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UNDERSTANDING DISCREPANCIES IN MODULE DEGRADATION AND PERFORMANCE LOSS RATE

PVPMC: Closing the loop from operations to design

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INTRODUCTION

- Industry frequently mixes up degradation rate (Rd) with performance loss rate (PLR) with misleading conclusions
- They are related but not identical
- This can bias conclusions about reliability and energy predictions
- Real PLR and Rd values are unknown in field data and are challenging to estimate
- Here we present Sandia's long-term exposure (SLTE) data to examine these differences [1]

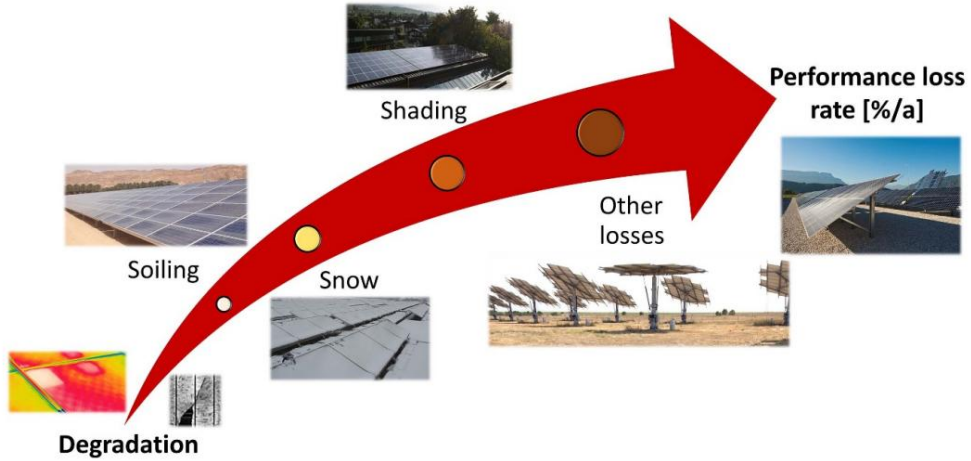

Figure 5. Relation between degradation and performance loss rate—PLR expresses all losses as a single rate.

Source: S. Lindig, M. Theristis, D. Moser, "Best practices for photovoltaic performance loss rate calculations", PRGE, 10.1088/2516-1083/ac655f

PROGRESS IN PHOTOVOLTAICS

RESEARCH ARTICLE | Open Access

Onymous early-life performance degradation analysis of recent photovoltaic module technologies

Marios Theristis, Joshua S. Stein, Chris Deline, Dirk Jordan, Charles Robinson, William Sekulic, Allan Anderberg, Dylan J. Colvin, Joseph Walters ... See all authors

First published: 07 August 2022 | https://doi.org/10.1002/pip.3615 | VIEW METRICS

Check for full text at Sandia Technical Library

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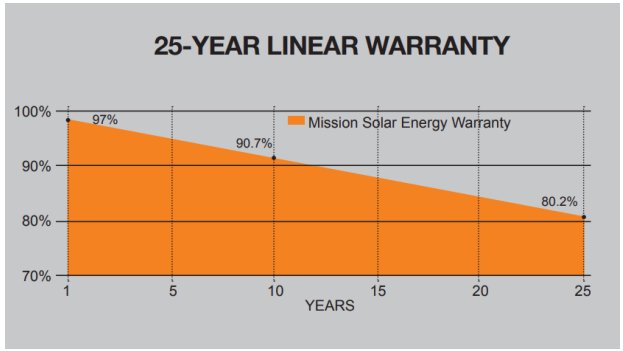
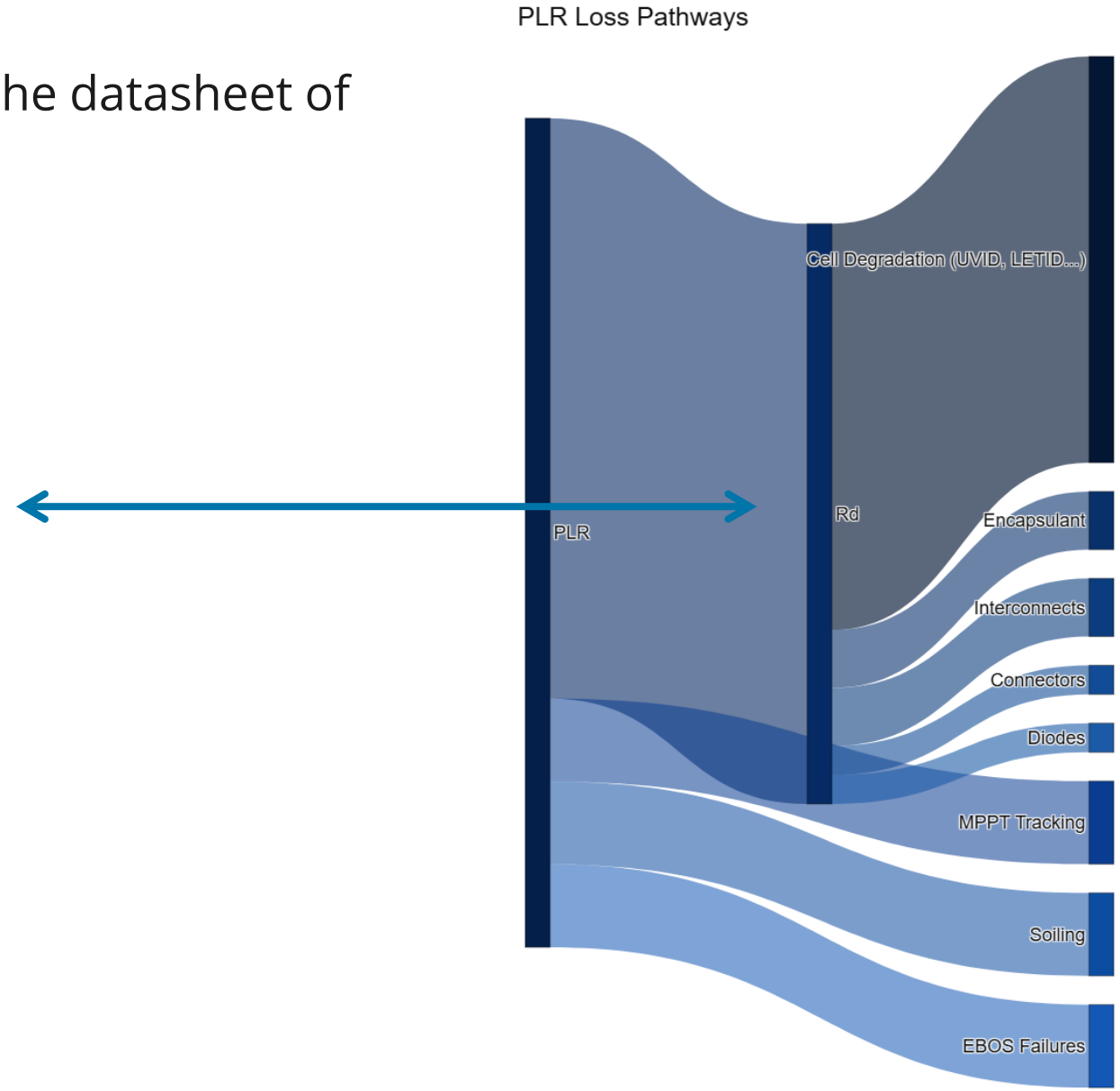
[1]: 10.1002/pip.3615

PLR VS Rd: CLARIFICATION

- Module degradation (Rd) is reported on the datasheet of the modules
  - It is derived from indoor testing data

