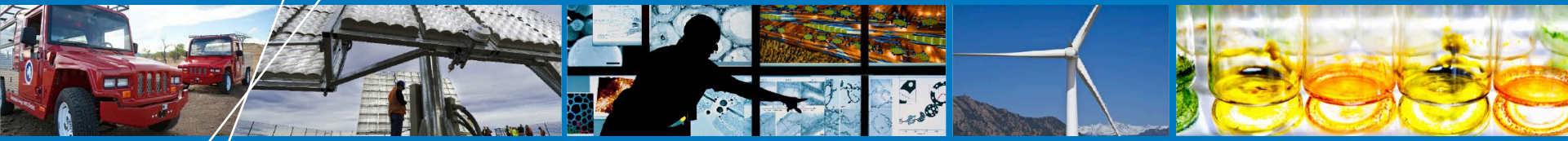
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Overview of Field Experience - Degradation Rates & Lifetimes



Solar Power International

Anaheim, CA

Dirk Jordan, Sarah Kurtz

9/14/2015

NREL/PR-5J00-65040

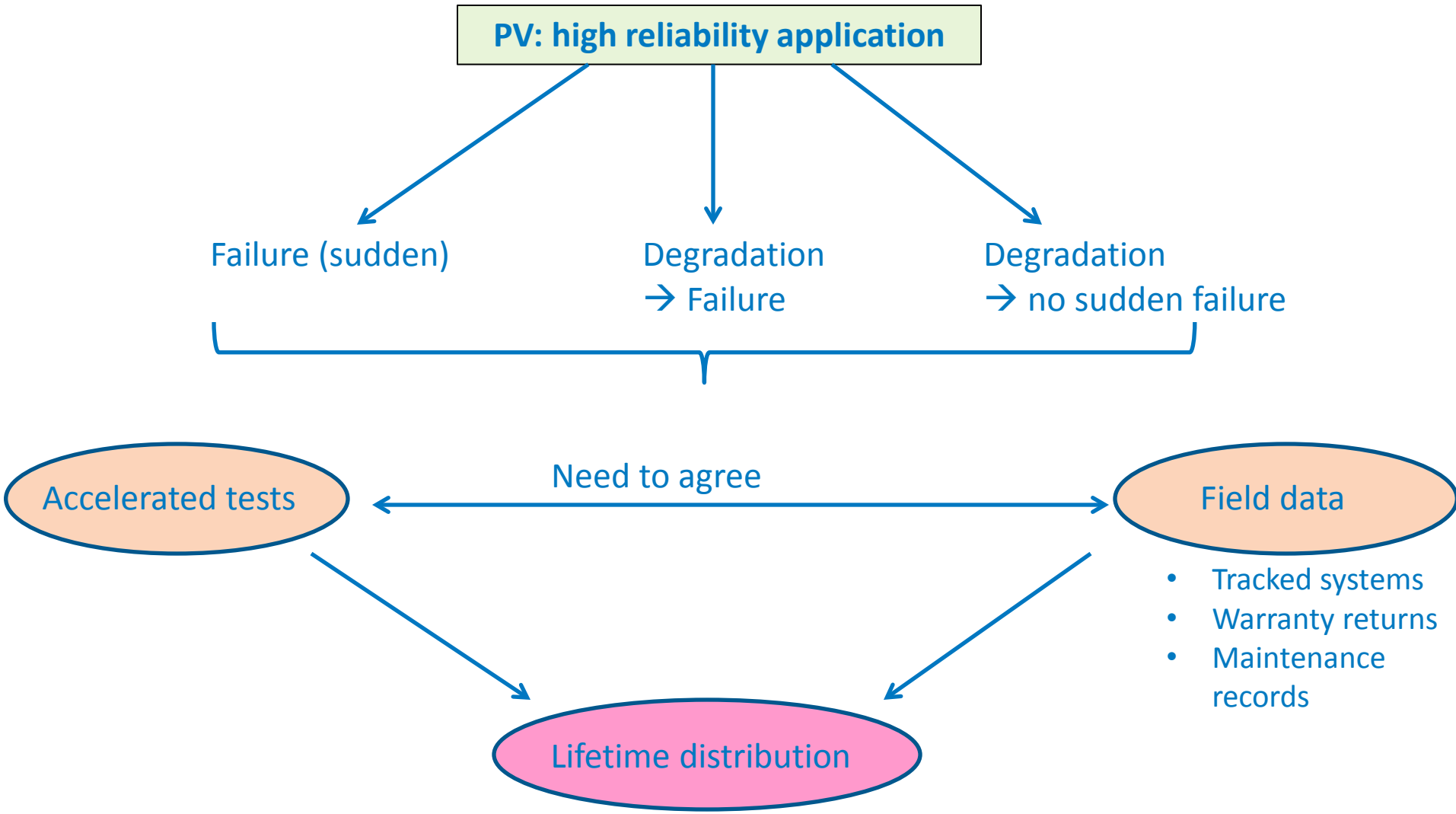
Outline

- Definitions
- Degradation rates
  - Study type (using nameplate rating vs. multiple measurements)
  - Climate
  - Module vs. system
- Degradation curves - non-linearity
- Failure modes

What is reliability?

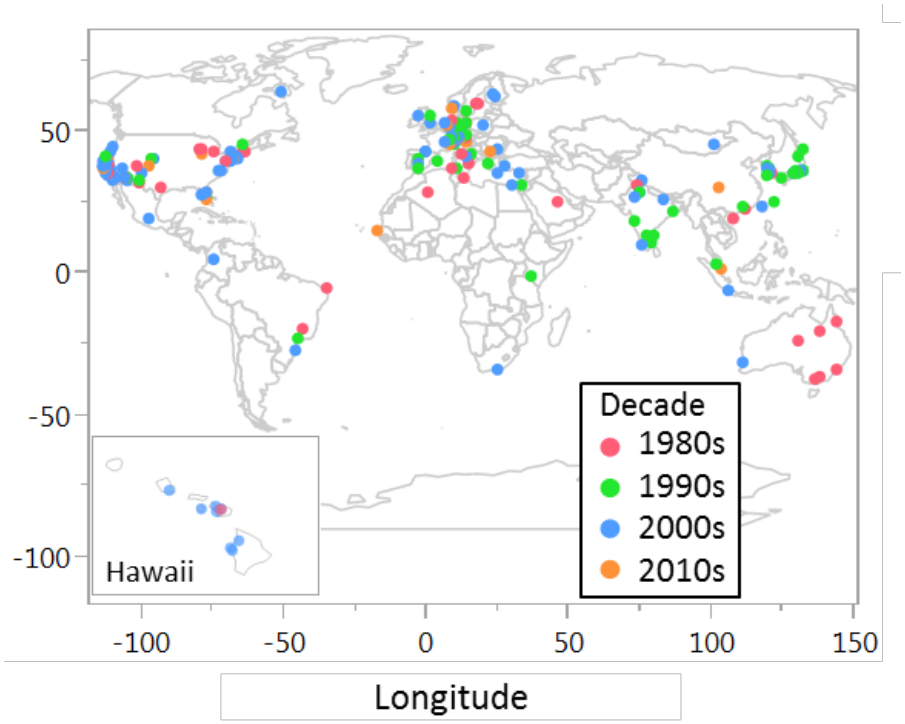
Merriam-Webster: "The quality or state of being reliable" ☹

