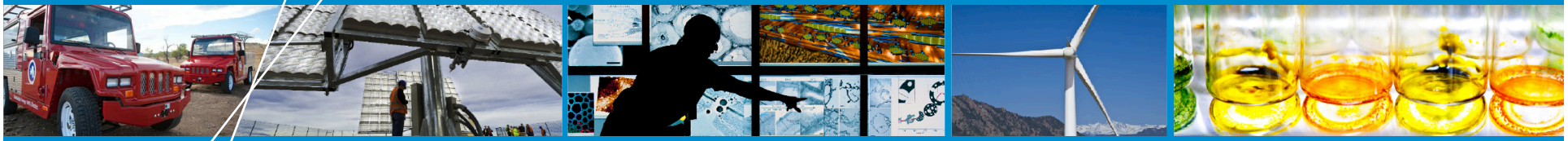
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Observed field failures and reported degradation rates



Thin Film PV Workshop,

Golden, CO

Dirk Jordan, Michael Kempe, David Miller, Corinne Packard, John Wohlgemuth, Sarah Kurtz

2/28/2013

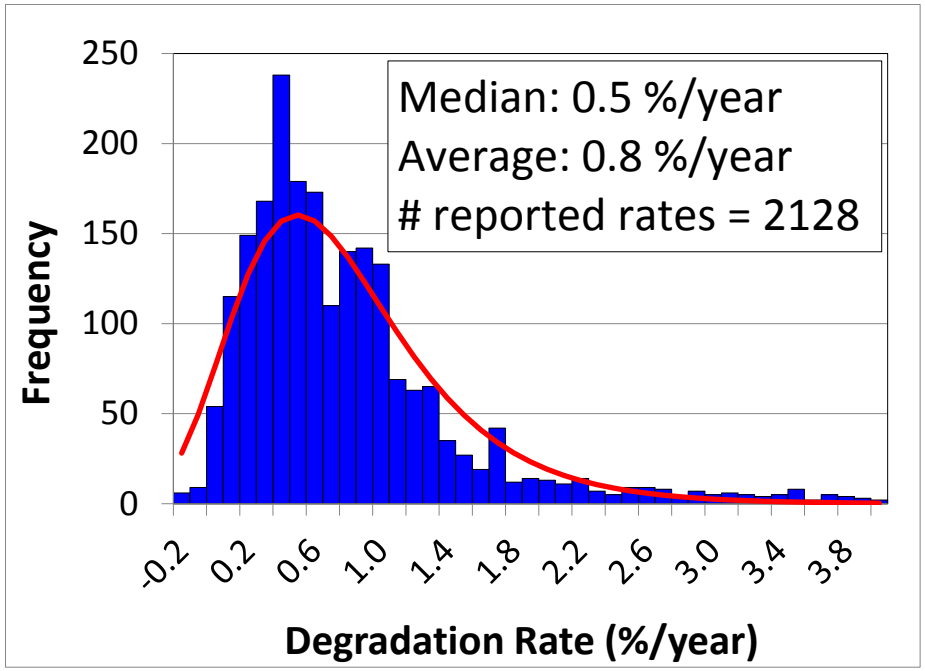
Outline

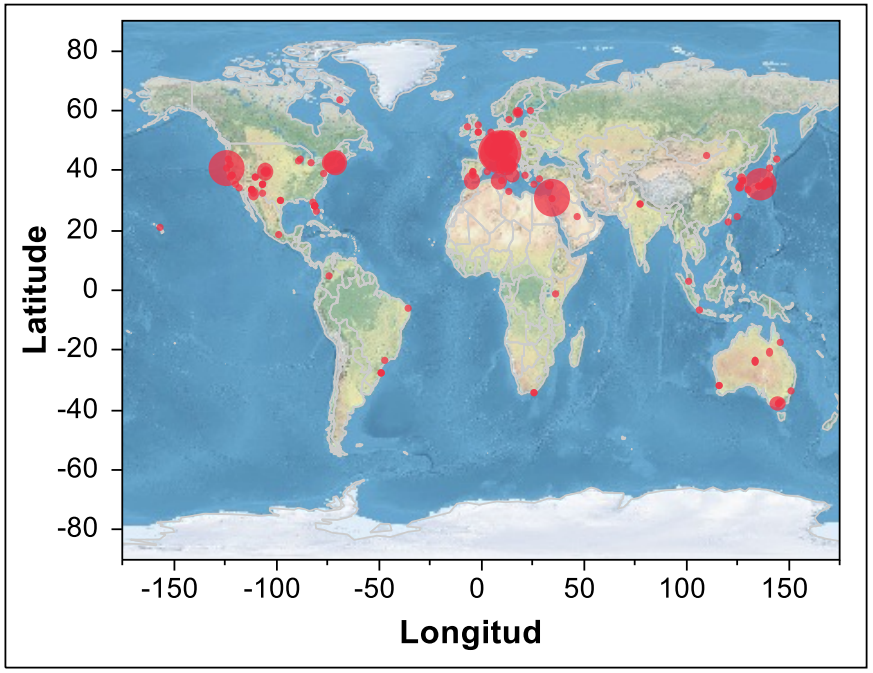
- Introduction
  - Degradation Rates
  - I-V parameter distribution
  - Field Failure
- Conclusion

Degradation Rates – Literature Survey

Number of Degradation rates (R_d) from literature: 2128

> 100 publications from 32 countries





Technology, age, packaging, geographic location

ca. 80% below 1%/year

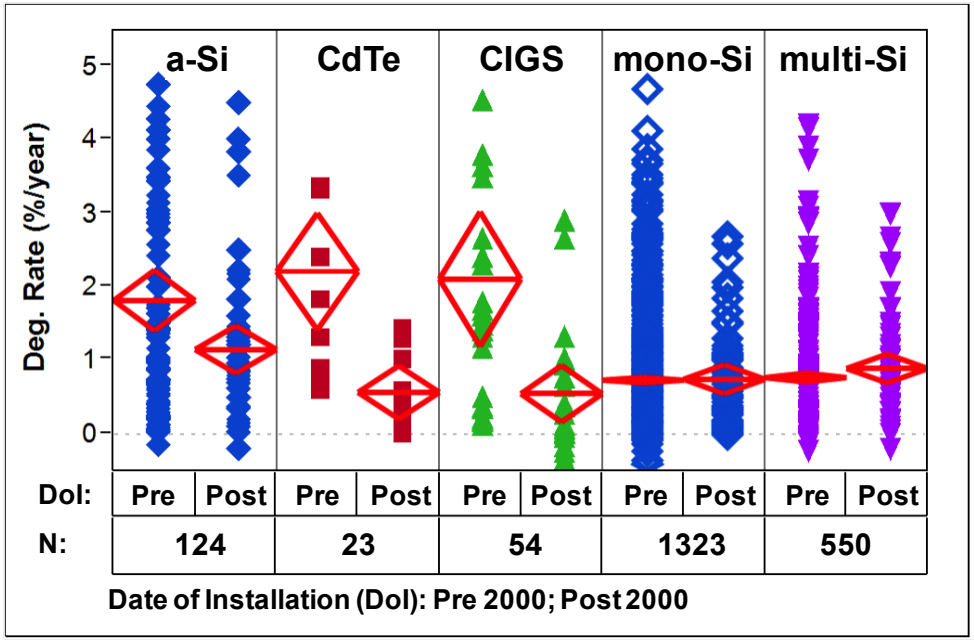
Circle size = number of data points from a given location.

Most modules degrade by ca. 0.5 %/year

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

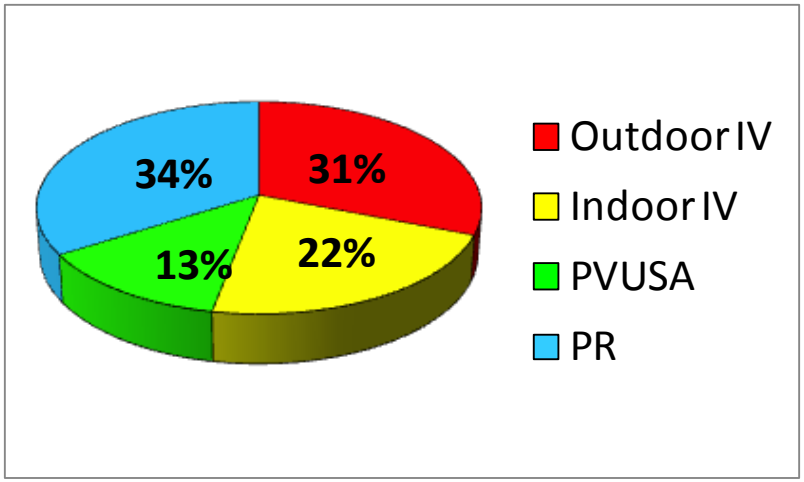
Literature Degradation Rates

Number of Degradation rates (R_d) from literature: 2128



Date of installation: Pre- & Post-2000
Red diamonds: mean & 95% confidence interval