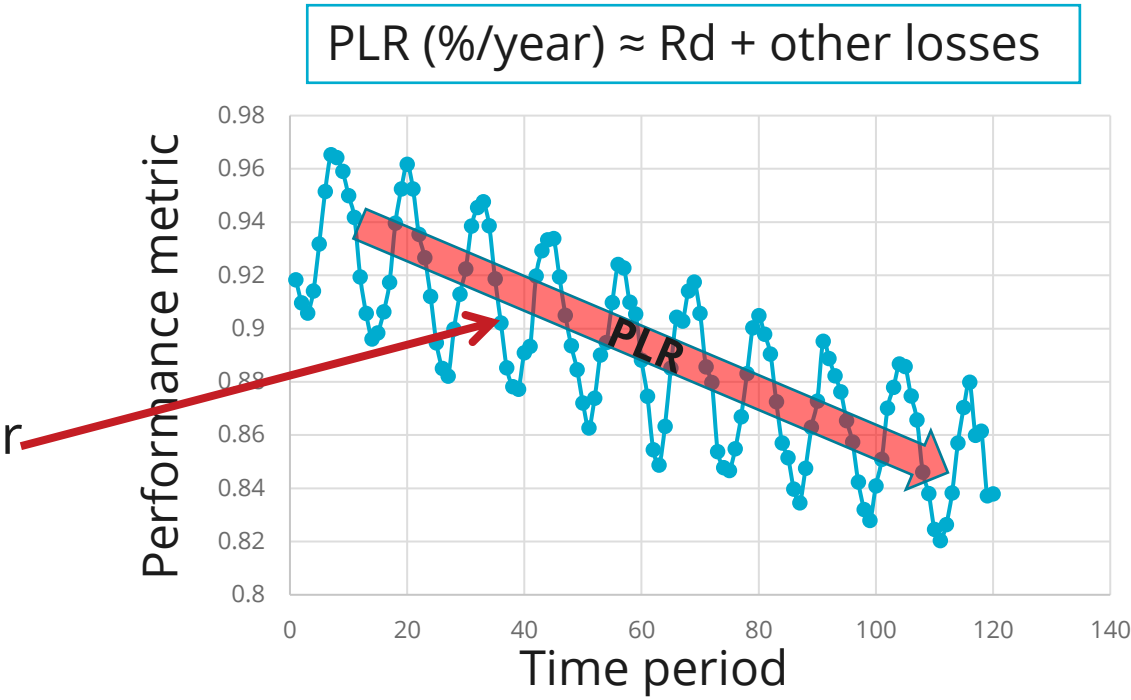




PLR VS Rd: CLARIFICATION

- Module degradation (Rd) is reported on the datasheet of the modules
  - It is derived from indoor testing data

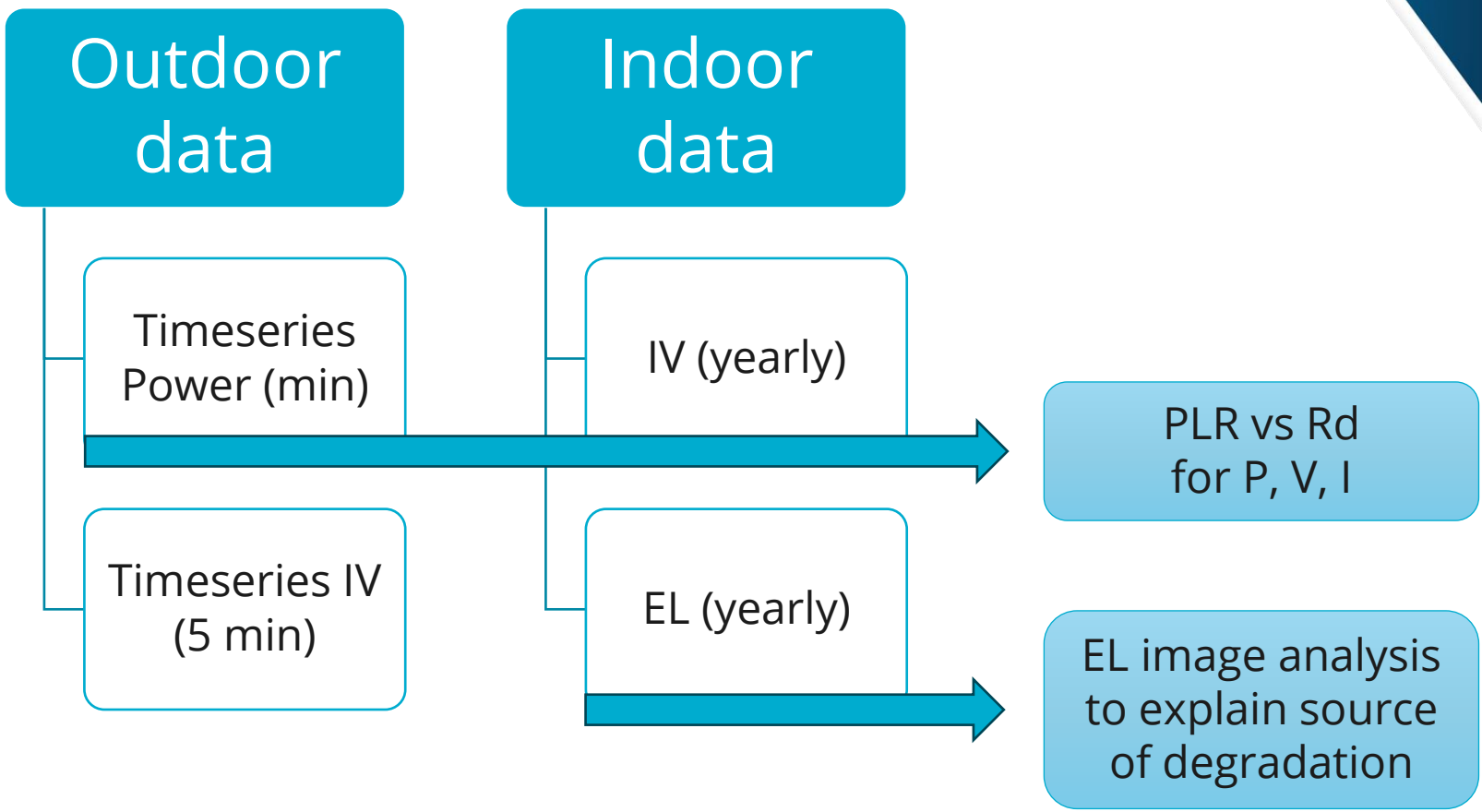
- Performance Loss Rate (PLR) is extracted analyzing outdoor (noisy) time-series
  - It does not only entail Rd but other system level losses like MPPT tracking, soiling, EBOS failures…
  - RdTools is a python package for PLR calculation
  - PLR represents the linear power decline in %/year



