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Uncertainty Analysis for Photovoltaic Degradation Rates

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1 Introduction

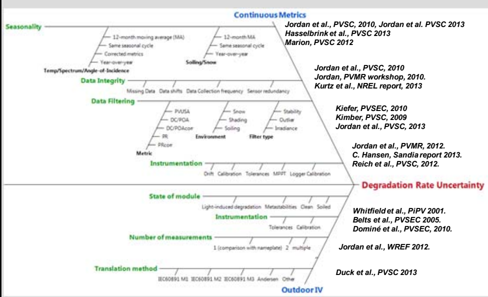
Long-term PV Performance

1. *Financially:*
   - *Cash flow*
   - *Uncertainty directly related to risk*
2. *Technically:*
   - *Lifetime prediction*
   - *Product improvement*

Need to determine degradation rates (R_d) accurately

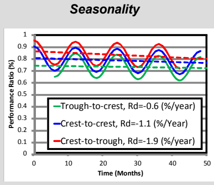
2 Ishikawa Diagram

Sources of variations & strategies for degradation rate uncertainty

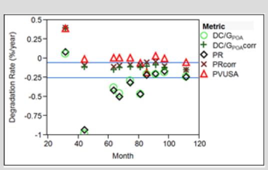


3 Seasonality & Metrics

Seasonality



Metrics



Seasonality can lead to systematic deviations

DC/G$_{POA}$: DC power/ plane-of-array Irradiance
DC/G$_{POA}$corr: temperature-corrected DC/G$_{POA}$
PR: Performance ratio
Prcorr: temperature-corrected PR
PVUSA: PVUSA regression methodology

Temp-corrected metrics: excellent agreement down to 3 ½ years.

Temperature-corrected metrics are preferred over non-corrected metrics.

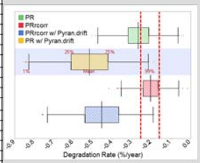
4 Total Uncertainty Simulation

Instrumentation Uncertainties

Category	Variable	Distribution	Type	Mean	Stdev	Lower Limit	Upper Limit	Most likely	Coverage factor	Ref
DC Electrical	Logger cal DC Voltage	Normal	A	-0.06	0.3				2	NREL
	Logger cal DC Current	Normal	A	0.15	1				2	NREL
	Logger tolerance DC Voltage	Uniform	B			-0.02	0.02		1.732	Datasheet
	Logger tolerance DC Current	Uniform	B			-0.03	0.03		1.732	Datasheet
	MPPT	Triangle	B			0	0.02	0.005	1.732	1,2
AC Electrical	Logger cal AC Voltage	Normal	A	0.14	0.47				2	NREL
	Logger cal AC Current	Normal	A	-0.10	1.3				2	NREL
	Shark tolerance AC Voltage	Uniform	B			-0.1	0.1		1.732	Datasheet
	Shark tolerance AC Current	Uniform	B			-0.1	0.1		1.732	Datasheet
	Inverter efficiency	Normal	A	93	3				2	NREL
	Inverter degradation (%/year)	Triangle	B			0	0.2	0.1	1.732	NREL
Optical	Pyranometer BORCAL	Triangle	A			-3	3	0	1.732	3
	Logger cal POA Irradiance	Normal	A	-0.05	1				2	NREL
	Pyranometer drift (%/year)	Triangle	B			0	0.5	0.2	1.732	5,6
	POA Irradiance non-uniformity	Uniform	B			-0.3	0.3		1.732	4
	Sensor misalignment	Uniform	B			-0.02	0.02		1.732	4
Temperature	Temp coefficient	Normal	B	0.47	0.03				2	Datasheet
	Temp logger cal	Normal	A	0.42	3				2	NREL
	Temp tolerance	Uniform	B			-0.2	0.2		1.732	Datasheet
	Temp non-uniformity	Uniform	B			-0.05	0.05		1.732	4
Rating	Nameplate rating	Triangle	B			-3	3	0	1.732	7

$$PR = \frac{E/P_0}{H/G}$$

PR=Performance Ratio
E=Net Energy output
P_0=Nameplate DC rating
H=In-plane Irradiance
G=Reference Irradiation



