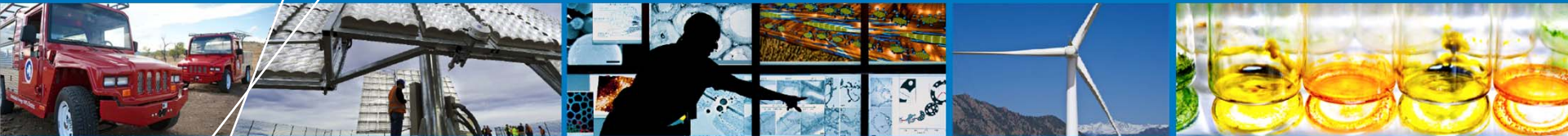


Technology and Climate Trends in PV Module Degradation



27th European PV Solar Energy Conference
Frankfurt, Germany

Dirk Jordan, John Wohlgemuth, Sarah Kurtz

9/27/2012

NREL/PR-5200-56690

Outline

➤ Introduction

- I-V parameter degradation analysis
- I-V parameter distribution
- Climatic trends

➤ Conclusion

Introduction- Degradation Rates (R_d)

NREL – Outdoor Test Facility



Photo by Warren Gretz, NREL/PIX 03877

$$R_d (\text{Module 1}) = 0.8 \text{ \%/year}$$

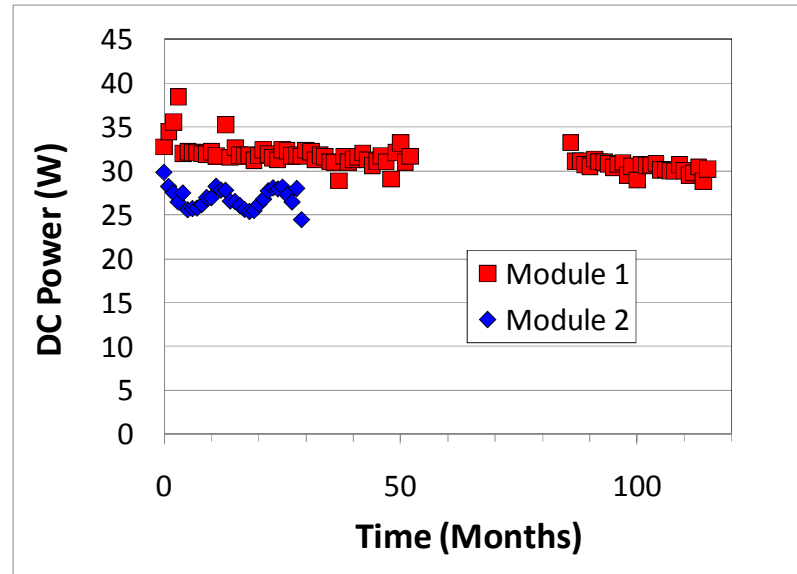
$$R_d (\text{Module 2}) = 0.8 \text{ \%/year}$$

Introduction- Degradation Rates (R_d)

NREL – Outdoor Test Facility



Photo by Warren Gretz, NREL/PIX 03877



2 modules: Different observation lengths, seasonality etc.

$$R_d (\text{Module 1}) = 0.8 \text{ \%/year}$$

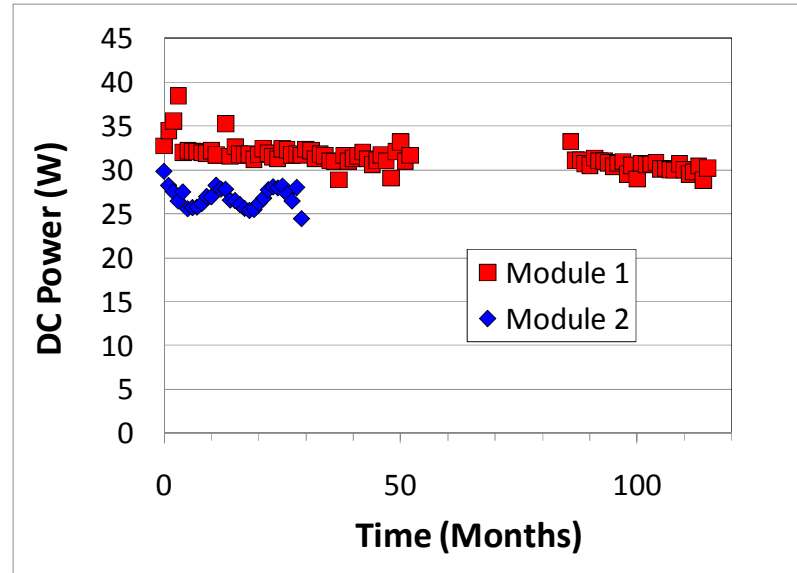
$$R_d (\text{Module 2}) = 0.8 \text{ \%/year}$$

Introduction- Degradation Rates (R_d)

NREL – Outdoor Test Facility



Photo by Warren Gretz, NREL/PIX 03877



2 modules: Different observation lengths, seasonality etc.