"Quality over time" ☺

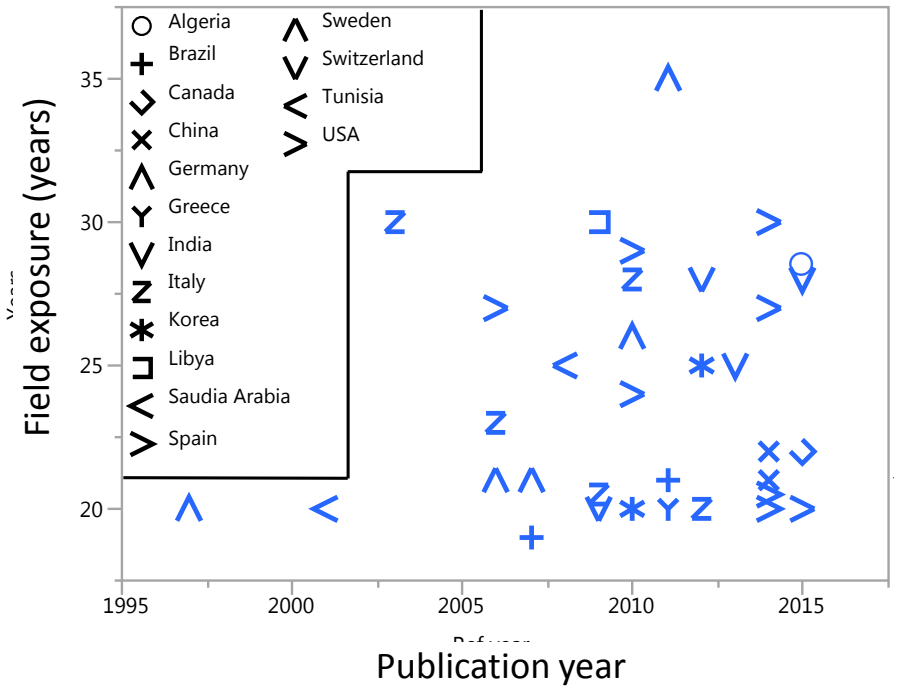


> 30 system studies of 20+ years field exposure

Geographic distribution of degradation rates (R_d)



Studies of systems > 20+ years in field



Increased interest in recent years in long-term performance & degradation

Presidential election 1948: Harry Truman defeated Thomas Dewey

It is difficult to obtain sample w/o bias.

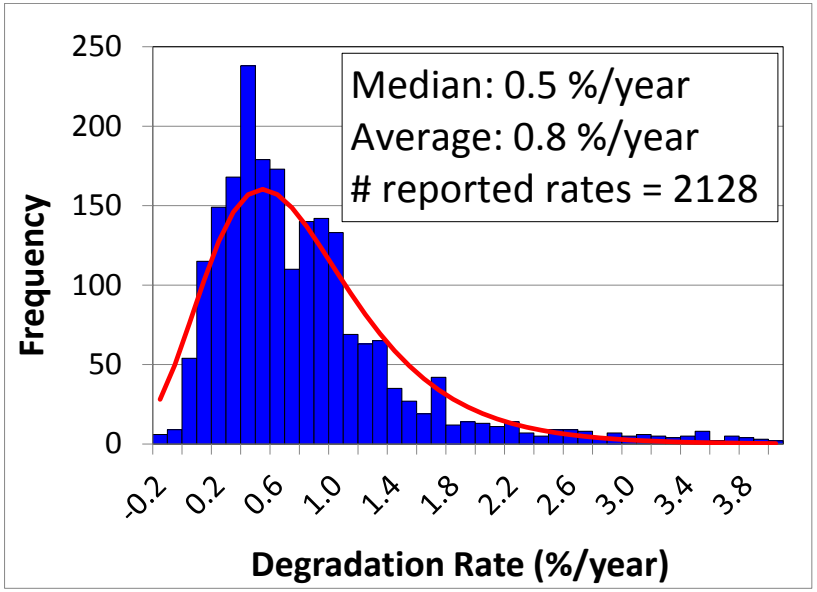
Presidential election 1948: Harry Truman defeated Thomas Dewey

Chicago Tribune conducted poll by telephone.
1948 telephone existed only in affluent homes, which voted overwhelmingly for Dewey.
The sample was biased because the telephone was used!

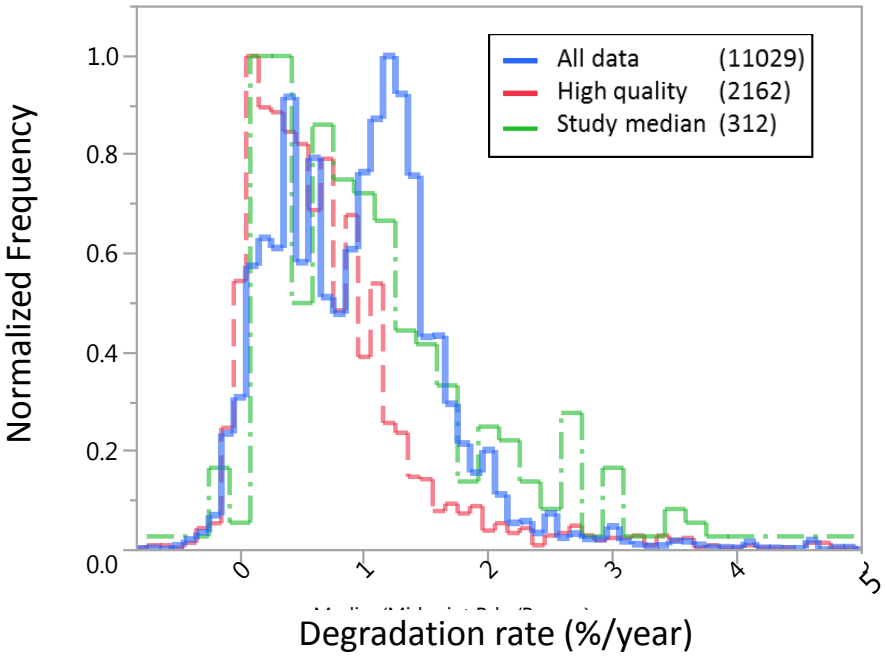
Sampling bias is present – representative of the population?

Literature survey

2011



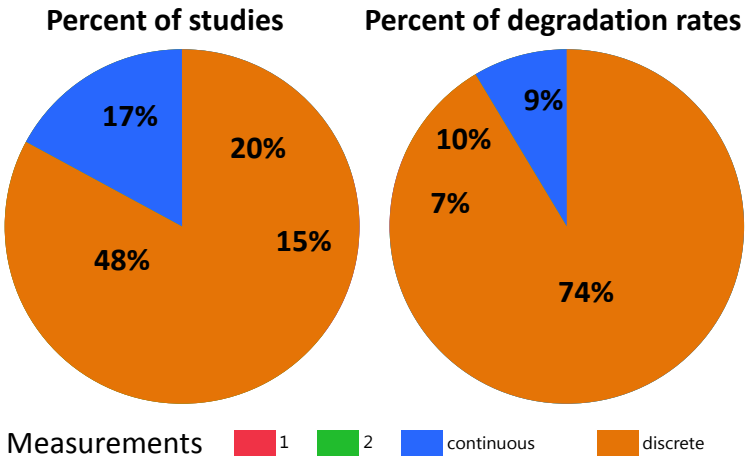
2015



- Few studies with > 1000 modules
- Aggregated distribution is dominated by particular module, system, mounting, method etc.
- Counteract overrepresentation → analyze in different ways
- Median per study & system → second peak disappears
- High quality data (multiple measurements, calibrations etc.) → second peak disappears

Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

Majority of R_d are determined by single measurement.