METHOD

- Available data →

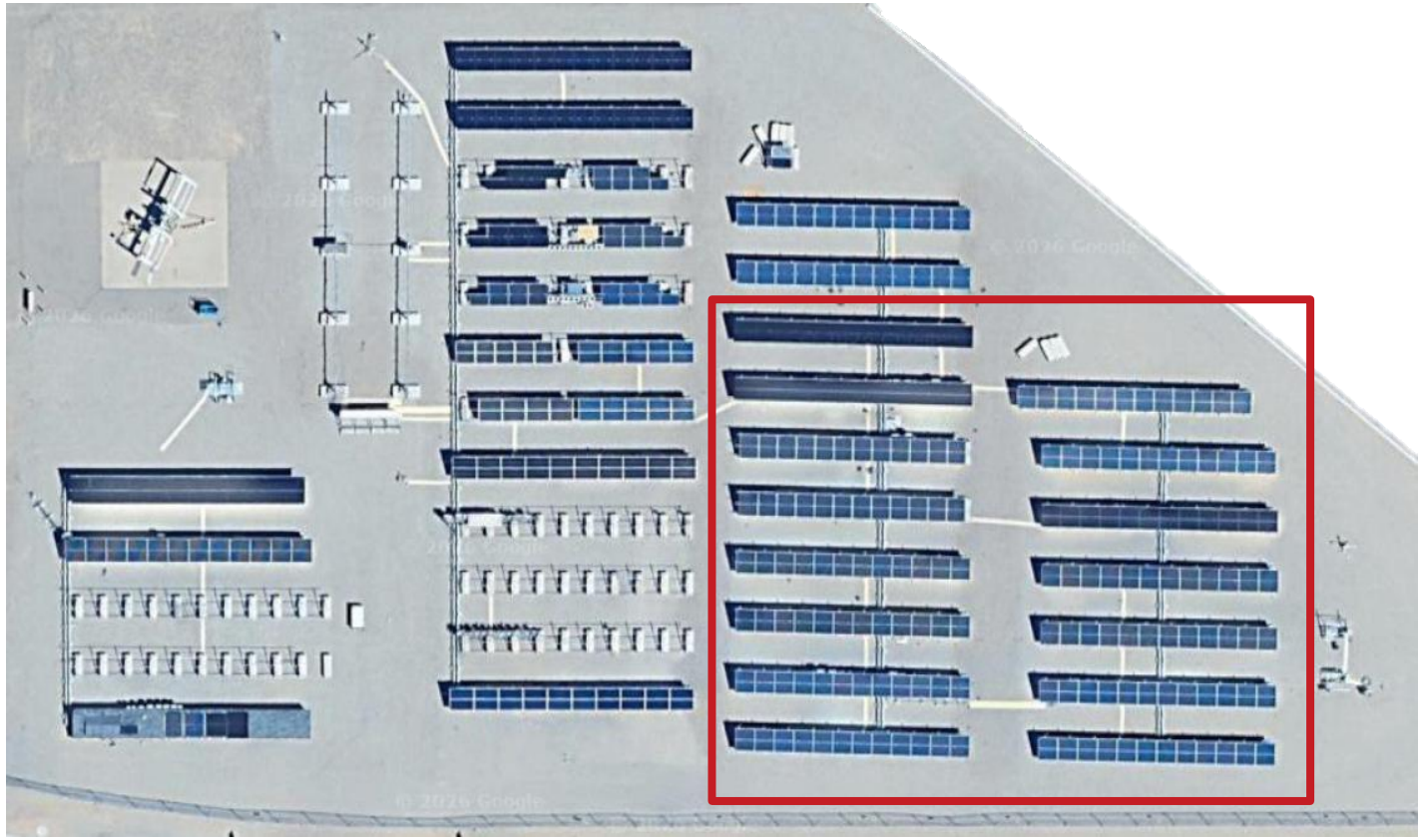
- PLR: RdTools YoY method [1]
- Rd: % change over time using first-flash (post stabilization) measurement [2]
- Electroluminescence Imaging (EL): shown alongside current-voltage (IV) measurements
- Timeseries IV (future work)



[1] D. Jordan et al. "Robust PV Degradation Methodology and Application" 10.1109/JPHOTOV.2017.2779779
[2] M. Theristis et al. "Onymous early-life performance degradation analysis of recent photovoltaic module technologies" 10.1002/pip.3615

SYSTEMS OVERVIEW

- Sandia's SLTE systems include 15 different types of modules
- The information is public:
  - https://pvpmc.sandia.gov/datasets/pv-lifetime-module-datasets-clone/

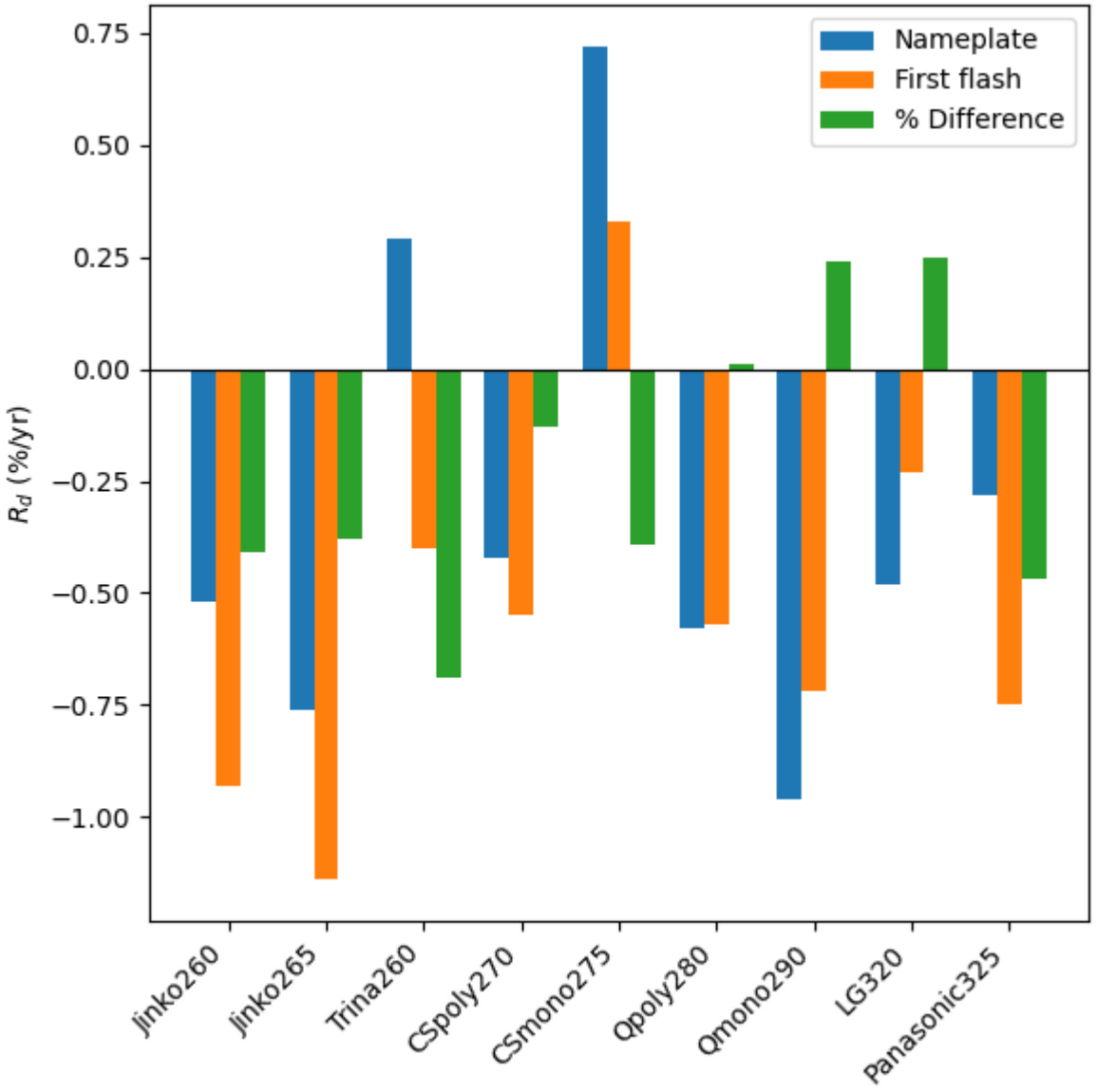


Manufacturer	Model	Cell Technology	Installation Date
Trina Solar	TSM-PD05.08 260W	**poly-Si**	Jun-16
Jinko Solar	JKM260P-60 260 W	**poly-Si**	Jun-16
Canadian Solar	CS6K-270P 270W	**poly-Si**	Oct-17
Canadian Solar	CS6K-275M 275W	**mono-Si**	Oct-17
Hanwha Q-Cells	Q.Plus BFR-G4.1 280W	**poly-Si PERC**	Oct-17
Hanwha Q-Cells	Q.Peak BLK G4.1 300W	**mono-Si PERC**	Oct-17
Panasonic	VBHN325SA16	**HIT Mono**	Jun-18
LG	LG320N1K-A5 320W LG NeON2	**N-PERT Si**	Jun-18
Mission Solar	MSE300SQ5T	**mono-Si PERC**	May-19
Itek Energy	IT-360-SE72	**mono-Si PERC**	Mar-20
Solaria	PowerXT-400R-PM	**mono-Si, shingled**	Oct-21
LG	LG400Q1C-A6	**mono n-type IBC**	Oct-21
REC	REC405AA pure	**HJT**	Nov-23
REC	reC360NP2	**TopCon**	Nov-23
Q-Cells	Q.Peak Duo XL-G11	**Bifacial**	2024 (Less than 2 years)