> 100 publications from 32 countries

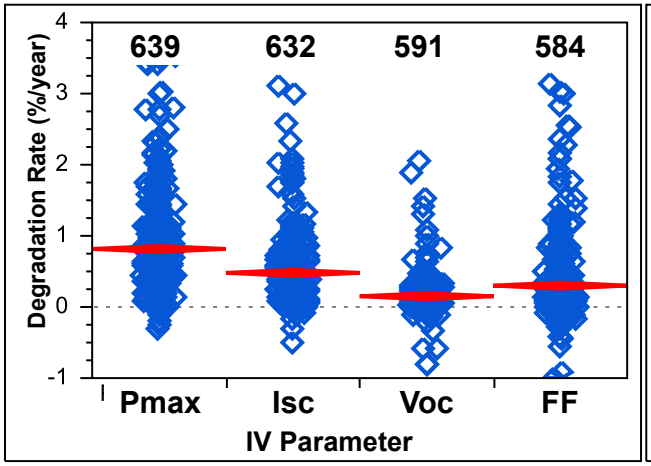


> 50% of Rd taken by I-V curves →
Information on short-circuit current (Isc), open-circuit voltage (Voc), fill factor (FF), Imax, Vmax

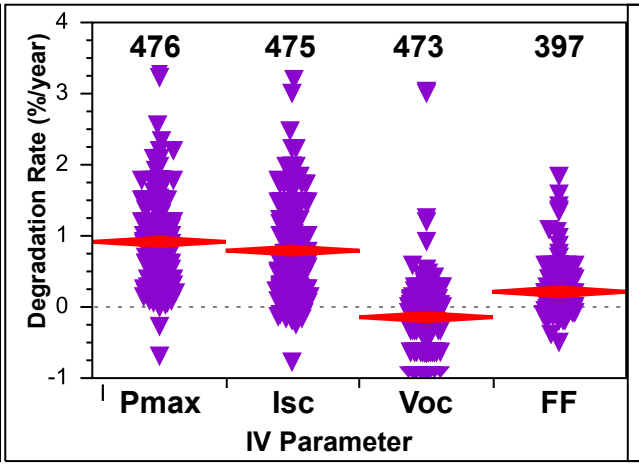
Thin-film technologies narrowed gap to c-Si in last 10 years
I-V parameter information for ca. 50% of all R_d

I-V Parameters by Technology

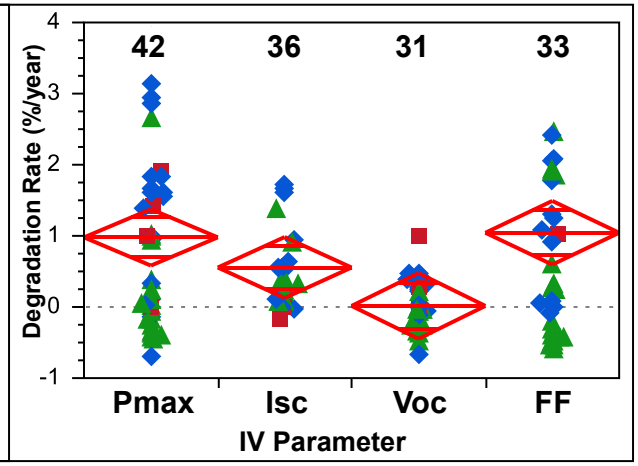
Mono-Si



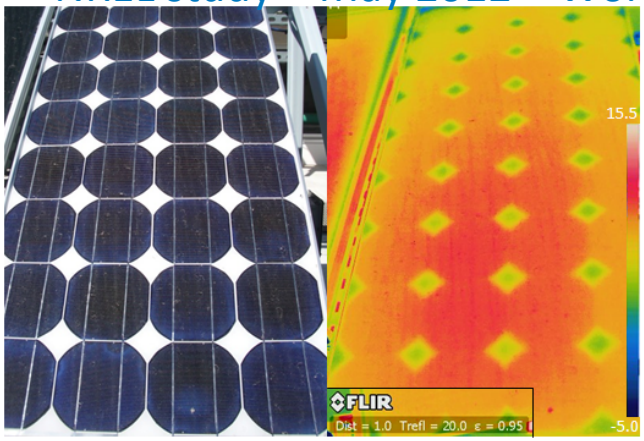
Multi-Si



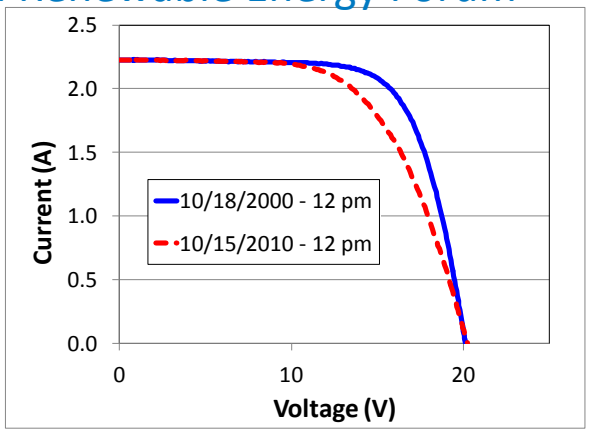
Thin-film



NREL study – May 2012 – World Renewable Energy Forum



Pmax correlated to Isc loss



Pmax correlated to FF loss

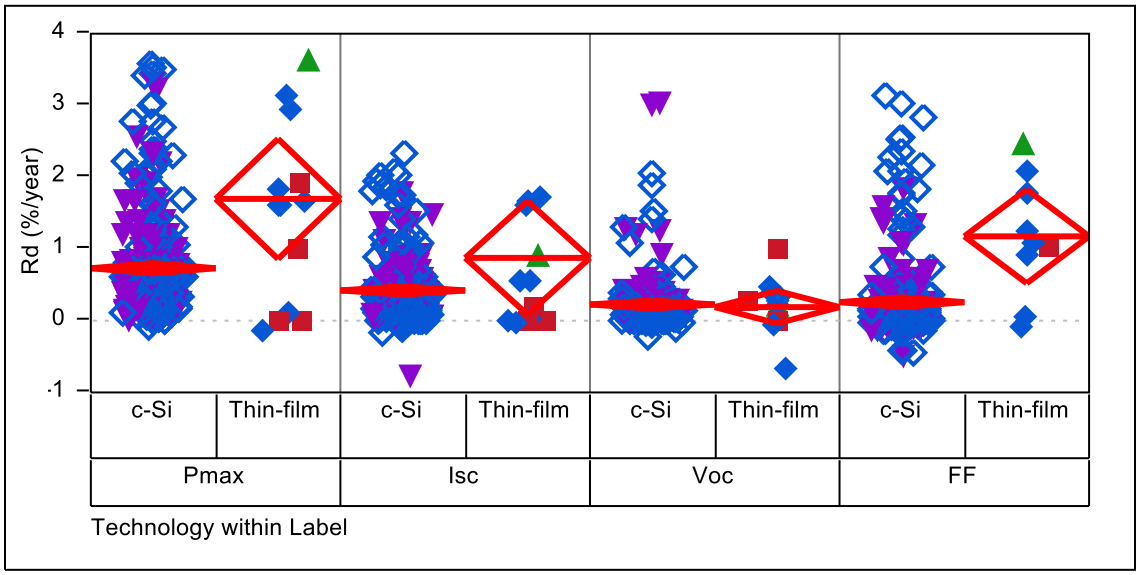
a-Si
CIGS
CdTe

Smith et al., World Renewable Energy Forum, May 2012

Degradation for c-Si Isc; Thin-film FF

c-Si – Thin-film Comparison

Hot & Humid Climate



mono-Si
multi-Si
a-Si
CIGS
CdTe

Thin-film show high FF R_d in humid climates

First Solar

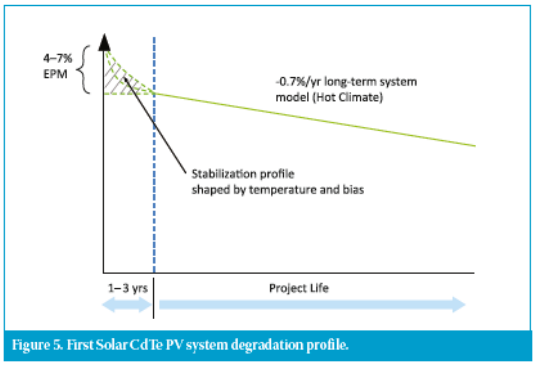


Figure 5. First Solar CdTe PV system degradation profile.

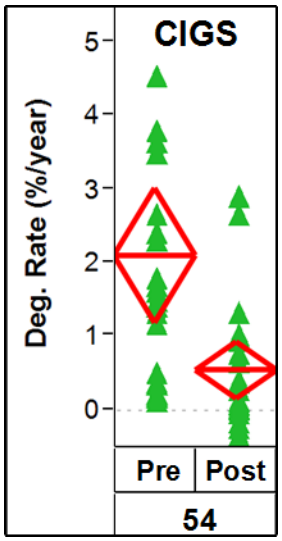
First Solar recommendation:
-0.7%/year for hot climate
-0.5%/year for all other climates

Different long-term performance recommendation based on climate

Strevel et al., 17th edition Journal Photovoltaics International, 2012

Different long-term recommendation based on climate

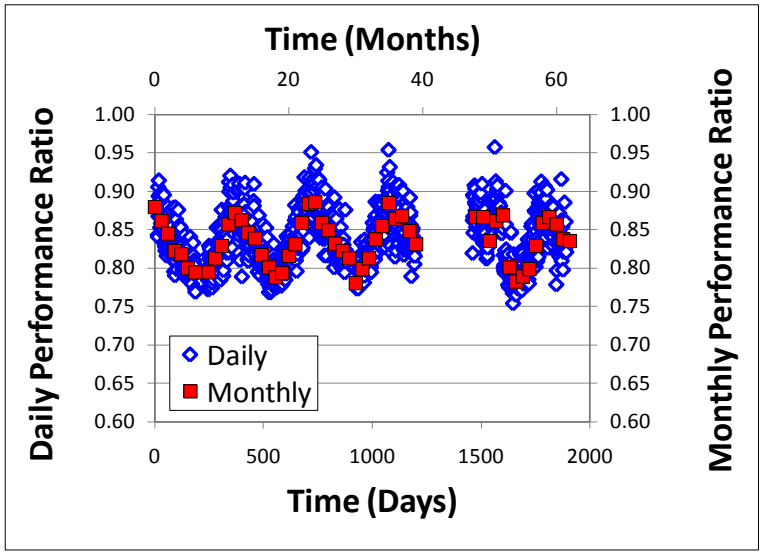
What about CIGS?