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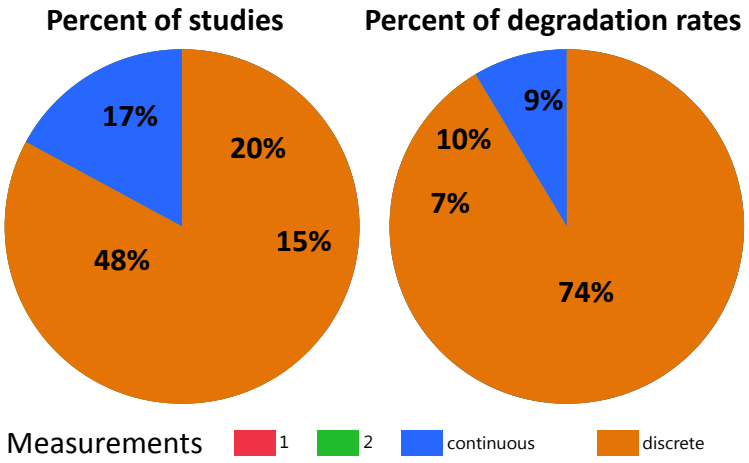
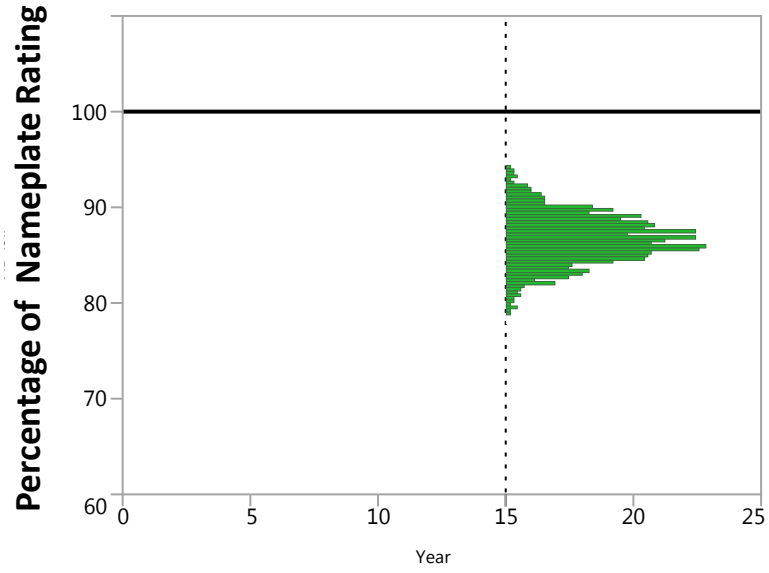


How are R_d determined with 1 measurement?



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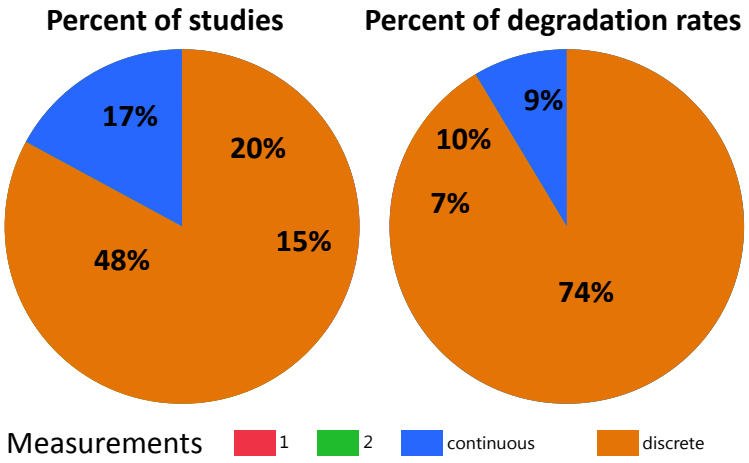

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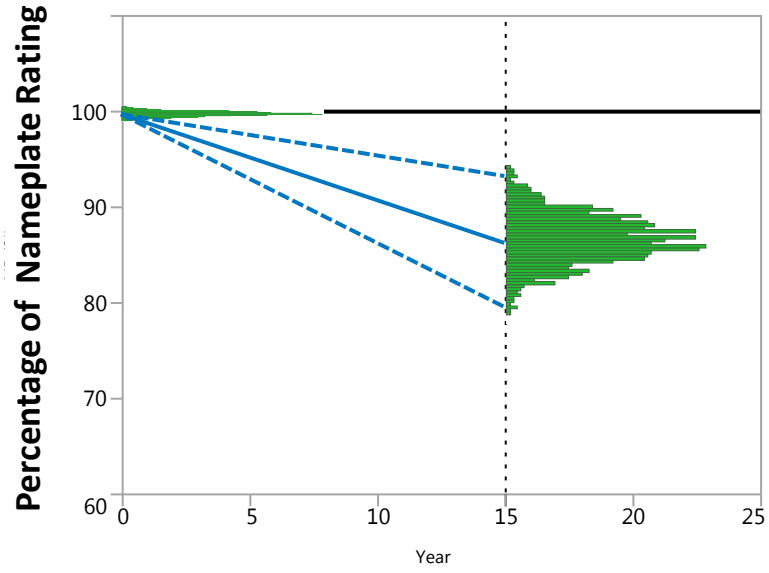

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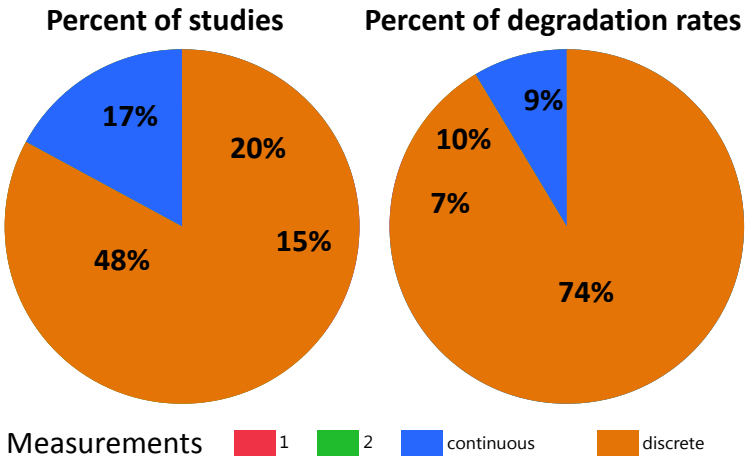