DISCUSSION POINT 1: Rd BASED ON NAMEPLATE VS FIRST-FLASH

- Nameplate ratings differ from actual measured initial power (PVEL-Scorecard)
  - 10+ years ago tolerances were not so tight and in ±
  - Then we see tighter positive tolerances
  - In past 2 years we are back to ±tolerance
- First-flash values capture actual module starting condition
- Using nameplate instead of measured initial power will bias Rd
- The bias direction depends on manufacturing tolerance and binning [1] →

Takeaway: 3rd party testing for initial power values



[1] M. Theristis et al. "Onymous early-life performance degradation analysis of recent photovoltaic module technologies" 10.1002/pip.3615

DISCUSSION POINT 2: Rd NOT EQUAL TO PLR

- Many critiques of PV design assumptions incorrectly compare system PLR against module Rd
- PV design software default Rd range from 0%/yr to 0.5%/yr [1]
- Module Rd assumptions are only for one component so comparing to PLR is not apples-to-apples
- A different PLR than software degradation assumptions does NOT automatically mean the software assumptions are wrong

Default derates and loss models in software.

	3E SynaptiQ	RatedPower	SAM	PlantPredict	SolarFarmer	Solargis Evaluate	PVsyst
Far shading	Model-PVGIS	Model-beam occlusion	Model-Options	0 % - Model-PVGIS	Model-beam shading	Model-ray tracing	0 % -Model
Near shading	Model-Inf. sheds	Model-Linear	Model-Linear or Nonlinear	Model 2D - VF Model 3D-polygon clipping	Model 2D-Inf. Sheds Model 3D-Hemicube	Model-ray tracing	Model 2D - VF Model 3D - Polygon clipping
Soiling	1 % - Fixed	2 %-Fixed monthly or yearly	5 % - Fixed	2 % - Fixed	0 % - Fixed	3 % - Fixed monthly	0 % - Fixed
IAM	Model-Fresnel	Model-PAN profile	Model-Physical	Model-Tabular IAM	Model-Module Dependent	Model-Martin Ruiz	Model-fresnel & coating options
Degradation	0.5 %/year	0.3 %/year	N/A	0 % - Fixed	0 % - Fixed	2 % - initial 0.5 % subsequent	0.4 %/year
Spectral correction	0 % - Model Lee & Panchula	Model-Lee & Panchula CdTe Only	Model-SAPM	0 % - Model Lee & Panchula	Model-CdTe: Lee & Panchula, Non-CdTe: SAPM	Model-Lee & Panchula	0 % - Model Lee & Panchula
Quality	0 % - Fixed	−0.7 % - Fixed	0.5 % - Fixed	0 % - Fixed	0 % - Fixed	N/A	Fixed - Module Dep.
LID	Module Dep. - Fixed	2 % - Fixed	N/A	Module Dep. - Fixed	0 % - Fixed	N/A	0 % - Fixed
Bifacial mismatch	N/A	% - Fixed, 3 % for 2P SAT	0 % - Fixed	10 % - Fixed	0.5 % - Fixed	Model-ray tracing	10 % - Fixed
Module mismatch	1 % - Fixed	N/A	2 % - Fixed	1 % - Fixed	0 % - Fixed	N/A	2 % - Fixed
String mismatch	0 % - Fixed	1 % - Fixed	N/A	N/A	Model - Mod. IV curve	Model - Mod. IV curve	0.1 % - Fixed
Shading mismatch	N/A	Model	N/A	N/A	Model-Mod. IV curve	Model-Mod. IV curve	0 % - Model
DC Cable	Model-Ohmic	1.5 % - Ohmic	2 % - Fi	- Ohmic	0 % - Fixed	2 % - Fixed	1.5 % - Ohmic
DC clipping	N/A	N/A	Model	- Off MPPT	Model	Model	N/A
AC clipping	Model	Model	Model		Model	Model	Model
Inverter aux.	N/A	Model	Model	800 W/Inverter station	0 % - Fixed	Module Dep.	0 % - Model
Tracker loss	N/A	N/A	0 % - Fixed	2.028 MWh/MWp/year	N/A	N/A	N/A
AC cable	Low - N/A, Med - N/A, High - N/A	Low - 4.5 %, Med - 0.5 %, High - 0 %	Low - 1 %, Med - N/A, High - N/A	Low - 1 %, Med - N/A, High - 0 %	Low - 0 %, Med - N/A, High - N/A	Low - 1 %, Med - 0.5 %, High - 0.05 %	Low - 0 %, Med - 0 %, High - 0 %
Transformer iron loss	0.0725 % of DC capacity	0.1 % - Model	0 % - Fixed	0.2 % - Fixed	0 % - Fixed	0.15 % - Fixed	0 % - Fixed
Transformer copper loss	Model-Ohmic	1 % - Model-PVsyst	0 % - Fixed	0.7 % - Ohmic	0 % - Fixed	1.2 % - Fixed	0 % - Model
Plant aux. consumption	N/A	0 kW - Fixed	N/A	N/A	0 % - Fixed	0.025 % - Fixed	0 kW - Fixed
Delivery point curtailment	0 % - Fixed	0 % - Fixed	N/A	0 % - Fixed	N/A	0 % - Fixed	0 % - Fixed
Plant unavailability	N/A	0 % - Fixed	N/A	N/A	0 % - Fixed	0.5 % - Fixed	0 % - Fixed
Night losses	0.0725 % of DC capacity	0 % - Fixed	N/A	Dep.	0 % - Fixed	0.025 % - Fixed	0 % - Fixed
Grid unavailability	N/A	0 % - Fixed	N/A		0 % - Fixed	0 % - Fixed	Defined by user
Total default fixed derate[15]	**1.99 %**	**11.37 %**	**10.13 %**	**6.24 %**	**0 %**	**7.21 %**	**3.56 %**

Rd

~PLR

[15] For fixed-tilt, monofacial system.

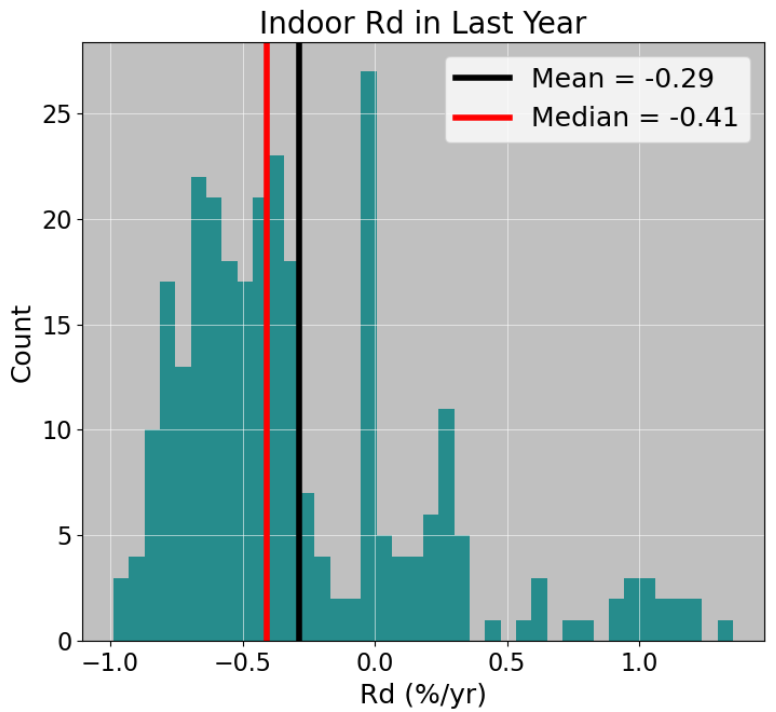
[1] L. Deville et al. "Feature review of photovoltaic modeling software utilizing blind performance assessment " 10.1016/j.solener.2025.114207