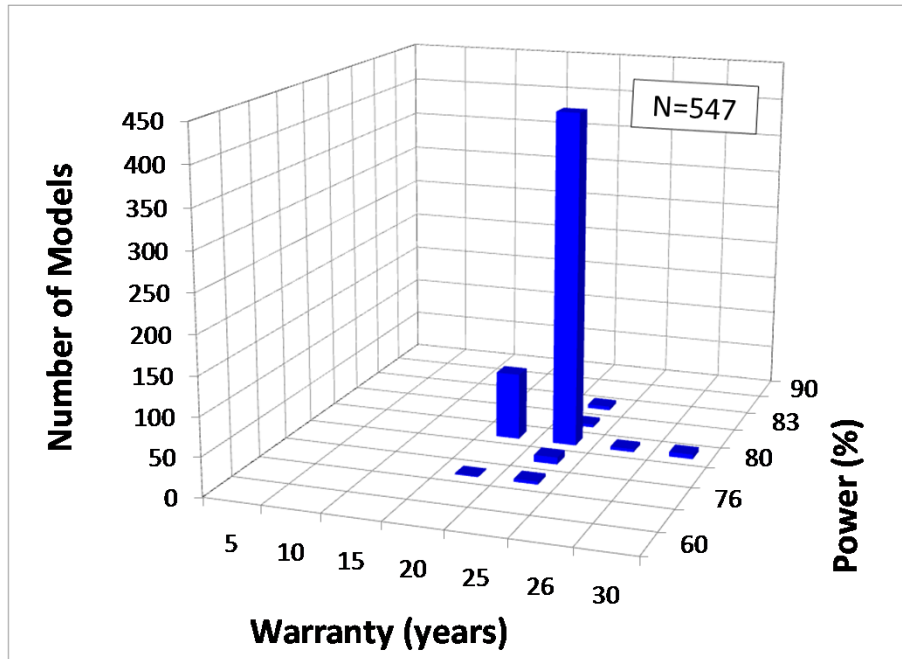
$$R_d (\text{Module 1}) = (0.8 \pm 0.2) \%/\text{year}$$

$$R_d (\text{Module 2}) = (0.8 \pm 1.0) \%/\text{year}$$

Same degradation rate, different Uncertainty

R_D Uncertainty Impact on Warranty

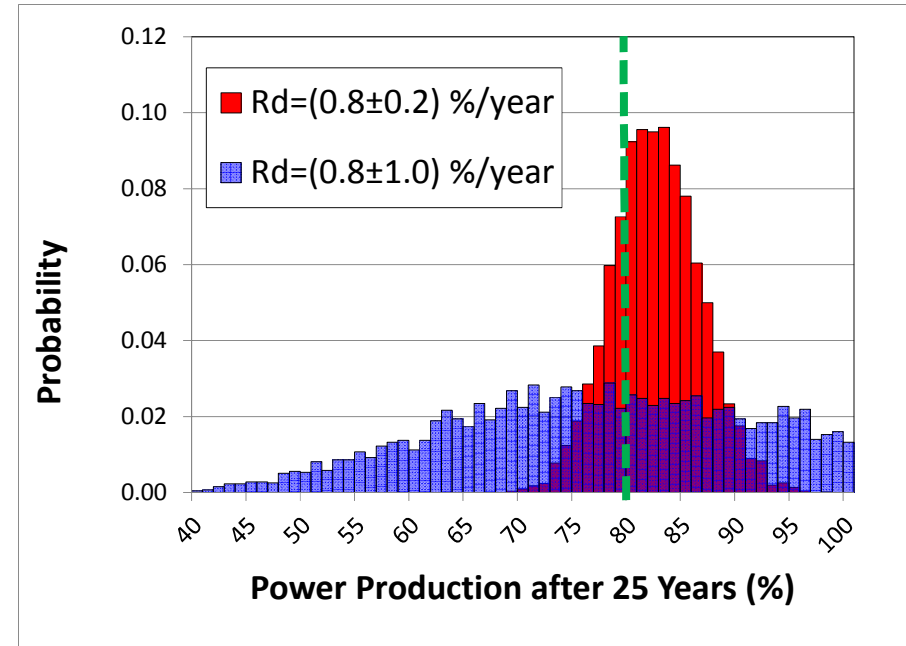
Maximum module warranty - 2010



Source: Photon International, Feb 2010

$$\text{Power}(\text{Year}_n) = \text{Power}(\text{Year}_1) \cdot (1 - R_d)^n$$

Monte Carlo Simulation for year 25



Probability to default on warranty:

