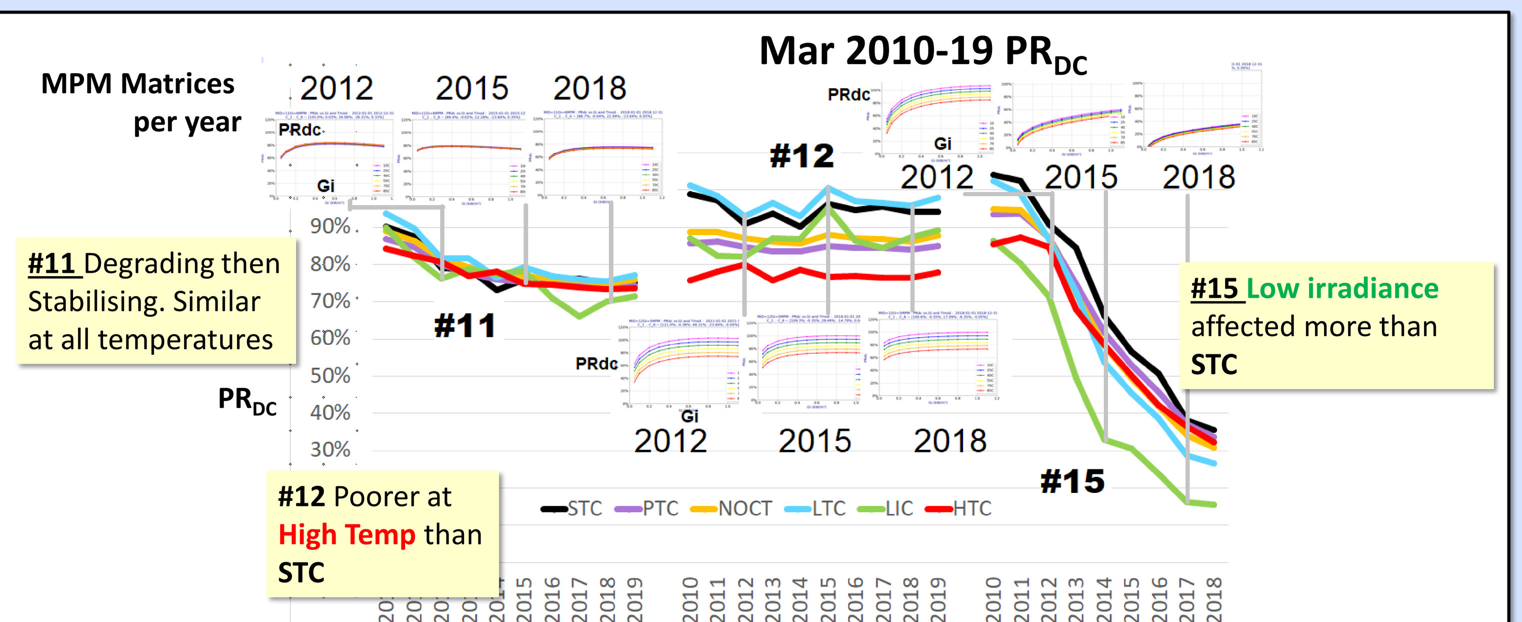
#11 LOW Gi<0.7kW/m²

Loss	2010	2019
R_{SC}	4%	10%
R_{OC}	18%	21%
V_{OC}	9%	14%
PR		
PR_{DC_T}	90%	74%

(Fewer low light measurements in AZ so more scatter)

DEGRADATION @ WEATHER CONDITIONS (e.g. IEC 61853)

IEC 61853 weather conditions	standard test	PVUSA	Nom op.cell temp	low temp.	low irrad	high temp
Abbreviation / Value (approx)	STC	PTC	NOCT	LTC	LIC	HTC
G_I (kW/m²)	1	1	0.8	0.5	0.2	1
T_{AMB} (C)	-	20	20	-	-	-
T_{MOD} (C)	25	(~55)	(~47)	15	25	75
WS (ms⁻¹)	0	1	1	0	0	0
Tilt (degrees)	-	-	45	-	-	-
AM (#)	1.5	1.5	1.5	1.5	1.5	1.5



DEGRADATION/yr 2010-2019 vs. IRRADIANCE

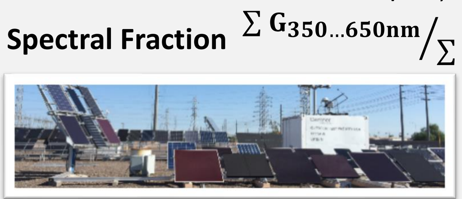
MID	Gi	PRdc_U	sIsc_U	sRsc	sRoc	sVoc_U
11	ALL	-1.6%	-0.2%	-0.5%	-0.4%	-0.5%
11	HIGH	-1.5%	-0.3%	-0.4%	-0.4%	-0.4%
11	LOW	-1.8%	-0.1%	-0.8%	-0.3%	-0.6%
12	ALL	-0.1%	-0.2%	0.0%	0.0%	0.1%
12	HIGH	-0.1%	-0.3%	0.0%	0.0%	0.1%
12	LOW	0.0%	-0.1%	0.1%	0.0%	0.1%
15	ALL	-8.8%	0.2%	-2.2%	-1.6%	-5.2%
15	HIGH	-8.6%	0.0%	-2.1%	-1.3%	-4.9%
15	LOW	-9.3%	0.4%	-2.3%	-2.2%	-5.7%

#11 R_{SC} R_{OC} and V_{OC} degradation, worse @low light

#12 "Stable" ~0.1%/yr

#15 Mostly R_{SC} V_{OC} and R_{OC} degradation, worse @low light

GLOSSARY

Loss Factors	%losses due to parameters such as R_{SERIES}, underperformance etc.
LFM	Loss factors model (previous 6, more detailed 12) meaningful, normalised loss coefficients
MPM	Mechanistic performance model optimally fits PR_{DC}=f(G_I,T_{MOD})
Empirical	Simple model with non normalised, non meaningful coefficients
Mechanistic	Better model with normalised, meaningful coefficients
Matrix method	Measure PV performance at given array of (GI, Tmod) points
Normalised	Divide by reference values, area independent quality factors ~1
PR_{DC}	DC performance ratio = meas.Pmax/ref.Pmax/Irradiance(suns)
G_I	Plane of array instantaneous irradiance (kW/m²)
T_{MOD}	Module temperature (C)
STC	Standard Test Conditions 1kW/m², 25C T_{MOD}, AM1.5, WS 0 ms⁻¹
SF	Spectral Fraction $\sum G_{350...650nm} / \sum G_{350...1050nm}$
GI OTF	

CONCLUSIONS

The enhanced **Loss Factors Model (LFM-12)** and **Mechanistic Performance Model (MPM)** have been used together to

- Find reasons and magnitudes for any faults/underperformance
- Quantify long term degradation rates at different weather conditions such as IEC 61853.
- The LFM/MPM method has been added to Gantner Instruments' Outdoor Facility Solution and Analytics platform gantner-instruments.com/products/software/gi-cloud/, can be accessed with API interface, e.g. for machine learning or model verification
- **[*] "Checking the new IEC 61853.1-4 with high quality 3rd party data to benchmark its practical relevance in energy yield prediction" 46th PVSC Chicago 2019**