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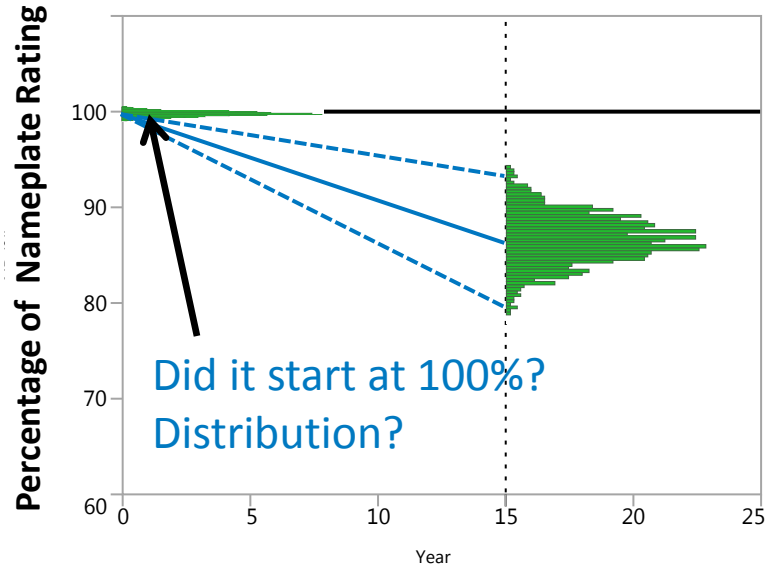
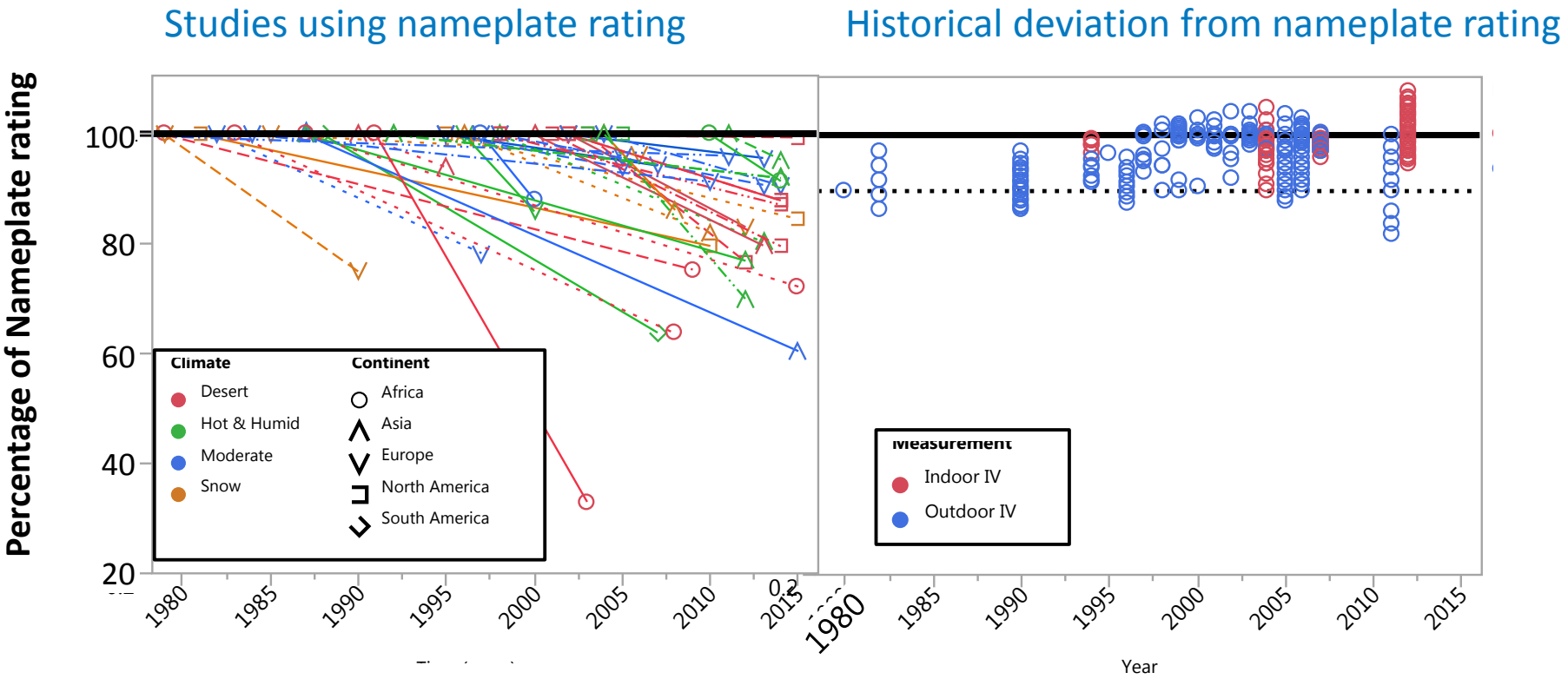


R_D using nameplate rating may have significant error.

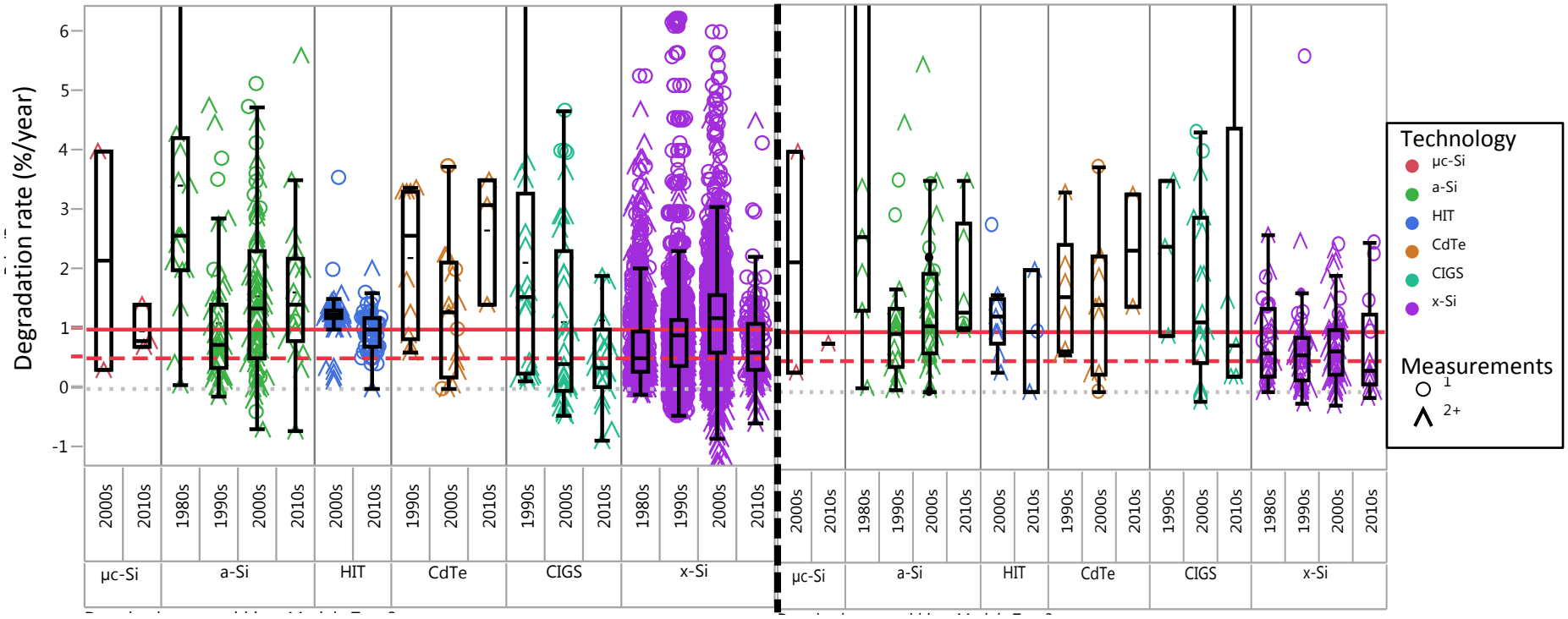


- Indoor IV seem closer to nameplate rating (though limited data)
- Outdoor seem farther away trending towards nameplate rating. Outdoor data may include light-induced degradation (LID)