Shell Solar System - NREL

Shell Solar E80-C modules deployed at NREL.
Photo credit: Harin Ullal, NREL PIX 14725

Performance Ratio



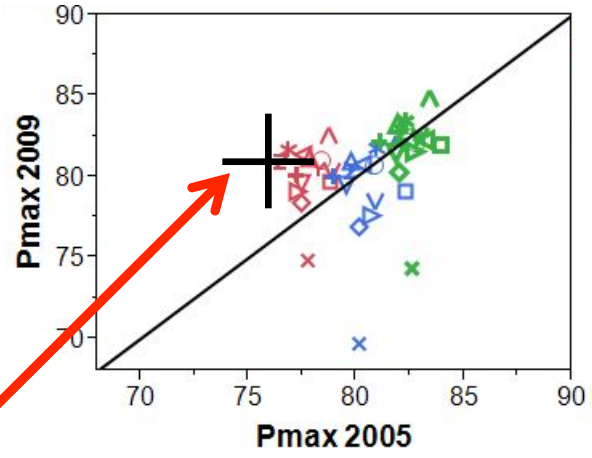
2 reports about stable CIGS array in the field

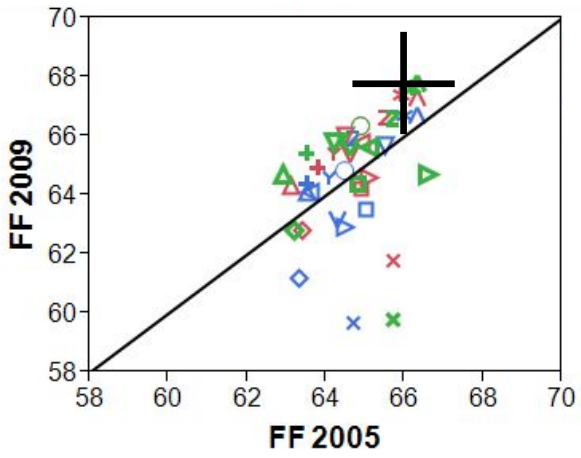
1. Germany, Musikowski et al., PVSEC, 2010, 3942
2. NREL, Jordan et al. , IEEE PVSC, 2011

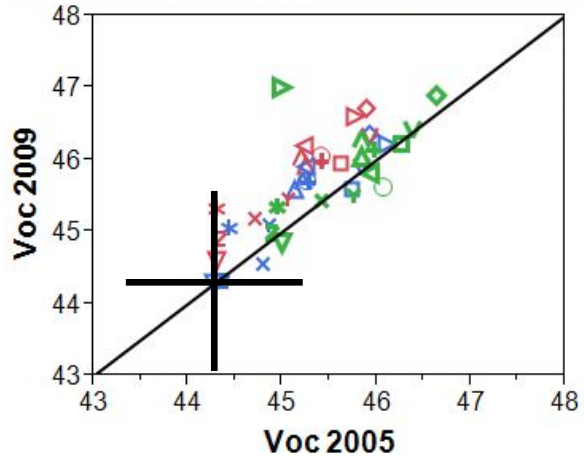
2 reports of CIGS arrays w/o measurable degradation

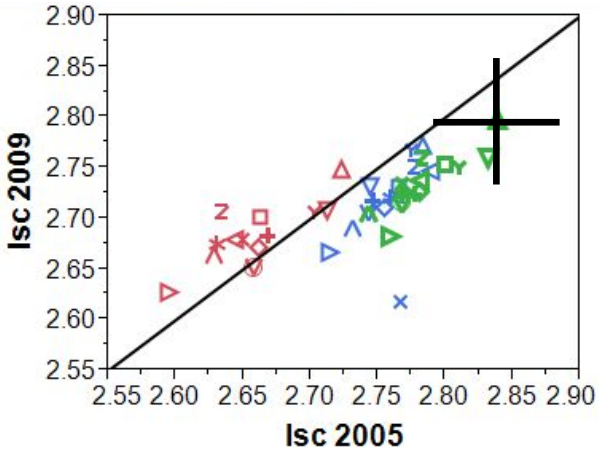
Device Performance Measurement

Representative Uncertainty bar

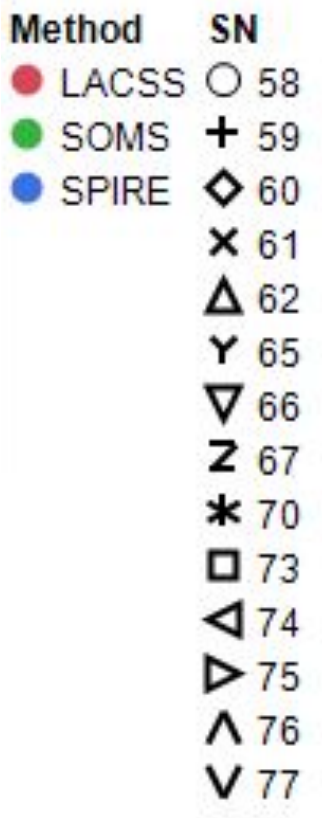








SN: Serial Number

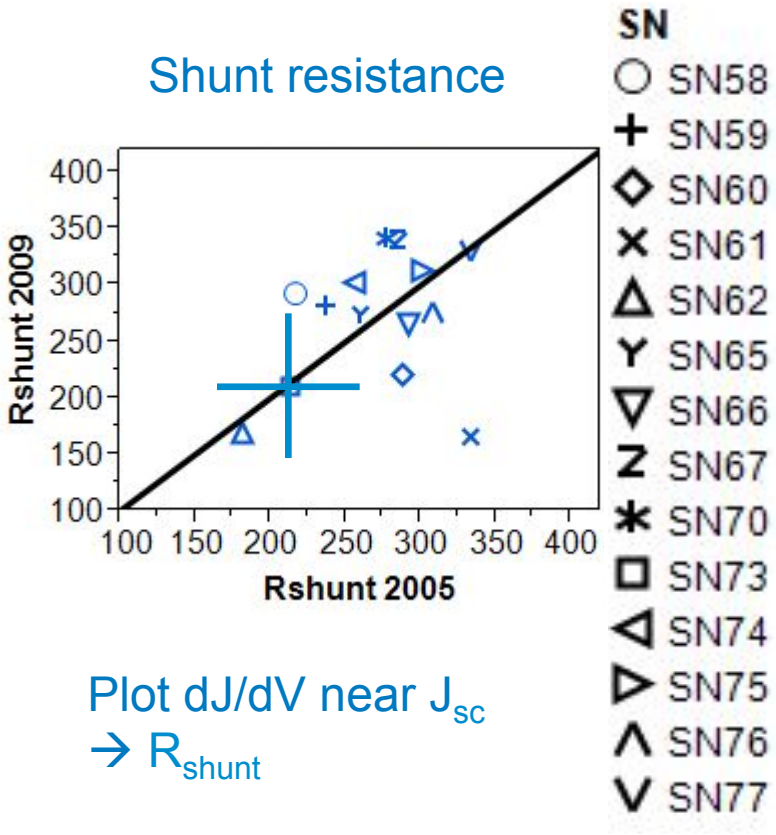


1. LACSS: Large area continuous solar simulator
2. SOMS: Standard outdoor measurement system
3. Spire 240A pulsed simulator