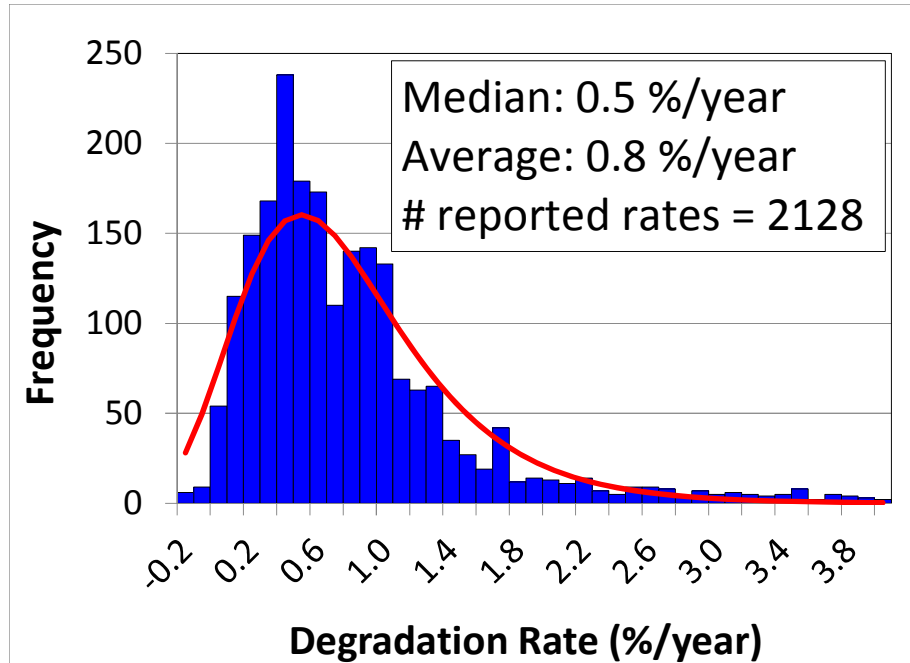
Module 1: Probability = 24%

Module 2: Probability = 57%

Need to determine R_d accurately

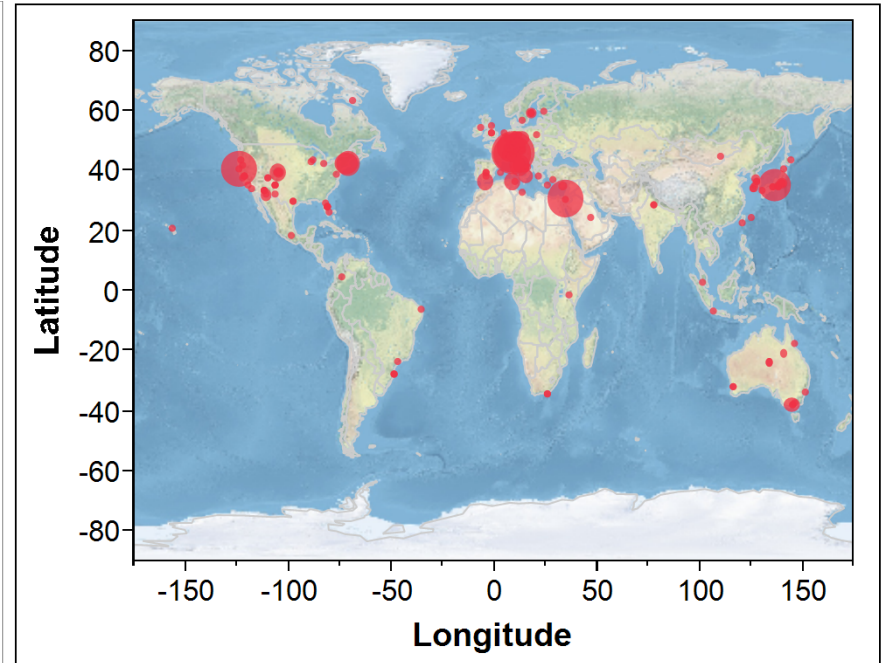
Degradation Rates – Literature Survey

Number of Degradation rates (R_d)
from literature: 2128



Technology, age, packaging, geographic location
ca. 80% below 1%/year

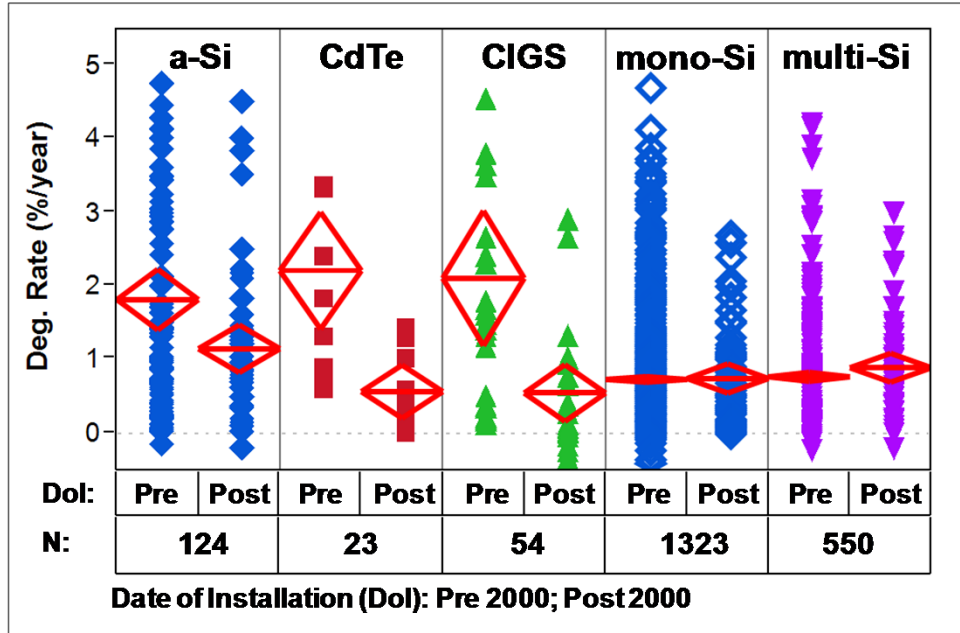
> 100 publications from 32 countries