Reducing sampling bias x-Si → median 0.5 - 0.6, mean 0.8 %/year

All degradation rates

Median per study & system



Significant difference between all R_d & median per study & system

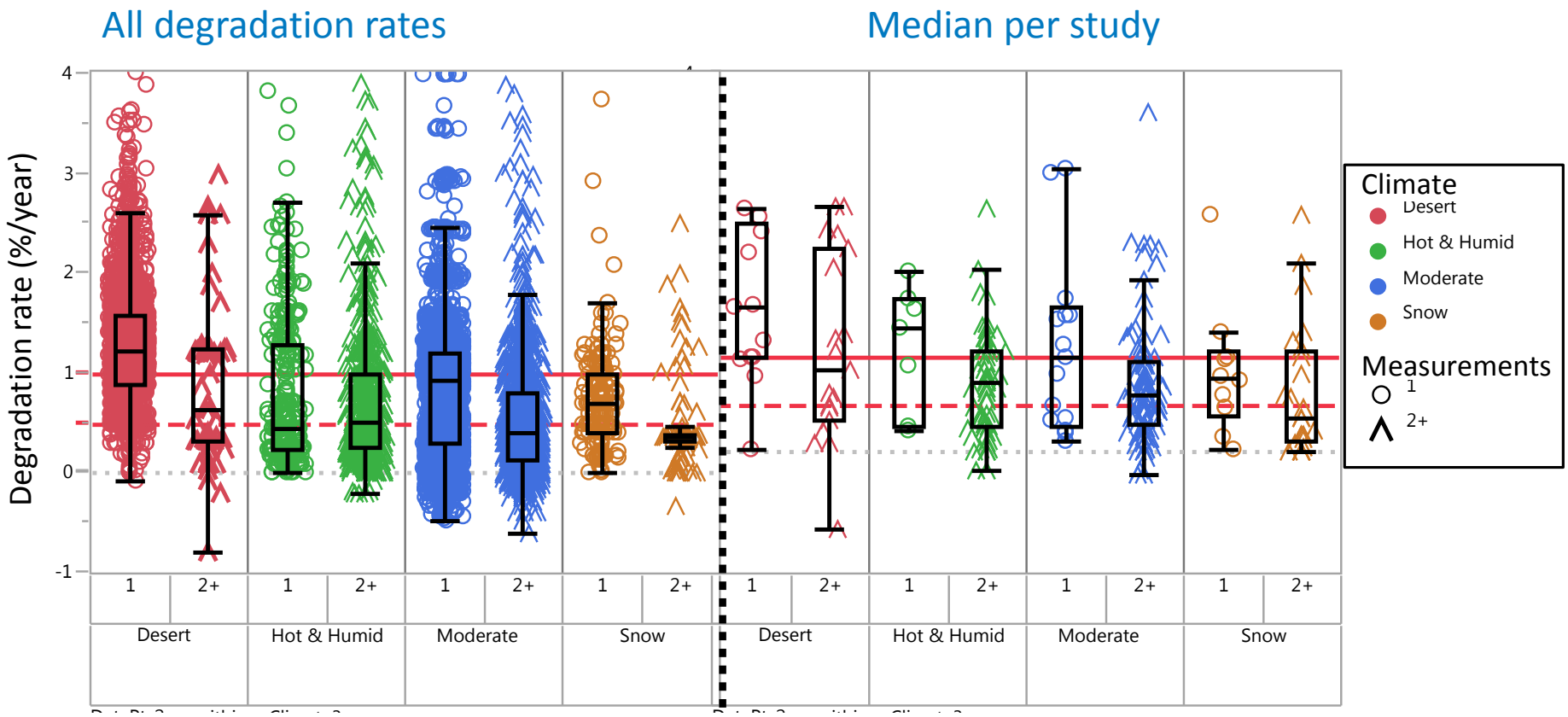
a-Si R_d > 1 %/year

Hetero interface (HIT) R_d similar to a-Si than x-Si

CIGS around 0.5 %/year

Hotter climates appear to show higher R_d

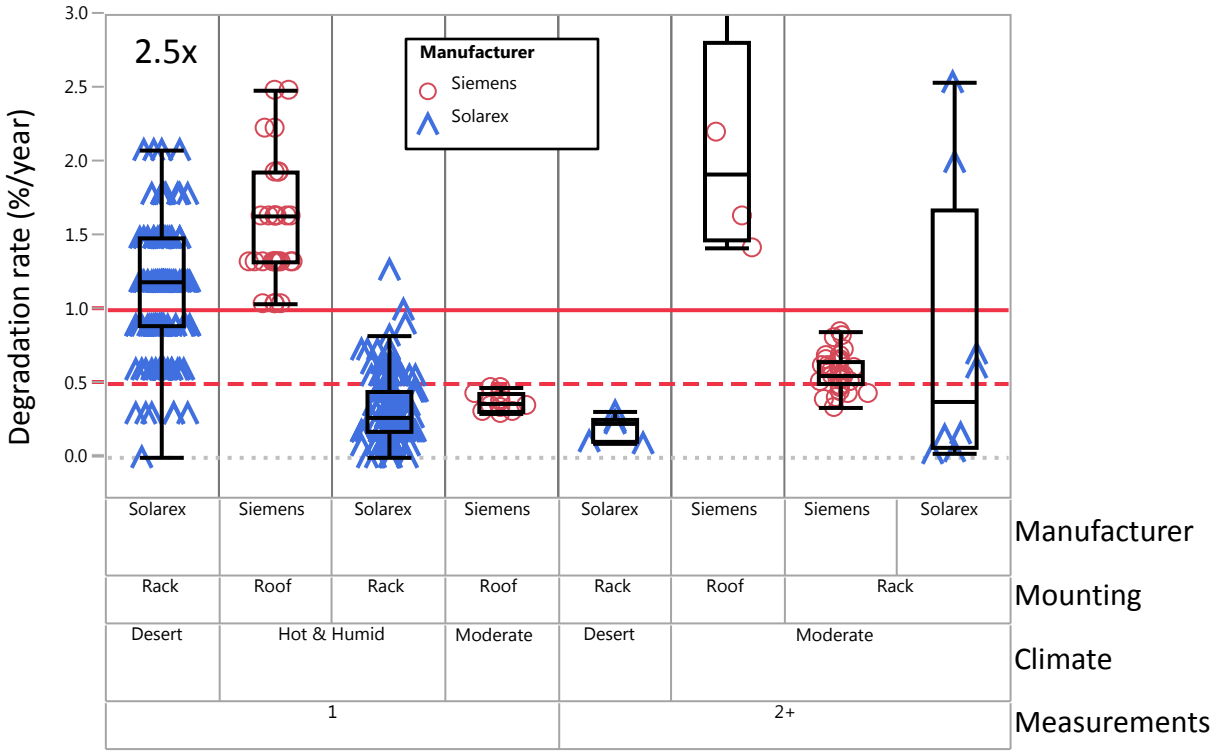
Climate category: simplified Köppen-Geiger



1-measurement studies show statistically significant higher rates

Climate statistically *not* significant … but…

Some modules more susceptible to hotter climates & mounting.



Solarex:

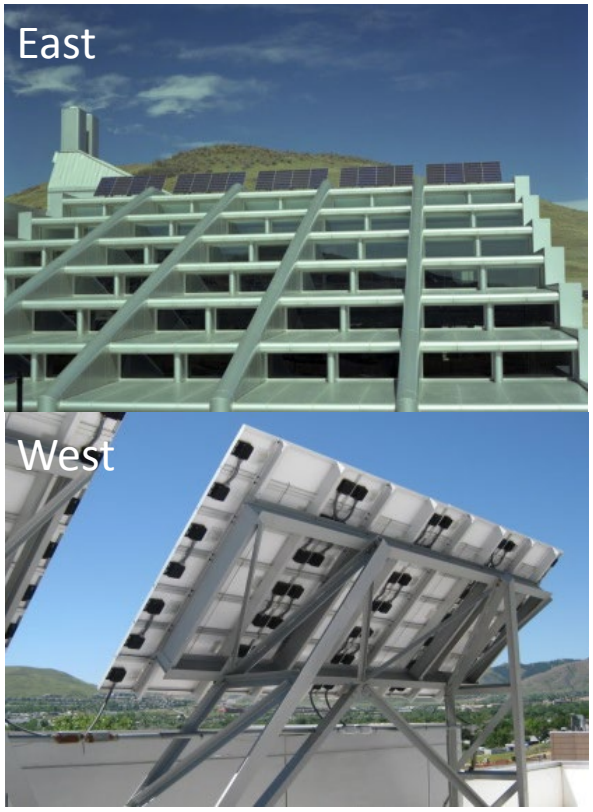
- Show low median R_d across climates
- Desert (1-measurement) shows higher R_d → 1-axis tracker & 2.5x concentration