Only Module 61 shows clear signs of degradation

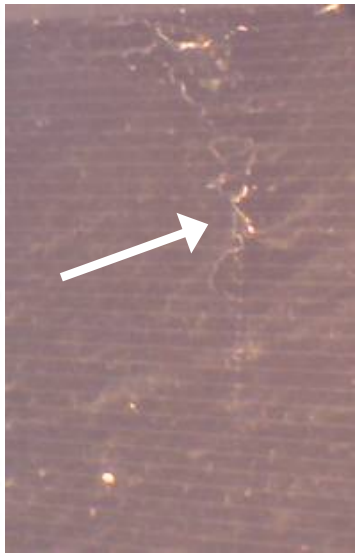
Module 61

Shunt resistance



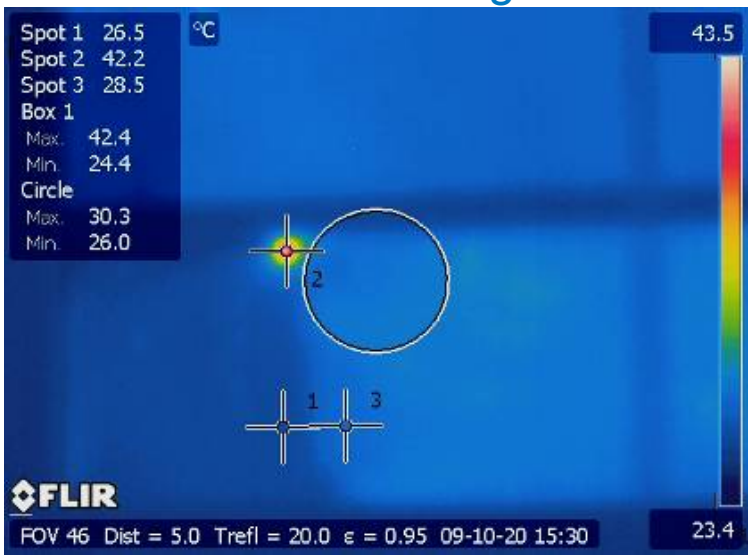
Plot dJ/dV near J_{sc}
→ R_{shunt}

Optical image



Scratch across cells

Infrared image



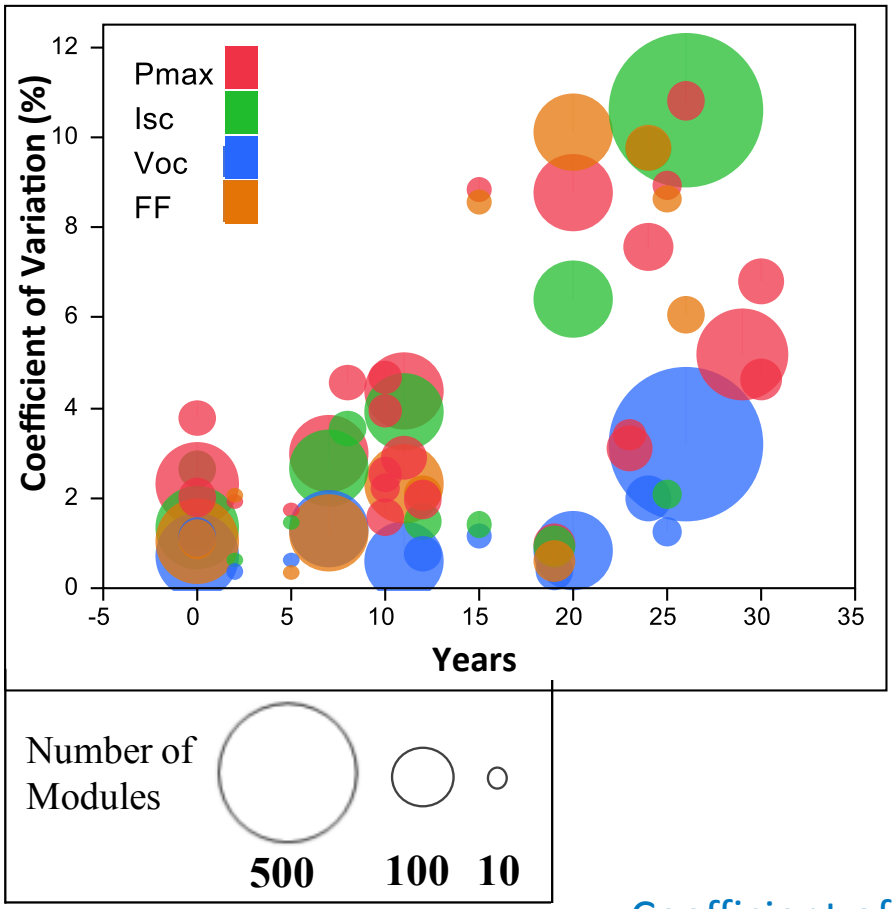
Hot spot at the end of scratch

Hot spot developed along presumed manufacturing defect

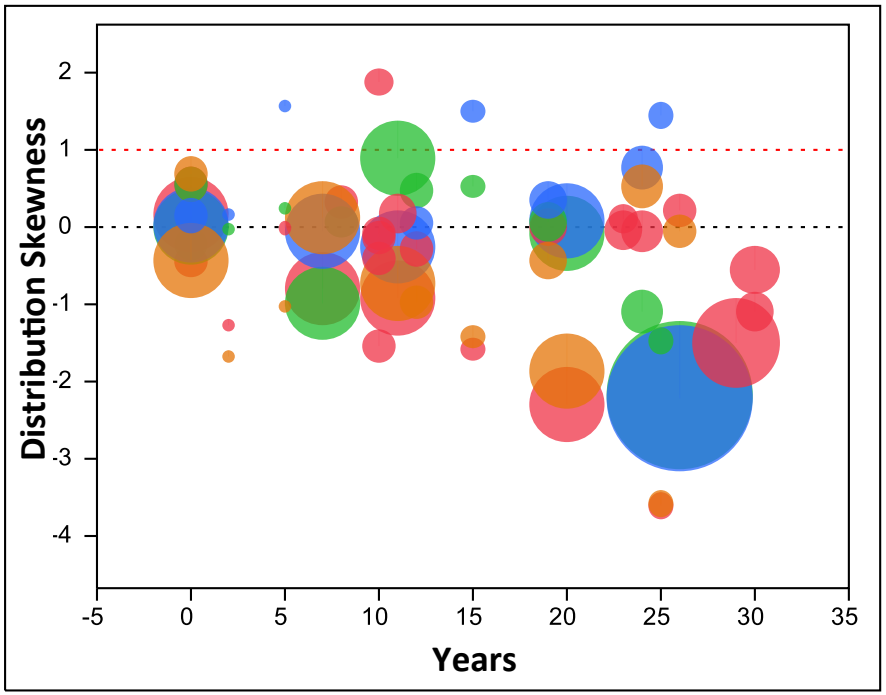
Hegedus et al., "Thin-Film Solar Cells: Device Measurements and Analysis", Progress in PV: 2004, **12**, 155.
Palm , "Second Generation CIS Solar Modules", Solar Energy, 77, 2004, 757–765.

Module I-V Distribution

Distribution width



Distribution symmetry



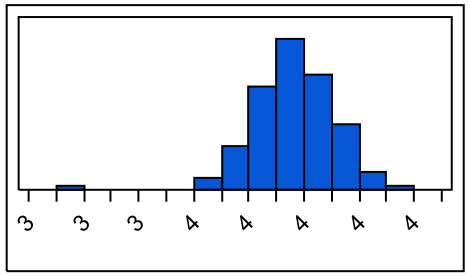
Color: I-V parameter
Size: Number of modules in study

Coefficient of Variation (CoV): Standard deviation/ Mean

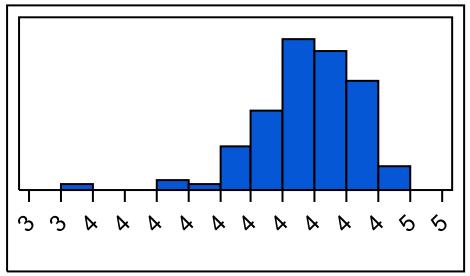
Distributions widen and skew with field exposure