Even a small drift dominates other uncertainties

[1]R. Faranda, S. Leva, WSEAS Transactions on Power Systems, 2010.
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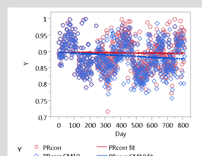
[3]D.R. Myers et al., 2004, NREL Conference Paper NREL/CP-560-36320.
[4]H. Müllejans et al., Meas. Sci.Technol. 20 (2009) 075101.
[5]D.C. Jordan et al., NREL PVMR Workshop, Golden CO, USA, 2013.
[6]N.H. Reich et al., PVSC, Austin, TX, 2012, 1551 – 1555.
[7]http://www.solarabcs.org/

Precision (relative accuracy) more important than absolute accuracy

5 Intentionally Drifting Pyranometer

Condensation film on dome



Pyranom.	R_d (%/year)	Uncertainty (%/year)
Regular	-0.18	0.38
High humidity	-1.15	0.36

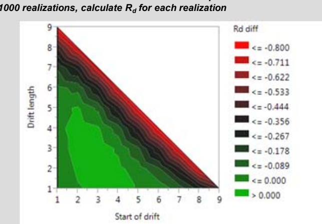
CM10 pyranometer (high humidity) drifted about 1%/year

Apparent high "R_d" due to drifting pyranometer

6 Drift Occurrence

Monte Carlo Simulation

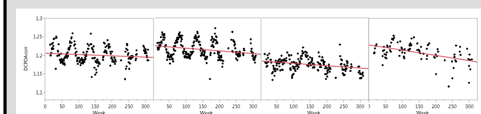
1. *1.4 kW multi-Si system*
2. *Use temperature-corrected Performance ratio (PR)*
3. *Use a drift of 1%/year on average (low: 0.5%/year, high: 1.5%/year, triangle distribution)*
4. *Let the drift have different length 1,2,3… years*
5. *Let the drift occur at different times of field exposure*
6. *1000 realizations, calculate R_d for each realization*

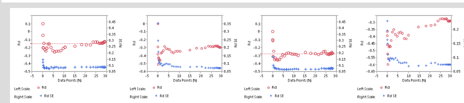


If drift occurs during middle of field exposure→ negligible effect
If drift occurs at end of field exposure → may have large effect

7 Irradiance Source Strategies

Pyranometer mounted on system | *Median of 10 pyranometers at OTF* | *Precision pyranometer, ¼ km distant* | *RMIS: OTF weather station*





R_d=-0.15 %/year | *R_d=-0.30 %/year* | *R_d=-0.28 %/year* | *R_d=-0.33 %/year*

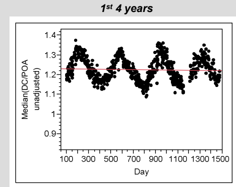
Instrumenting every system with pyranometer may not be necessary

Using Irradiance from nearby system may be adequate

8 Uncertainty for "Clean" Data Set

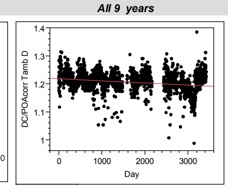
Multi-Si 1400kW system at NREL

1st 4 years



Rd=-0.21+/-0.16 (%/year)

All 9 years



Rd=-0.22+/-0.02 (%/year)

Uncertainties are only statistical uncertainty and do not include instrumentation

With a "clean" data set Rd can be determined to within 0.2%/year after 4 years of field data

9 Conclusion

- *Seasonality caused by temperature, angle-of-incidence, spectral effects can lead to systematic errors and higher uncertainties*
- *Temperature-corrected metrics are preferred over non-corrected metrics.*
- *Changes (drift) of instrumentation during field exposure is more critical than absolute accuracy*
- *Drift has significantly more impact at the end of the monitoring period than in the middle*
- *Nearby irradiance sensors may be used to determine degradation rate*

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