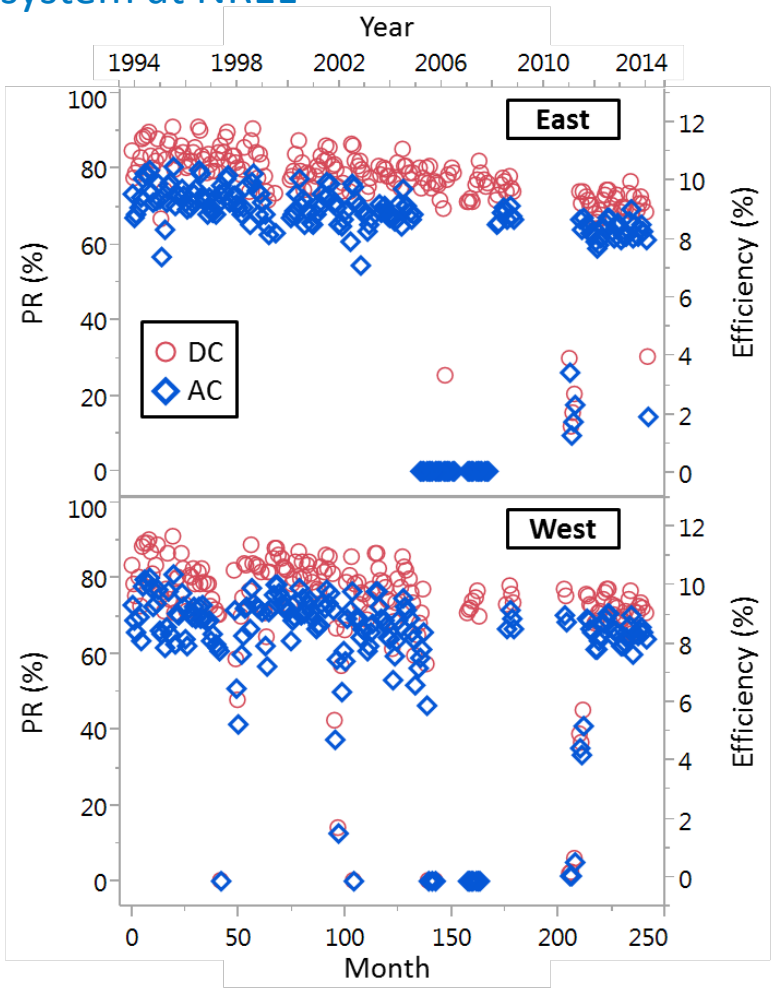
Siemens:

- Roof mounting shows higher R_d even for moderate climate
- Hot & Humid shows higher R_d than Solarex

System vs. module degradation?

20 year old mono-Si system at NREL

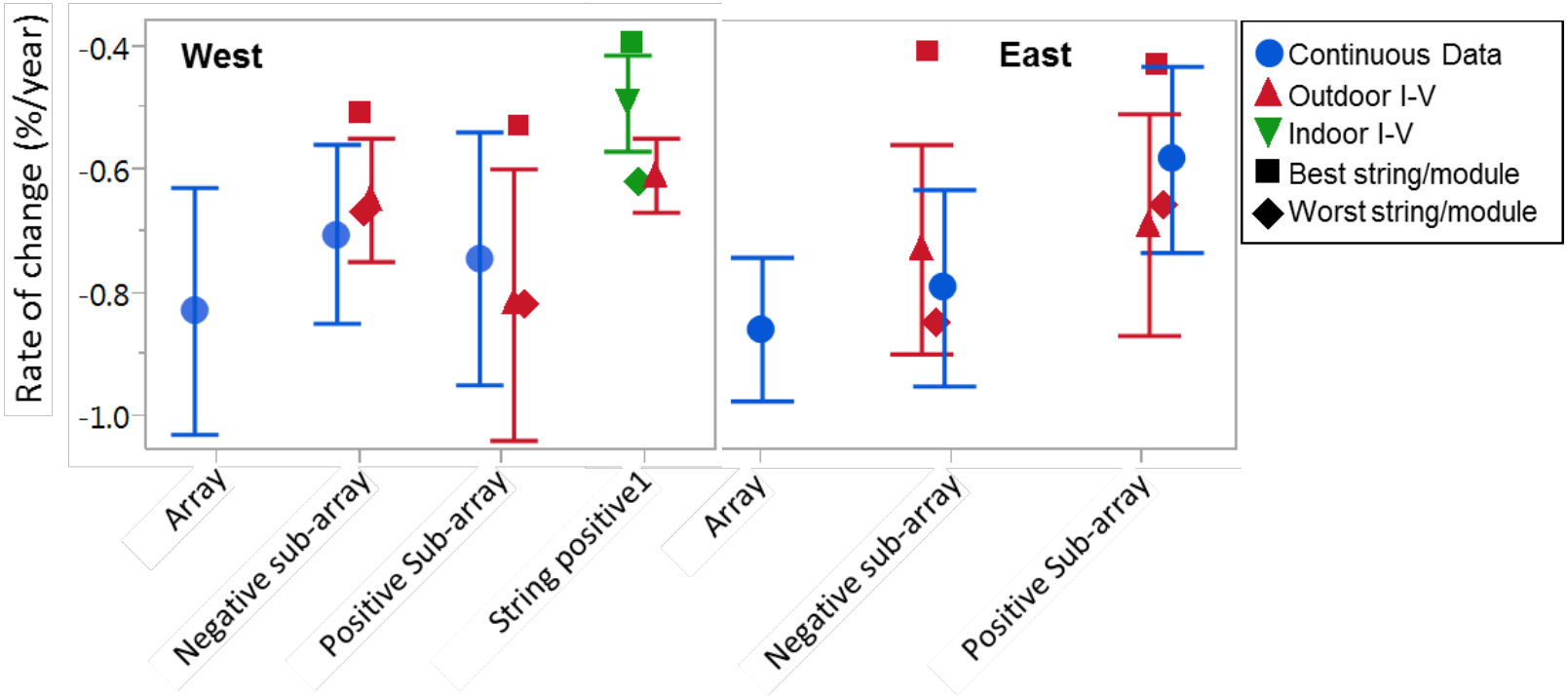




Siemens M55 modules
Size: 7.4kW

Performance and Aging of a 20-Year-Old Silicon PV System, Jordan et al., J. PV, 2015.

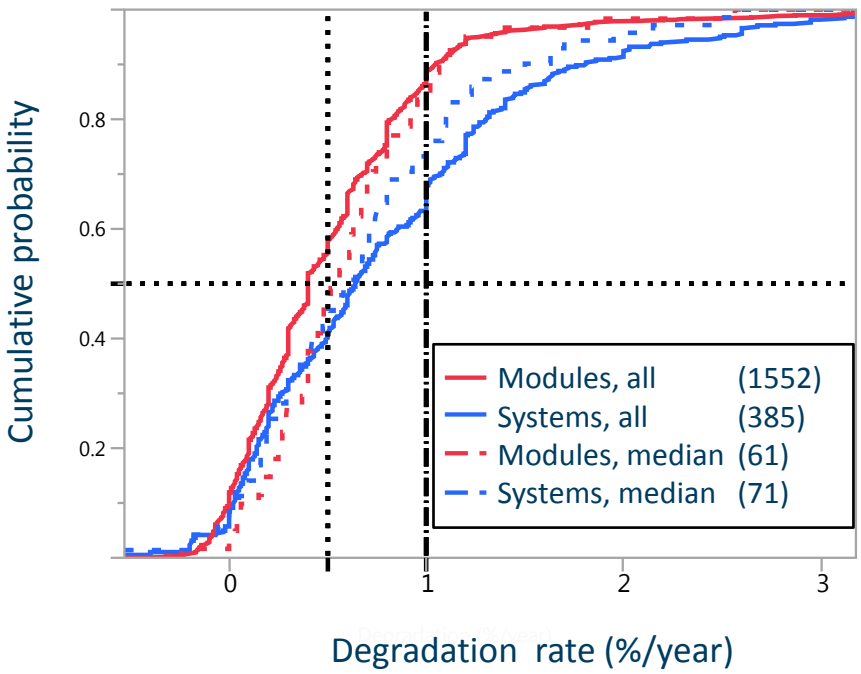
System & module degrade similarly



- The worst string appears to determine the subarray and array performance
- System degradation matches module degradation if modules degrade similarly, System degradation > average module degradation when large spread