I-V Distributions

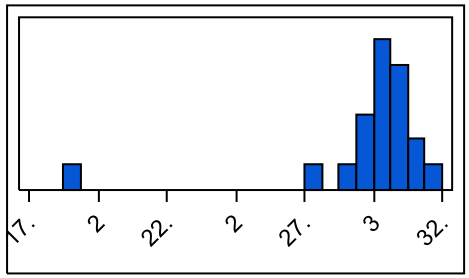
Israel – 1995 – 7 years



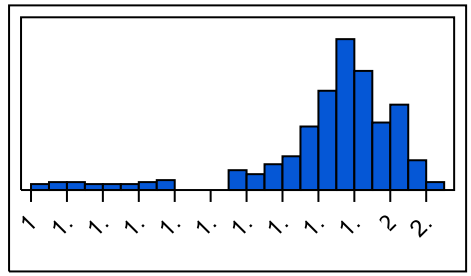
Japan – 2003 – 10 years



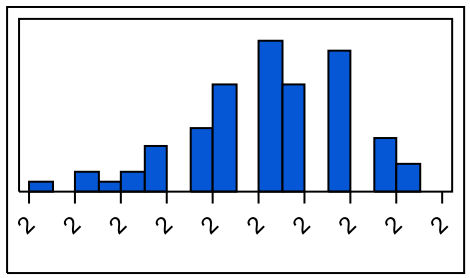
Sweden – 2006 – 25 years



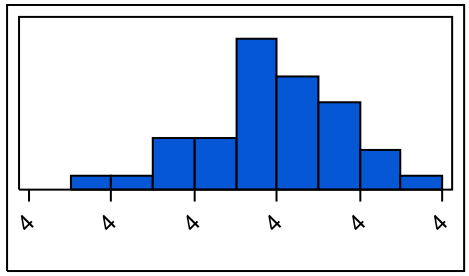
Tunisia – 2008 – 25 years



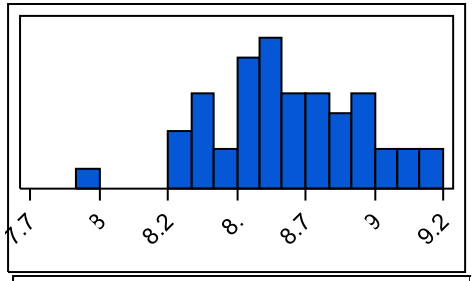
MA – 2010 – 30 years

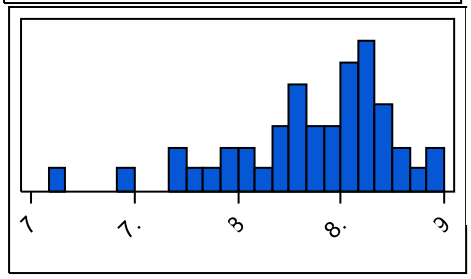


Spain – 2011 – 12 years

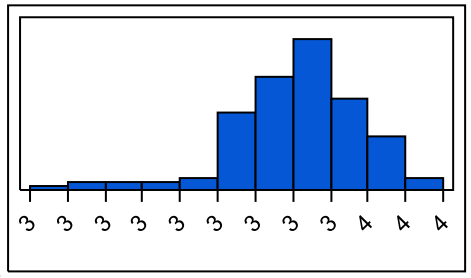


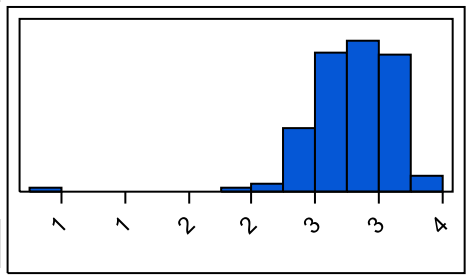
Italy – 2010 – 23 & 30 years



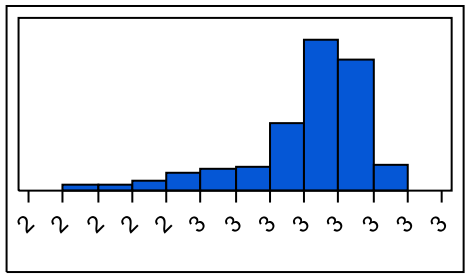


CA – 2011 – 11 & 20 years

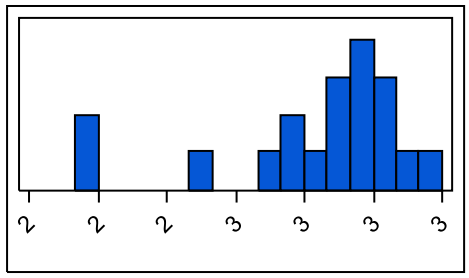




Switzerland – 2010 -20 years



CO – 2012 – 15 years



I-V Distributions

Israel – 1995 – 7 years

Japan – 2003 – 10 years

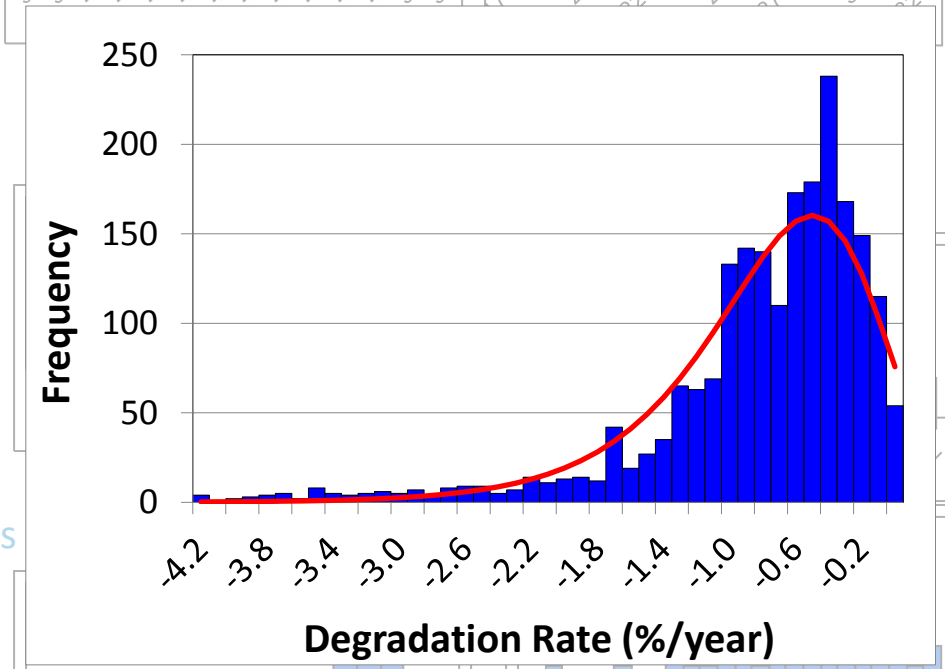
Sweden – 2006 – 25 years

Tunisia – 2008 – 25 years

MA – 2010 – 30 years

CA – 2001 –
11 & 20 years

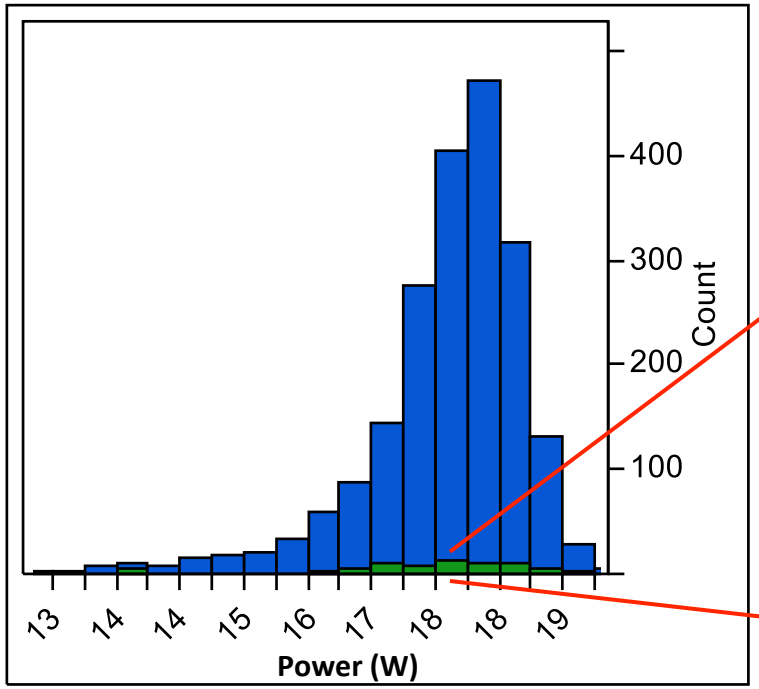
Switzerland – 2010 -20 years

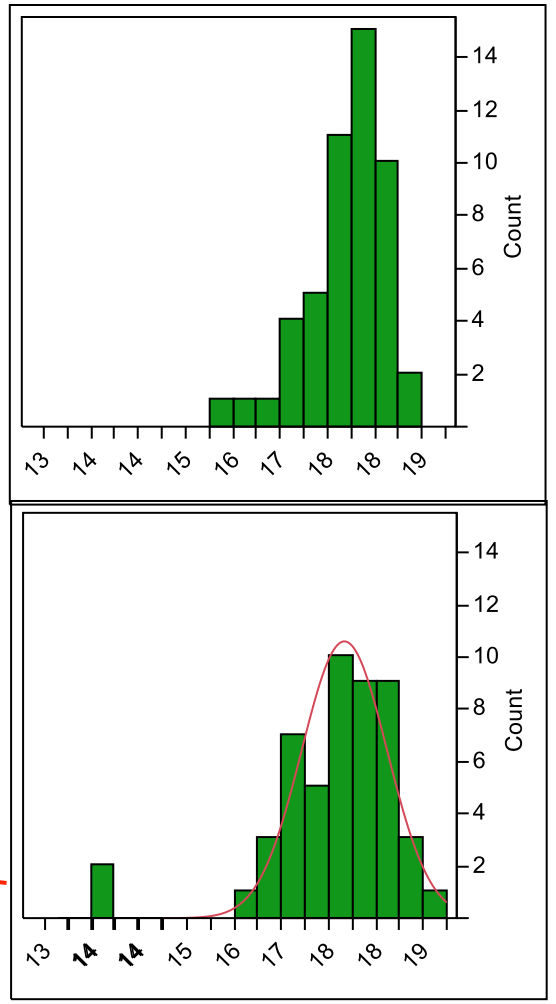


Module Parameter Distributions similar to R_d Distribution

System Performance

Skewed distribution with 2000 data points
Very few studies investigate that many modules
--> take 50 random sample

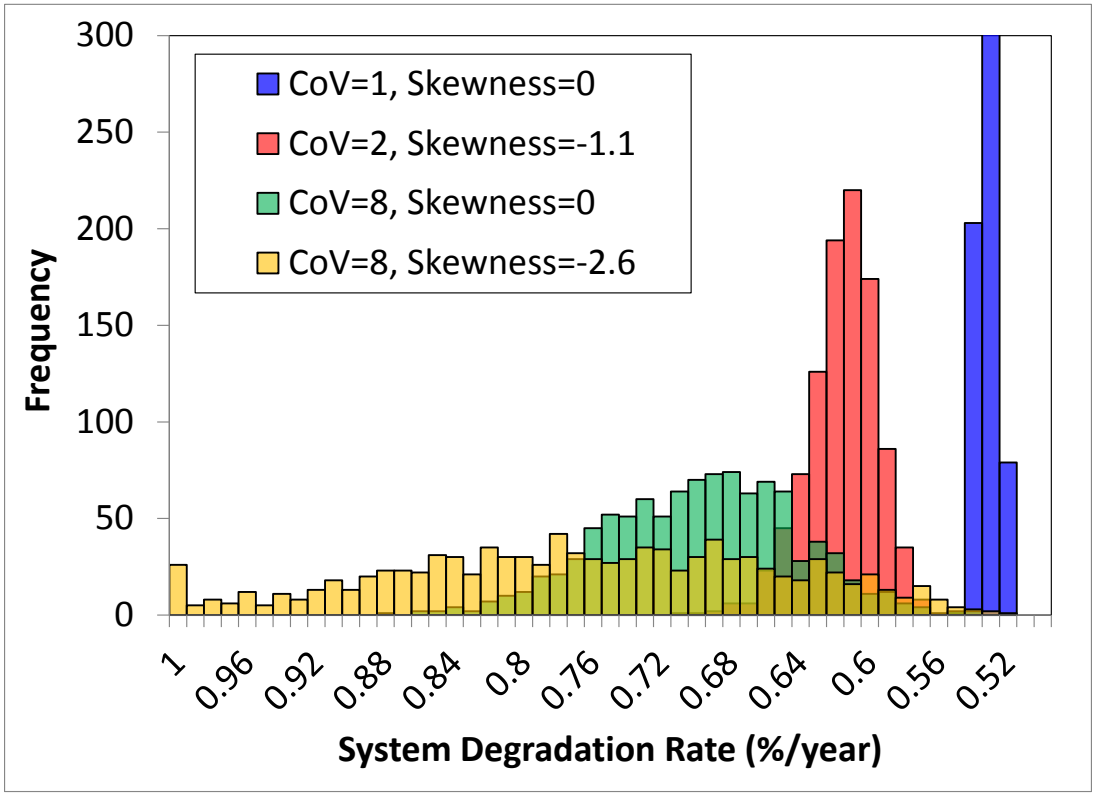




Outlier may be indicative of skewed distribution
Takes sufficient field exposure & sample size to see it

Why do we care?