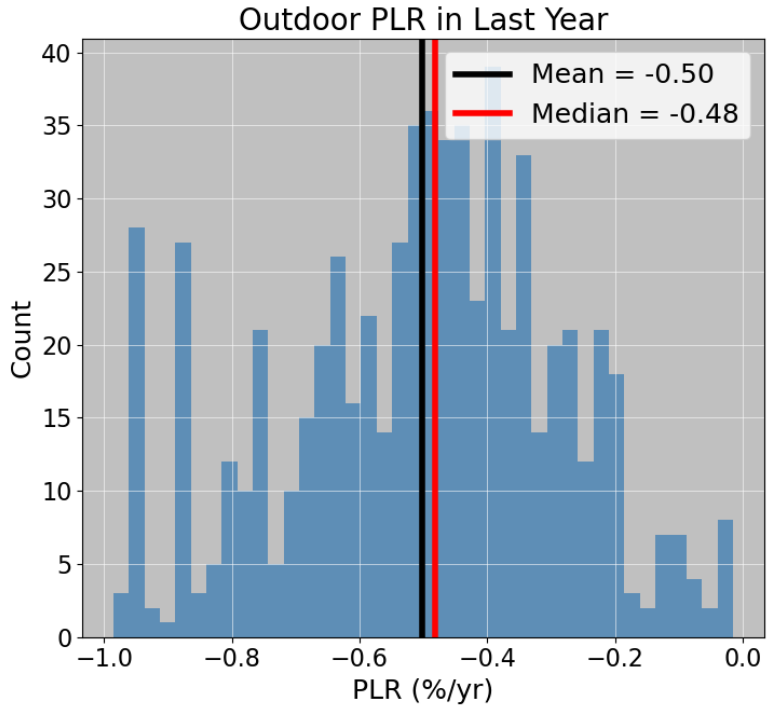
Takeaway: Different PLR to software assumptions is not wrong. PLR is affected by many factors beyond Rd

DISCUSSION POINT 2: Rd NOT EQUAL TO PLR

- Rd and PLR results for all systems
- Rd theoretically is lower than PLR, but the gap between Rd vs PLR varies with technology
- We do see Rd > PLR for certain makes (still investigating why)

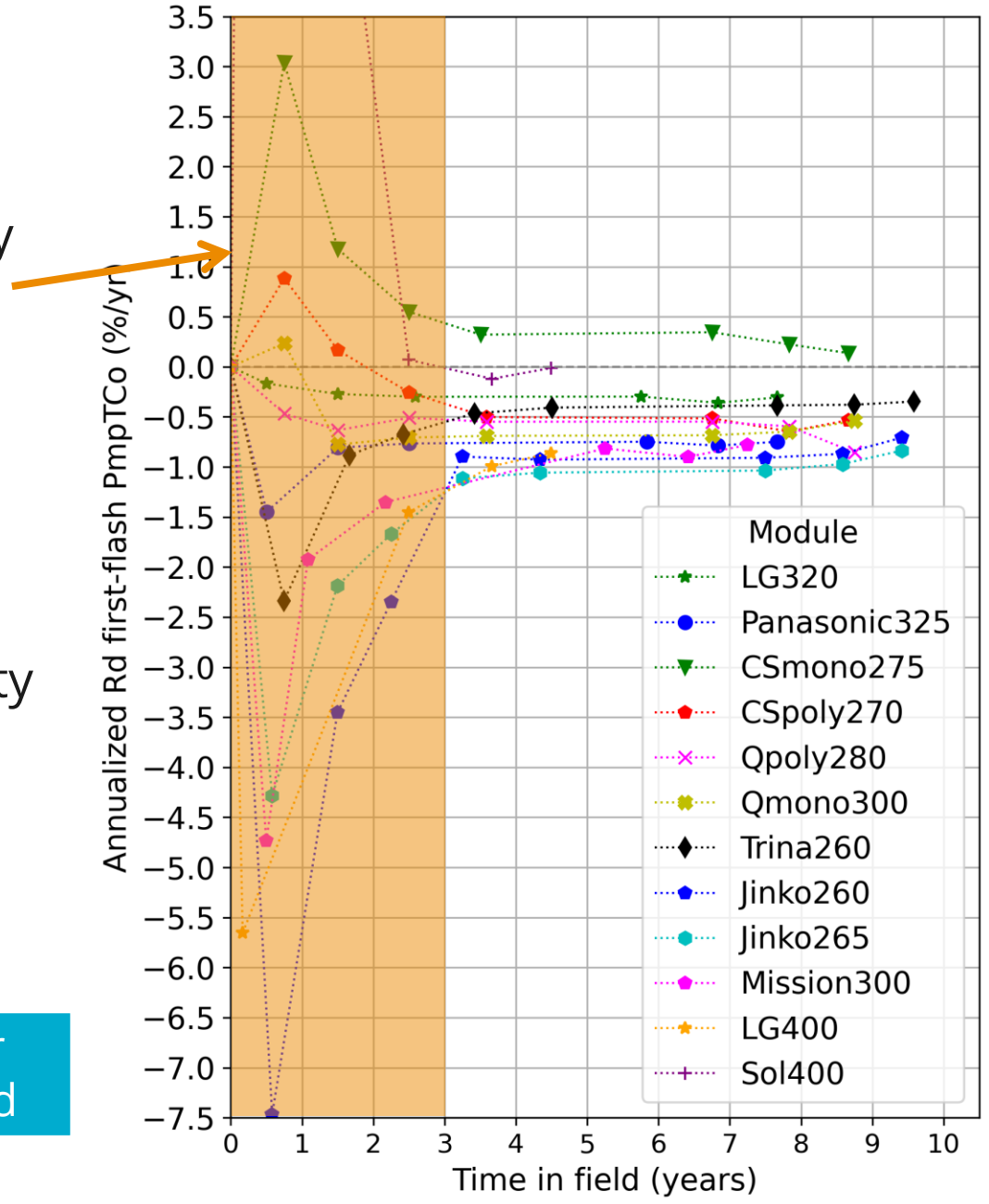
Takeaway: Rd vs PLR differences are not the same for all technologies





DISCUSSION POINT 3: NONLINEARITY

- Initial stabilization/break-in occurs in modules
- Highly nonlinear degradation behavior for many modules of all cell technologies (AlBSF, Poly, PERC, TOPcon)
- Unnecessary O&M alerts might be triggered when expectations differ in any year
- Apply nonlinear PLR approaches [1-2]
- For yield predictions, apply higher Rd uncertainty in the first years then tighten it