At median systems & modules degrade similarly

High –quality, x-Si data



At median modules degrade a little less than systems but in general very similar

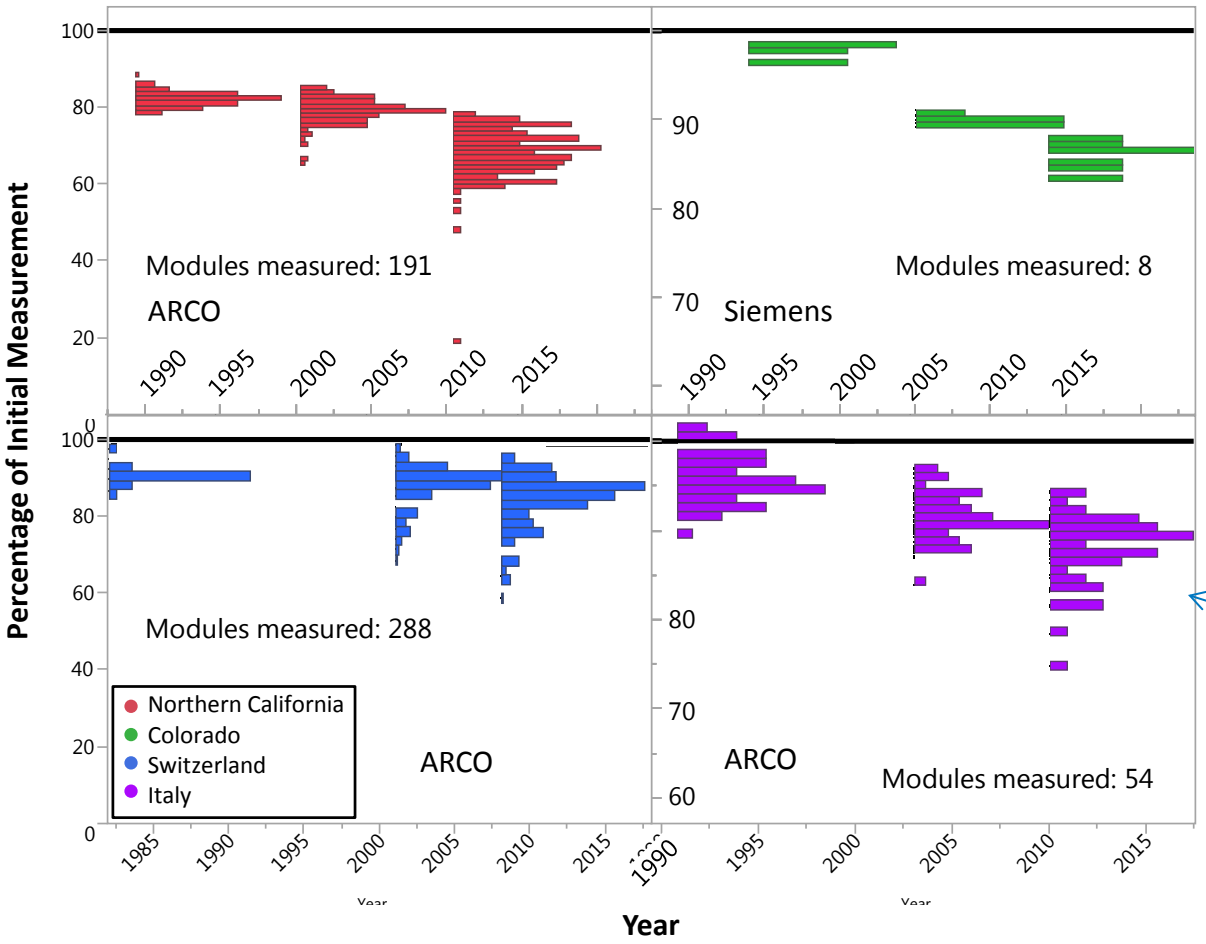
For less well-performing products more significant gap between modules & systems

Appears linear for most modules, worst modules non-linear

Studies that measured sample modules several times in 20+ years

20 years

30 years



1st measurement taken after 11 years

Distribution skews towards low end → worse performing modules show some non-linearity

Central tendency & better modules → fairly linear

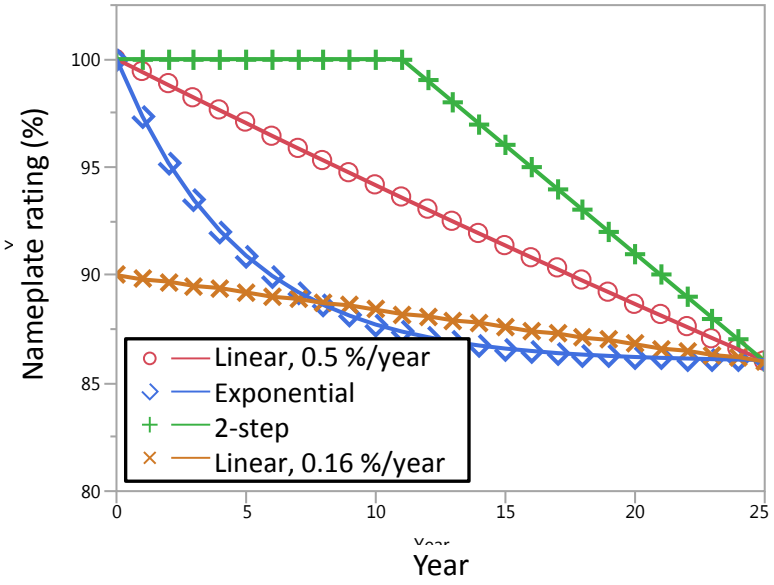
Simulation assumption for LCOE impact

Hypothetical commercial PV system near NREL:

Size: 100 kW, tilt: 40º, azimuth: 180º → PVWatts
Tax rate: 30%

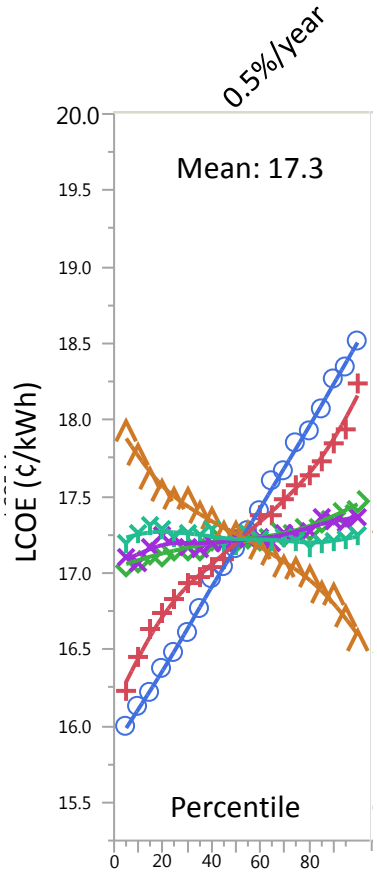
Parameter	Distribution	Mean	Range	Unit
Initial production	Normal	159,437	± 2%	kWhr/year
Initial cost	Triangular	2.6	2.4 – 2.8	$/W
Discount rate	Uniform	7.5	6 – 9	%
Residual value	Uniform	5000	0 – 10,000	$
O&M cost	Triangular	20	17 – 25	$/kW/year
O&M escalation	Triangular	2	0 – 4	%

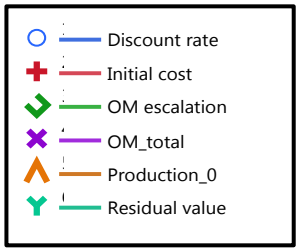
Input degradation curves



$$(1)\quad LCOE(\$/kWh) = \frac{Total\ Life\ Cycle\ Cost}{Total\ Lifetime\ Energy\ \mathrm{Pr}oduction} = \frac{Initial\ Cost + \sum_{n=1}^{N} \frac{O\&M\ \cos t \cdot (1 - Tax\ Rate)}{(1+r)^n} - \frac{\mathrm{Re}sidual\ Value}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Initial\ \mathrm{Pr}oduction \cdot (1-R_D)^n}{(1+r)^n}}$$

Sensitivity analysis: Spider plots





See most important factors, can read the impact directly of axis.