Monte Carlo Simulation:
Assumption: modules 0.5%/year degradation over 25 years
20kW array, 200W modules, 100 modules, 10 strings, 10 modules/string



Distribution of module degradation affects system degradation

Field Failures - Literature

Yellowing/browning	Front grid oxidation	Discoloration
Terminal+junction box oxidation	Glass	Soiling
Hot spot	Internal electrical circuit	Metallization discoloration
broken/cracked cells	Cells	arc
Backsheet detachment	Encapsulant & backsheet	String interconnect
Encapsulant delamination	Bubbles	backsheet crumbling
Sealant penetration	Delamination	Tedlar detachment
Grid oxidation	Frame	arc damage to earth
Insulation (dry)	Corrosion	J-box cracking
Insulation (wet)	Cell or Interconnect break	Milky pattern
Soiling	Diodes	Mortar soiling
Interconnects	Mechanical damages	Burn marks
Frame defects	LID	Electrochemical weathering
AR coating oxidation	Mismatch	Weathering

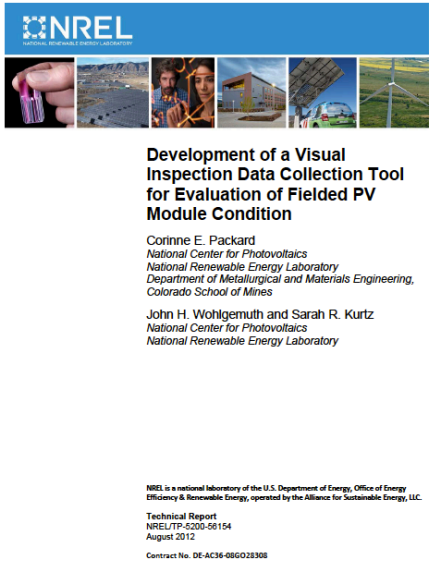
Lack of consistent terminology

Visual Inspection Data Collection Tools

- **Uses IEC/UL standard terminology**
- **Attempts to balance collection of sufficient detail for failure mode evaluation against minimizing recording time per module**
- **Consists of 14 sections- based on module component**
  - Long form & short form evaluations

Additional detail can be found in the full NREL report TP-5200-56154

Development of a Visual Inspection Data Collection Tool for Evaluation of Fielded PV Module Condition
C.E. Packard, J.H. Wohlgemuth, S.R. Kurtz


NREL

Development of a Visual Inspection Data Collection Tool for Evaluation of Fielded PV Module Condition

Corinne E. Packard
National Center for Photovoltaics
National Renewable Energy Laboratory
Department of Metallurgical and Materials Engineering, Colorado School of Mines

John H. Wohlgemuth and Sarah R. Kurtz
National Center for Photovoltaics
National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

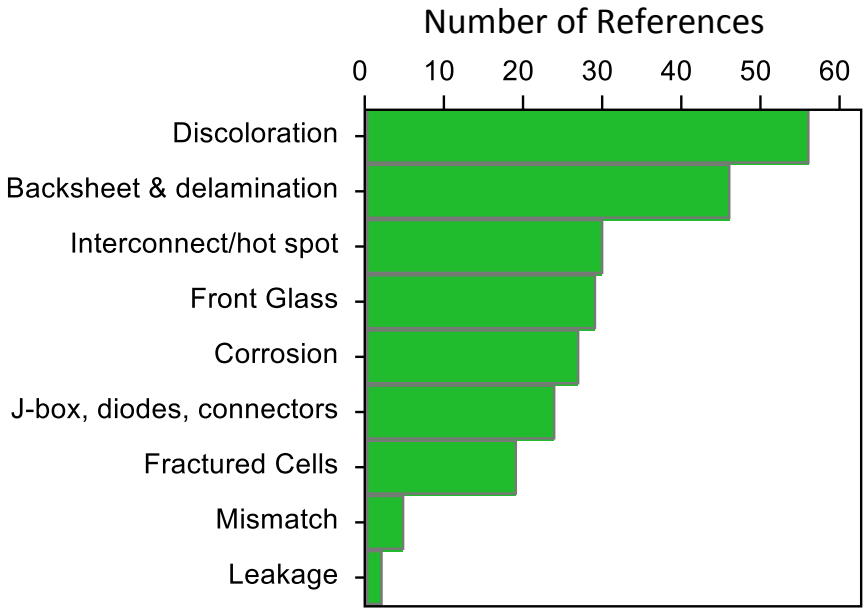
Technical Report
NREL/TP-5200-56154
August 2012

Contract No. DE-AC36-08GO28308

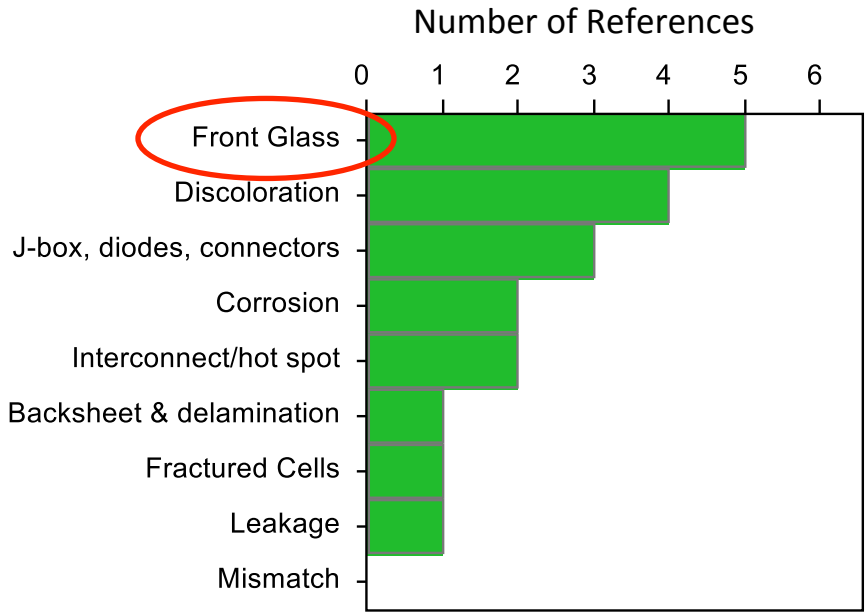
Field Failure - Literature

Almost 70 references

All Technologies



Thin-film



Front glass/cover moves up – but not a lot of statistics

Is it consistent with our own field observation?

BP (Solarex) Array - AZ

a-Si

Most common failure/degradation modes:

- Shading
- Delamination @ hot spot
- Soiling at periphery (frame)
- Delamination

Also:

- Site wiring
- Broken glass

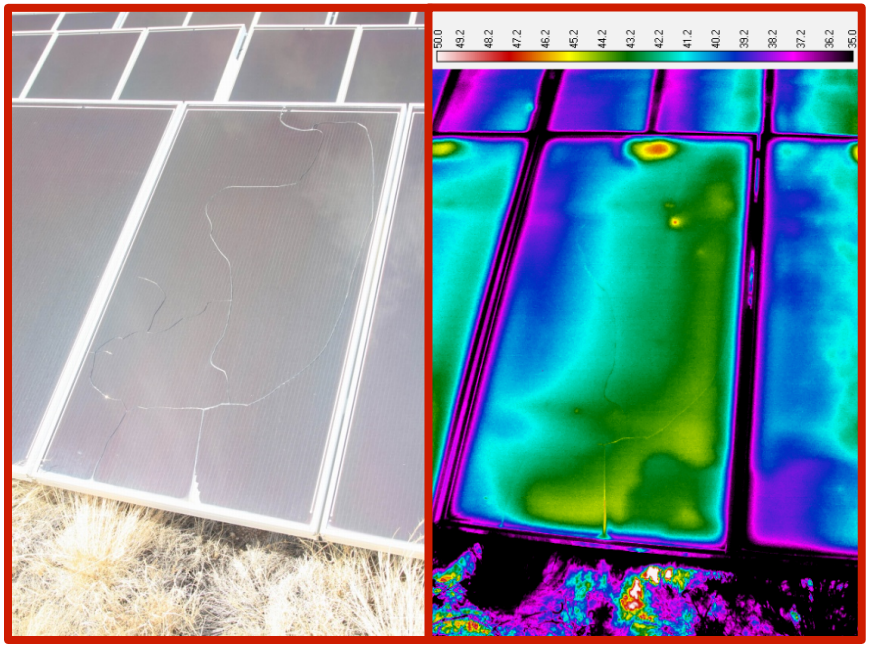
Modules:

- M/N MST-43MV
- 51W max, 45W rated.
- Manufactured July 2000 to May 2001
- Total of ~10,000 BP modules

BP Solar array, facing north (top) and facing south (bottom)

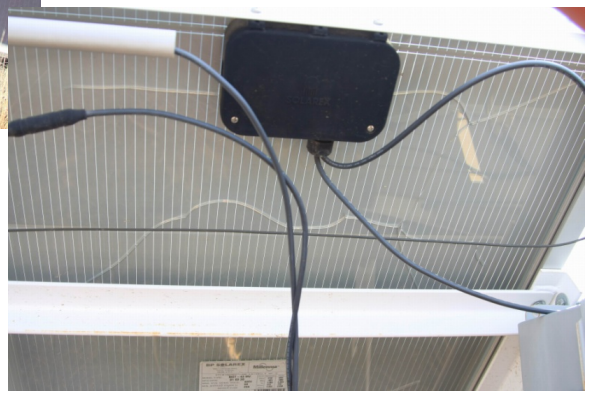
Broken Glass

Severely broken front



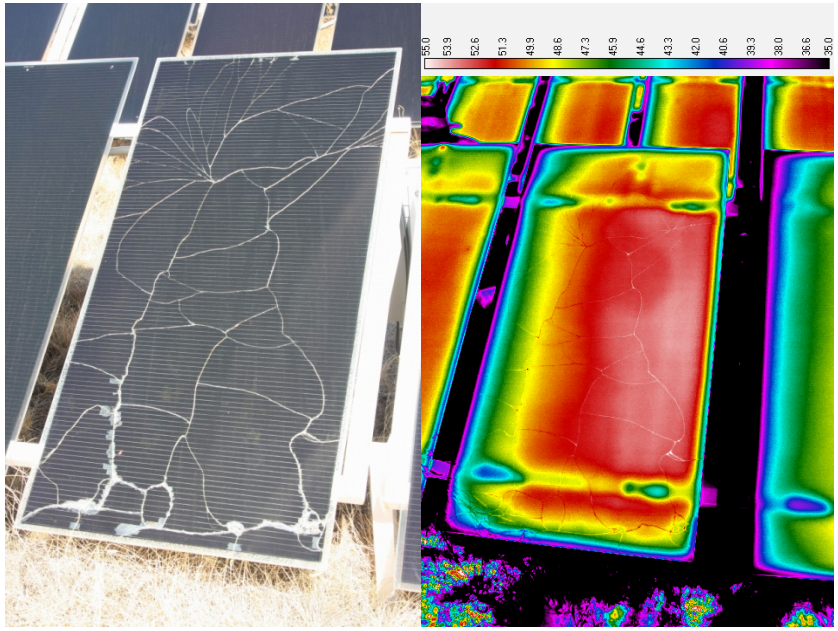
Less severely broken front

Broken back



- Wide variety of fracture morphologies and extent of damage
- Neither front or back glass is tempered.
- Front side: 6/400 modules.
- Back side: 11/400 modules.
- Both sides: 5/400 modules.

Broken Glass – different System



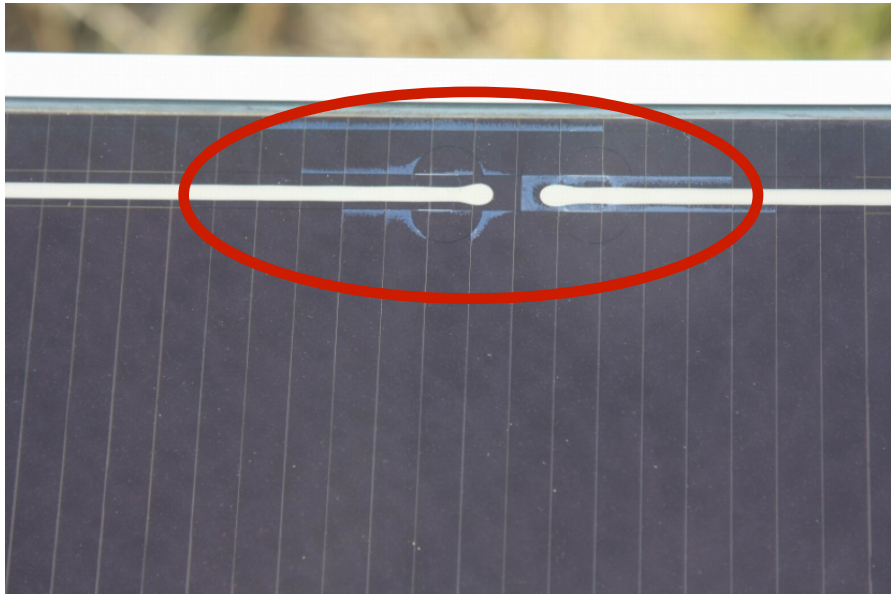
Optical (left) & IR (right) image

- Fracture did not always couple to the back from the front
- Extent of damage varied widely
- Usual hot spot may not be observed on modules with broken glass
- Relative occurrence: 3/450 in original (old edge seal) modules.
- Minimal thermal signature
- (diode is probably on)

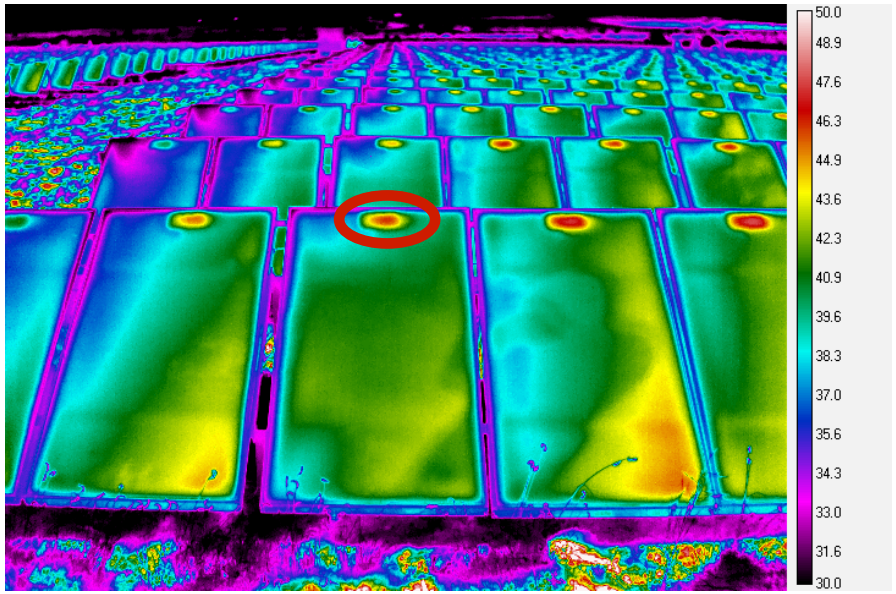
Optical image of only damage at base of module

Optical image of less damaged module

Delamination at hot spot



Optical image of delamination at module top

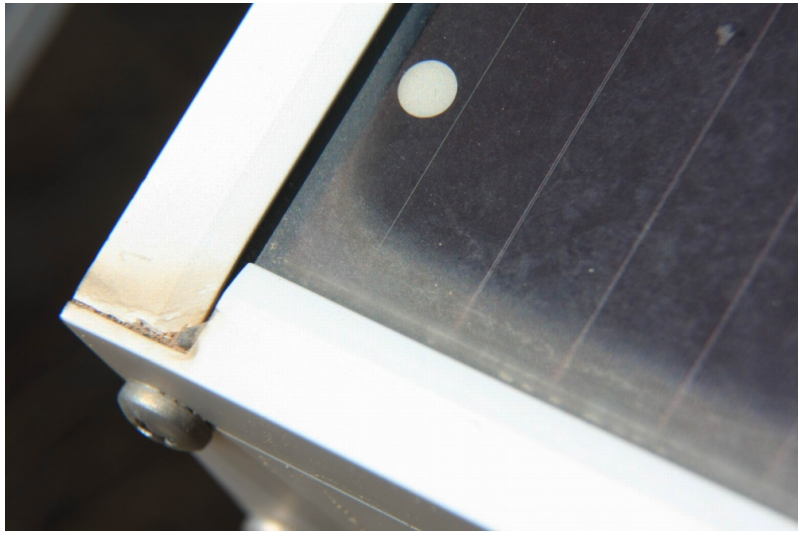


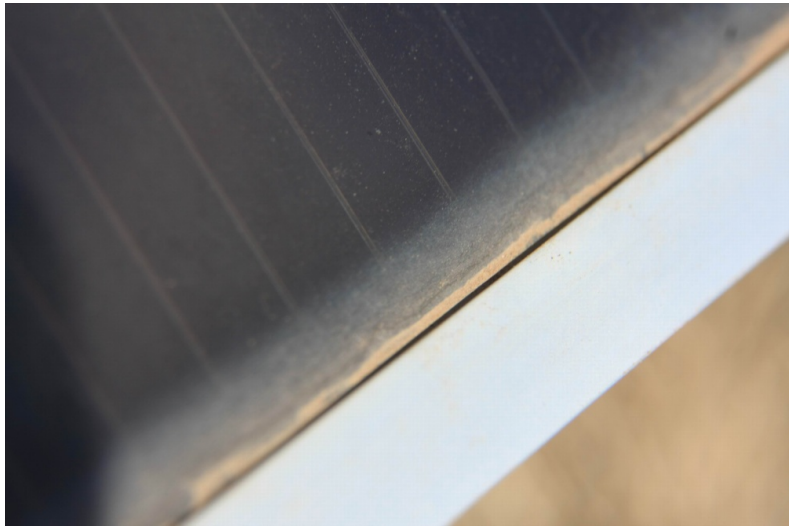
IR image of multiple modules within the array