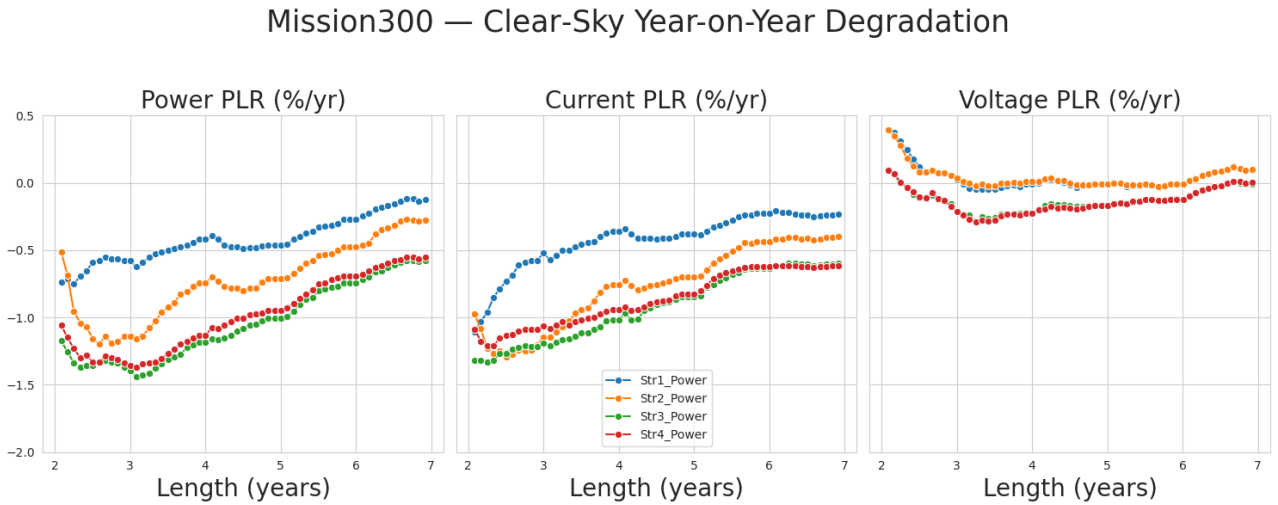


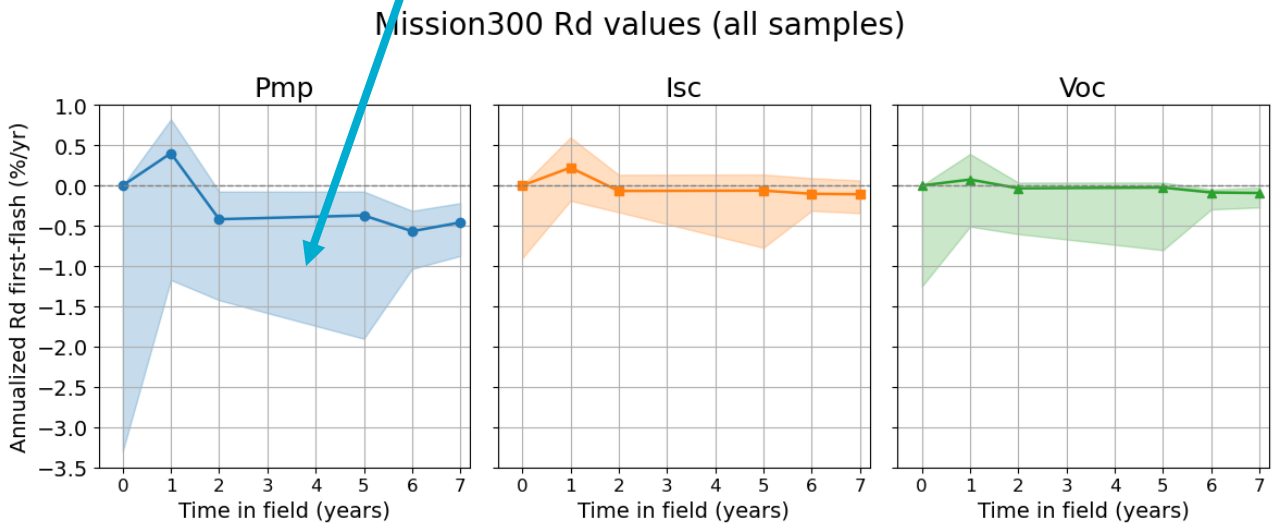
[1] M Theristis et al. "Nonlinear Photovoltaic Degradation Rates: Modeling and Comparison Against Conventional Methods" 10.1109/JPHOTOV.2020.2992432
[2] S. Lindig, M. Theristis, D. Moser, "Best practices for photovoltaic performance loss rate calculations" 10.1088/2516-1083/ac655f

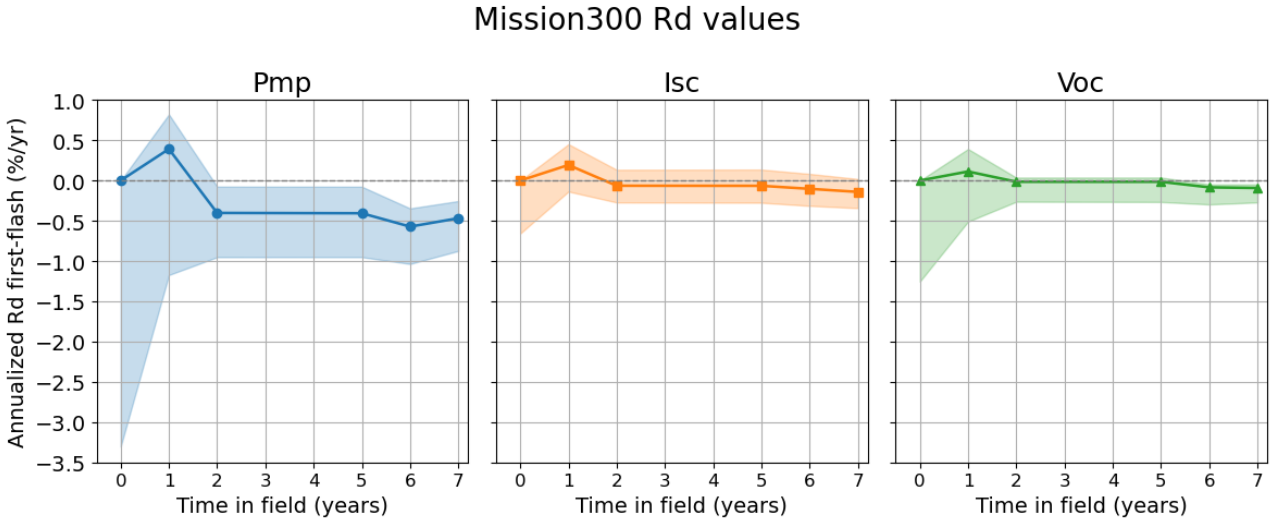
Takeaway: Do not to panic if the performance is all over the place the first 3 years. Initial stabilization is expected

DISCUSSION POINT 4: STATISTICAL SAMPLING

- Sampling methodology affects Rd
- Even the same module ID and consecutive serial numbers will exhibit differences
- Random samples show much lower performance