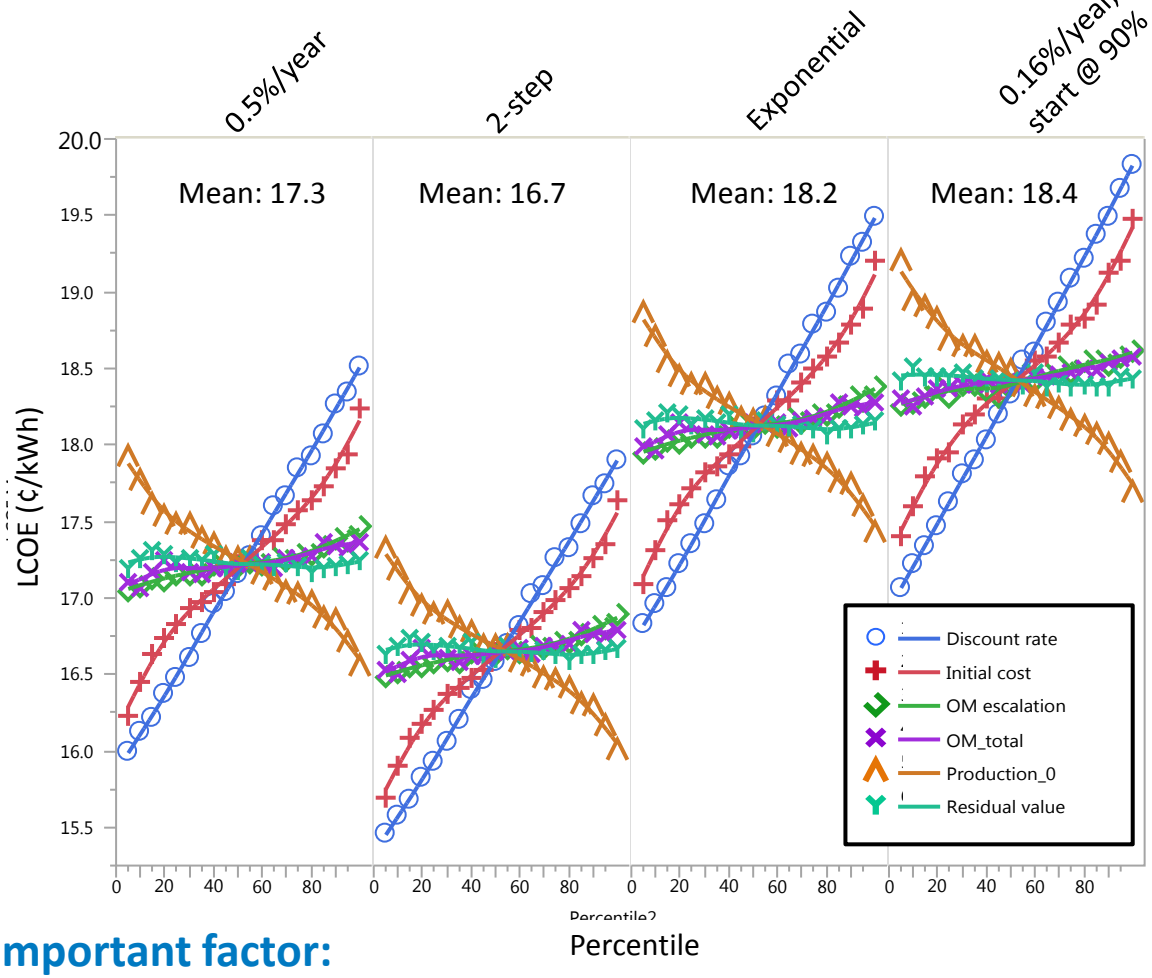
Different trends:
$\Downarrow$ $Production_{initial}$ $\Uparrow$ LCOE ;
$\Downarrow Cost_{initial}$ $\Downarrow$LCOE

Most important factor:

Discount rate ≈ 2.5 ¢/kWh; $Cost_{initial}$ ≈ 2 ¢/kWh; $Production_{initial}$ ≈ 1.5 ¢/kWh; O&M < 0.5 ¢/kWh

Degradation *curve* has significant impact on LCOE

Sensitivity analysis: Spider plots



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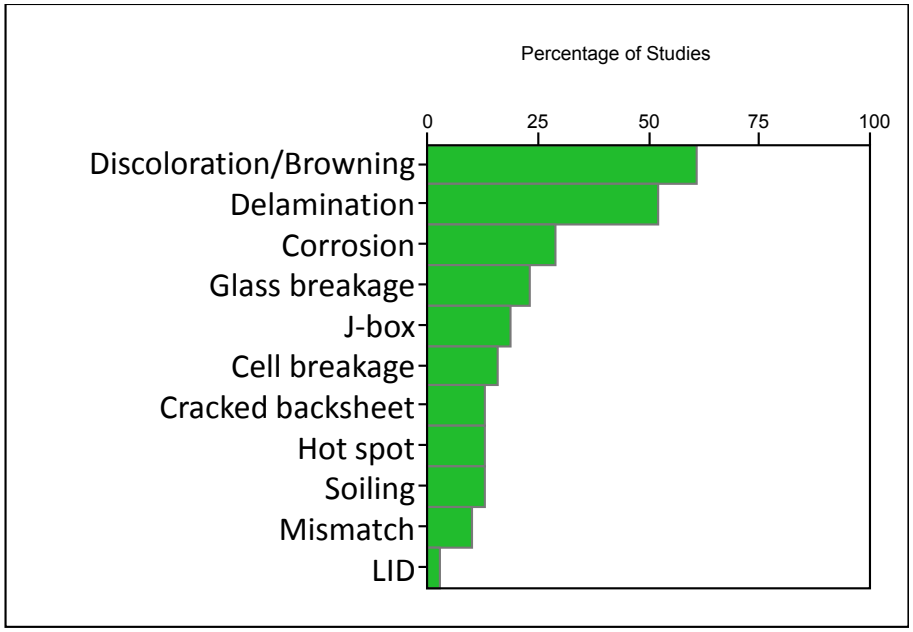
Degradation curve type ≈ 1.75 ¢/kWh

Discoloration & delamination most common

Pareto chart of failure modes in literature (2012)



Majority of studies report discoloration & delamination

Summary

- 1-measurement studies show significantly higher R_d because of nameplate rating deviation
- Increased R_d in hotter climates & mounting for some products
- x-Si has median in 0.5 – 0.6 %/year range, mean in 0.8 %/year range
- Non-linearities have significant financial impact, need more accurately measure curves instead of relying solely on rates.

Lifetime goal?

Tornado in Germany, May 2015

Roofs have substantial damage but modules appear for the most part undamaged.

Acknowledgments

Thank you for your attention

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