- Localized delamination observed at top of module (over j-box)
- $T_{hot\ spot}$ ~ 50°C; $T_{front\ glass}$ ~ 45°C
- Relative occurrence: every module
- Delamination corresponds to a hot spot observed on every module

Permanent Soiling

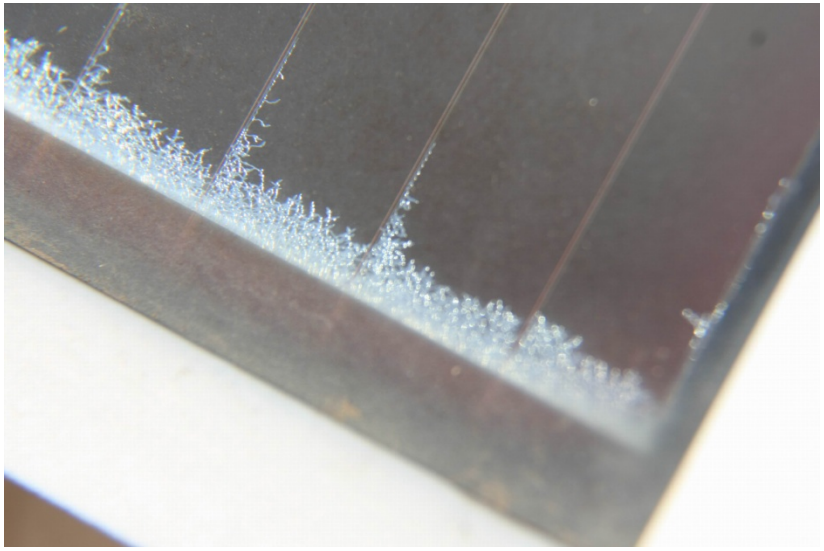
- A narrow (0.5”) region at the bottom of the area was typically soiled
- Location corresponds to where frame would retain water runoff
- The contamination is extremely difficult to remove
- The orientation of the modules (and cells) minimizes shading loss at the soiled region; also minimizes shading loss from grass, plants, etc.
- Relative occurrence: every module





Delamination

Effected region identified (circle) on module

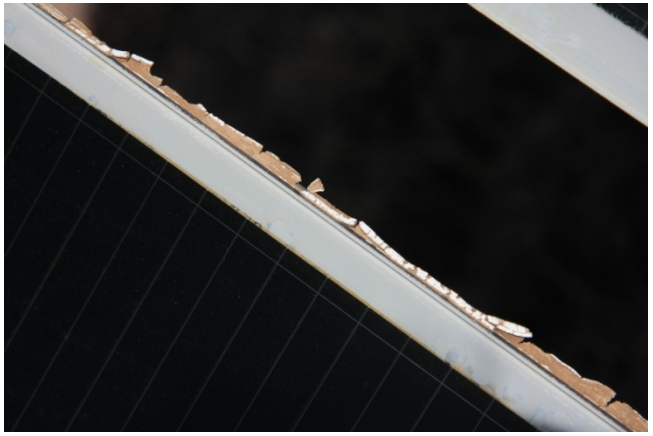


Detail of the effected region on the same module

Relative occurrence 128/400 modules

Other Observations

"Edge seal", from front



Less damaged region, photo from back

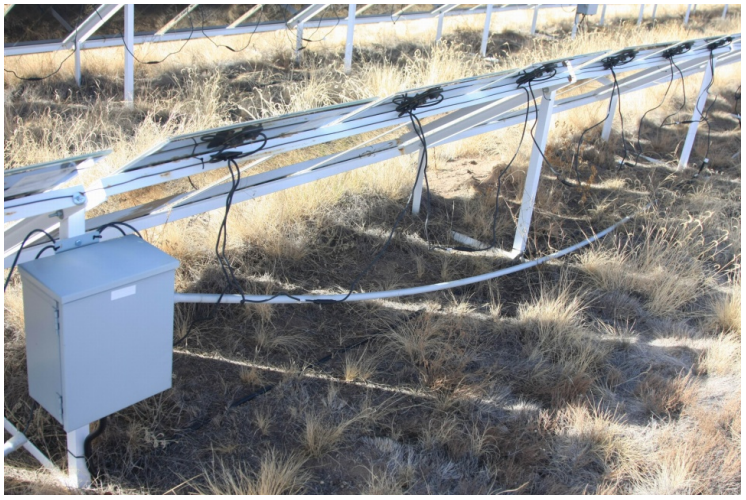
Severely damaged region, photo from back

- all "extruded" modules have at least bubbles.
- "Extrusion" could result from O_2 or N_2 absorption in sieve in seal or outgassing from residual peroxide in EVA
- No evidence of damage on replacement modules, all with edge seal.
- (change in material by manufacturer?)
- 3/450 "extruded" modules cracked.

Edge Seal Extrusion

Other Observations

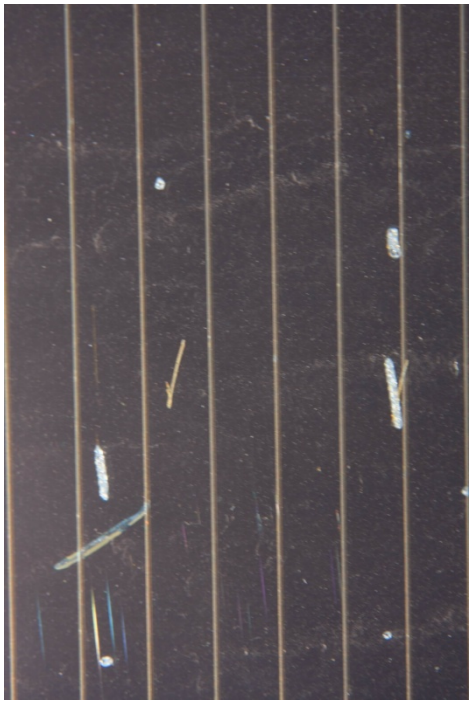
Shading



Weathered interconnect system

Delaminated relief pad

Cell defects



Any other observations

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PHOTOVOLTAIC POWER SYSTEMS PROGRAMME

13. Thin Film Module

13. Thin film module: ☐ not applicable ☐ applicable

Number of cells:

Number of cells in module _____

Number of cells in series/string _____

Number of strings in parallel _____

Cell size: Width _____ cm Length _____ cm

Distance between frame and cell: ☐ >10 mm ☐ <10 mm

Appearance: ☐ like new ☐ minor/light discoloration ☐ major/dark discoloration

Discoloration type (mark all that apply):

☐ spotted degradation ☐ haze (encapsulant browning) ☐ other

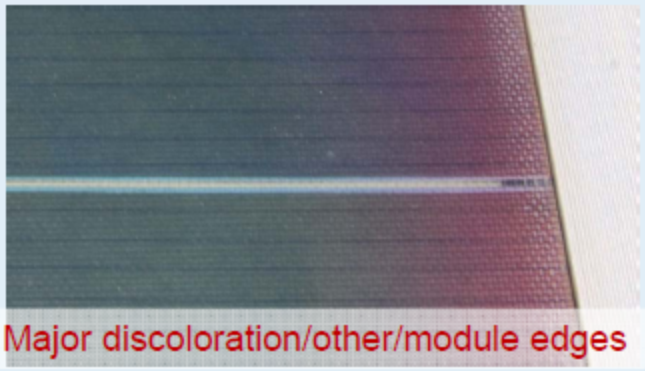
Discoloration location (mark all that apply):

☐ overall/no location pattern ☐ module center ☐ module edge(s)

☐ cell center ☐ cell edges ☐ near crack(s)

Minor discoloration/haze

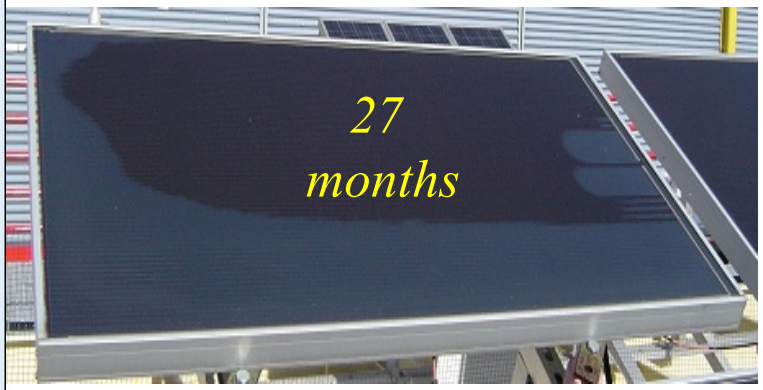
Major discoloration/spotted degradation/no pattern



Major discoloration/other/module edges

Any other observations

Packard. et al, EU PVSEC, 2012



Dhere et al., PVMR 2011

Summary

1. **Degradation rates**
   - c-Si Pmax decline is most strongly correlated with Isc , less FF
   - Thin-film are characterized by much higher FF degradation (do not have a lot of field data)
   - Module distributions widen and skew with increasing field exposure → can have significant impact on system performance
   - Thin-film systems with no measurable degradation have been shown

2. **Field Failure**
   - Need to use standard approach to characterize field failures
   - Need more data, particular percentage breakdown of failures

Acknowledgments

Thank you for your attention

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This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory

Thank you to :
Chris Deline
Josh Stein
NREL T&M team
Rest of the NREL reliability team