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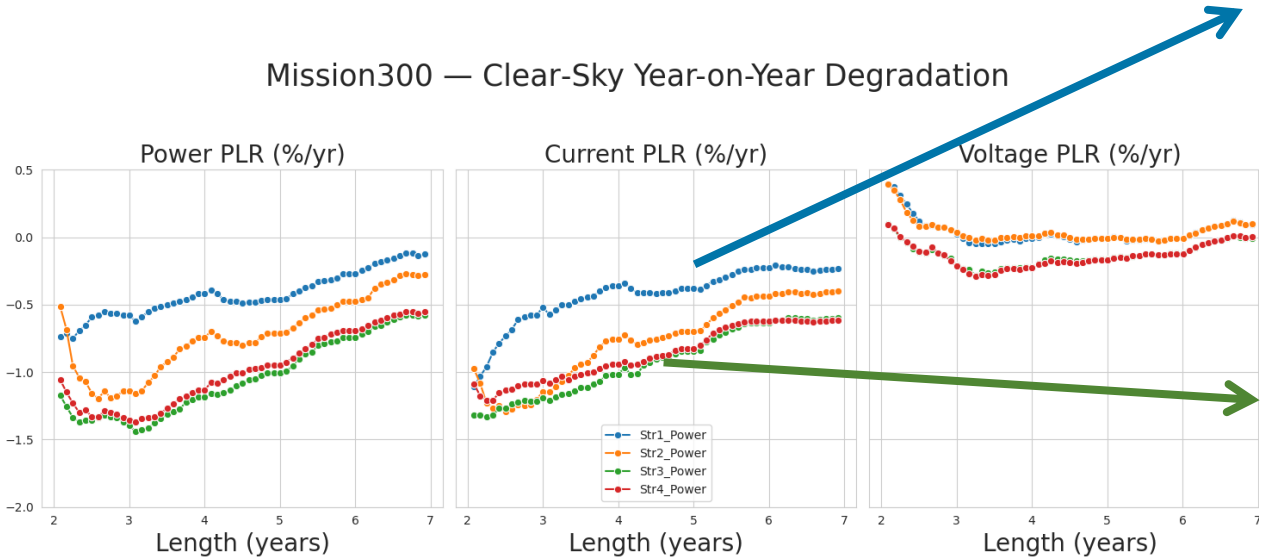
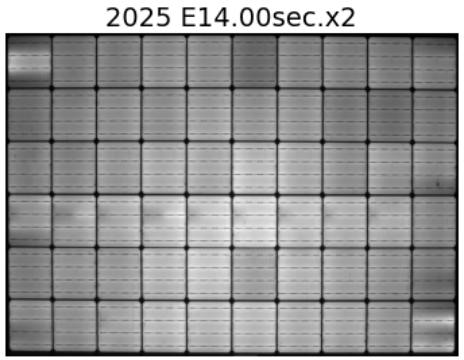
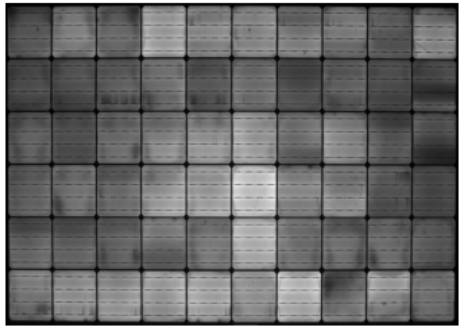
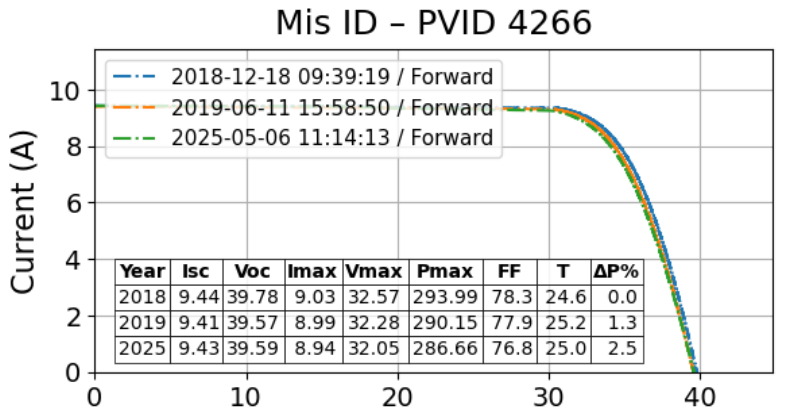
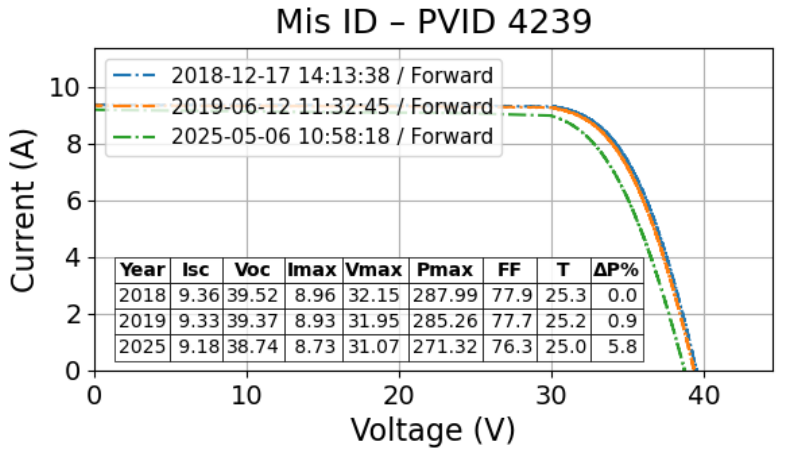








Year	Isc	Voc	Imax	Vmax	Pmax	FF	T	ΔP%
2018	9.44	39.78	9.03	32.57	293.99	78.3	24.6	0.0
2019	9.41	39.57	8.99	32.28	290.15	77.9	25.2	1.3
2025	9.43	39.59	8.94	32.05	286.66	76.8	25.0	2.5



Year	Isc	Voc	Imax	Vmax	Pmax	FF	T	ΔP%
2018	9.36	39.52	8.96	32.15	287.99	77.9	25.3	0.0
2019	9.33	39.37	8.93	31.95	285.26	77.7	25.2	0.9
2025	9.18	38.74	8.73	31.07	271.32	76.3	25.0	5.8

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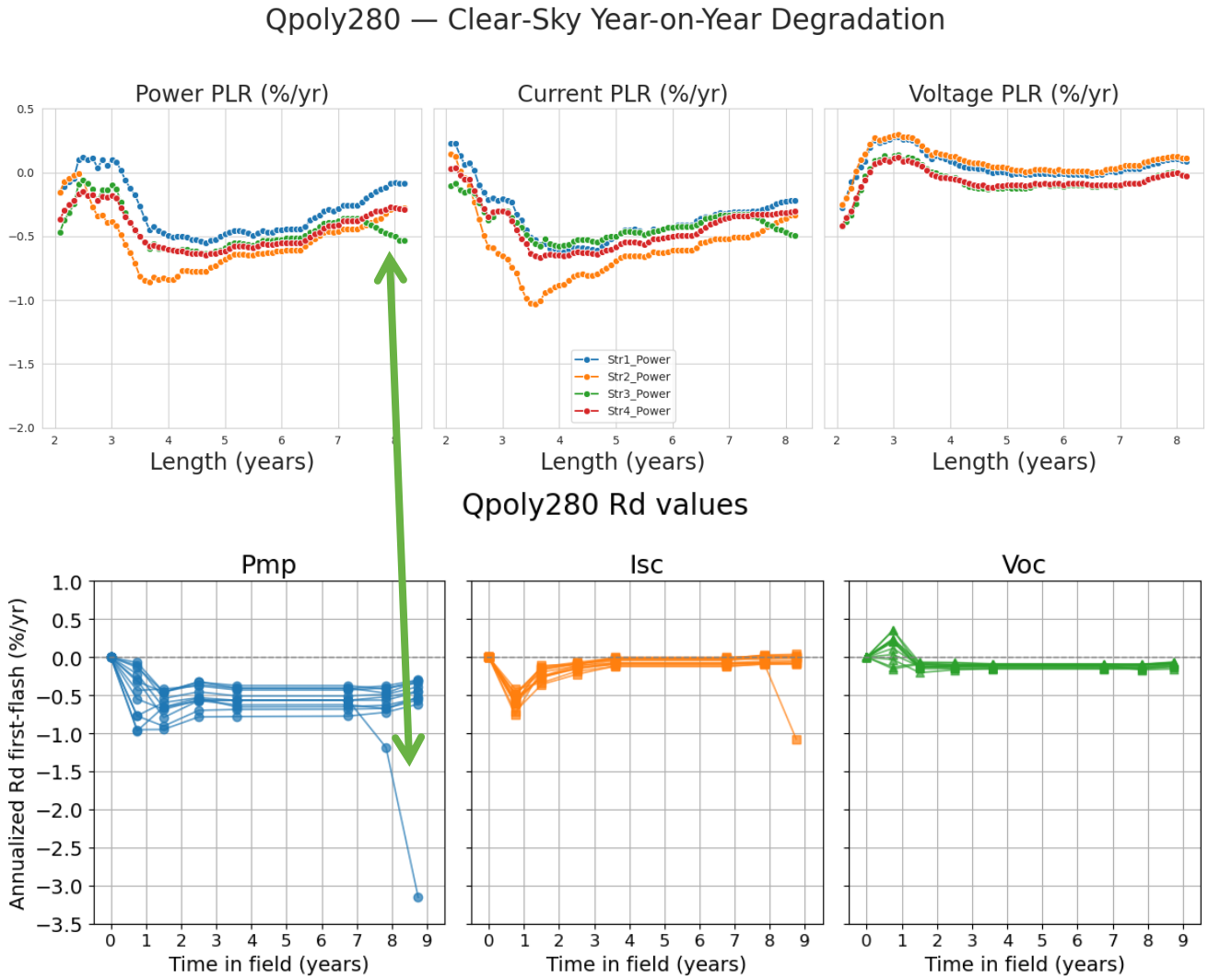
- Sampling methodology affects Rd
- Even the same module ID and consecutive serial numbers will exhibit differences
- Random samples show much lower performance
- Cracked module?



DISCUSSION POINT 4: STATISTICAL SAMPLING

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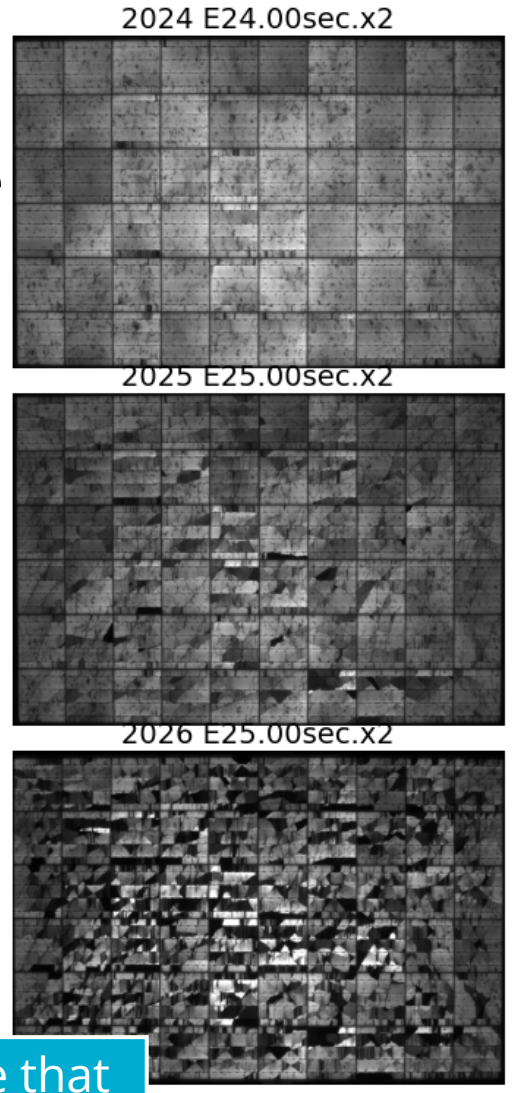
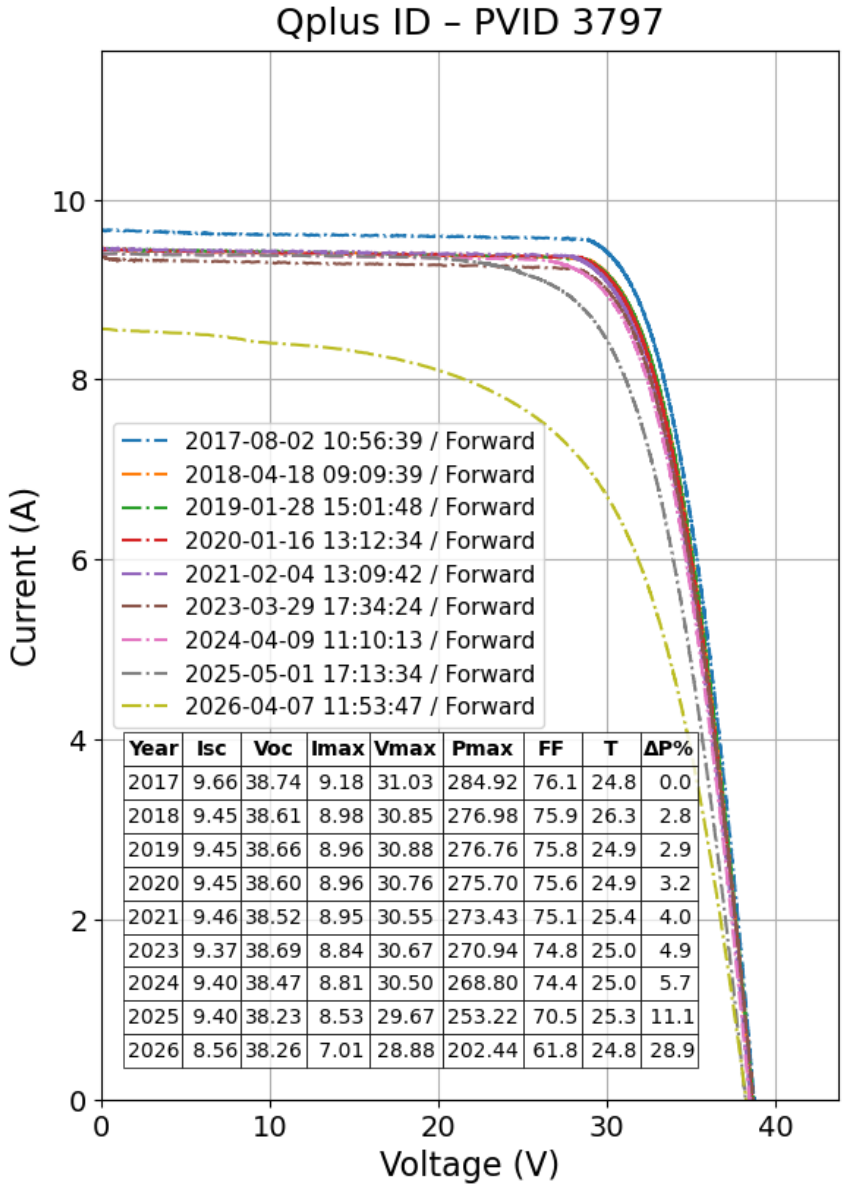
- Random samples show much lower performance
- Cracked module?
- Possible contributors: module heterogeneity, spatial/installation variability, damages
- Sampling strategy changes Rd conclusions





Year	Isc	Voc	Imax	Vmax	Pmax	FF	T	ΔP%
2017	9.66	38.74	9.18	31.03	284.92	76.1	24.8	0.0
2018	9.45	38.61	8.98	30.85	276.98	75.9	26.3	2.8
2019	9.45	38.66	8.96	30.88	276.76	75.8	24.9	2.9
2020	9.45	38.60	8.96	30.76	275.70	75.6	24.9	3.2
2021	9.46	38.52	8.95	30.55	273.43	75.1	25.4	4.0
2023	9.37	38.69	8.84	30.67	270.94	74.8	25.0	4.9
2024	9.40	38.47	8.81	30.50	268.80	74.4	25.0	5.7
2025	9.40	38.23	8.53	29.67	253.22	70.5	25.3	11.1
2026	8.56	38.26	7.01	28.88	202.44	61.8	24.8	28.9

Takeaway: Statistical sampling of module. Assume that not all serial numbers have the same power bin

CONCLUSION

- Rd and PLR are related but fundamentally different metrics
  - Avoid direct one to one comparison between PLR and module warranties
  - Understand system-level derate contributors

- Report your reference (nameplate vs 3rd party flash)

- Module degradation Rd is unstable in the first 3 years of operation

- Sampling methodology and early-life behavior influence Rd

ACKNOWLEDGMENTS

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