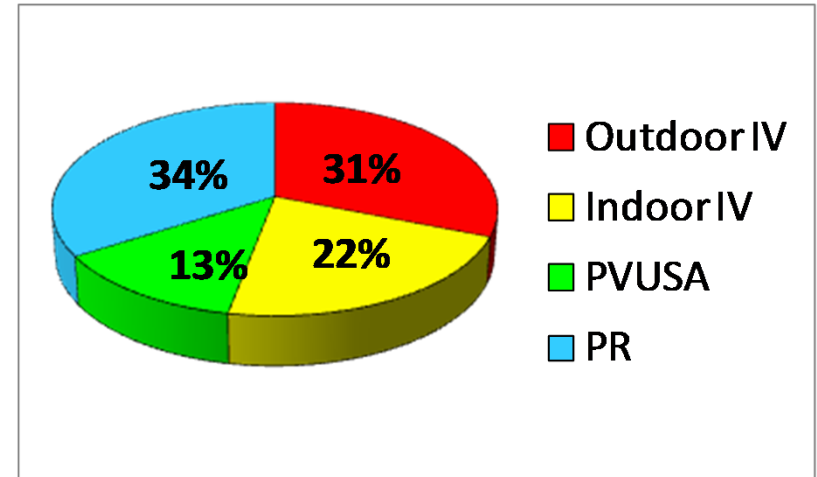
Circle size = number of data
points from a given location.

Most modules degrade by ca. 0.5 %/year

Literature Degradation Rates



No standard to determine R_d

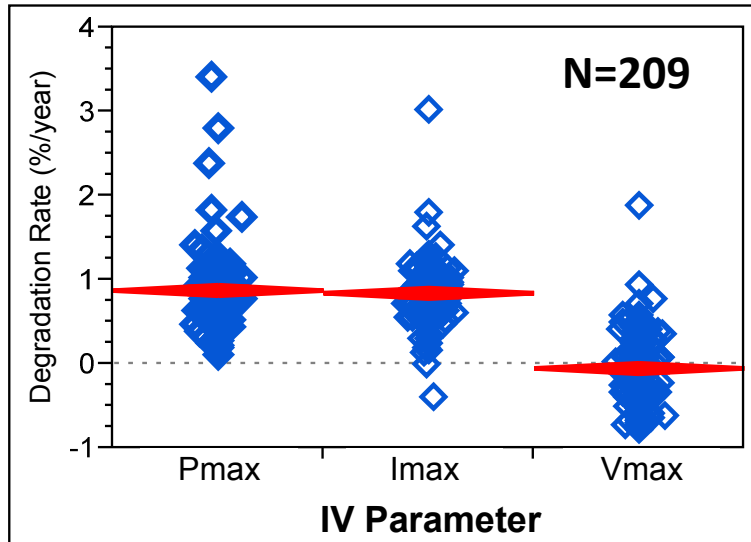


> 50% of R_d taken by I-V curves →
 Information on short-circuit current (I_{sc}),
 open-circuit voltage (V_{oc}), fill factor (FF),
 I_{max} , V_{max}

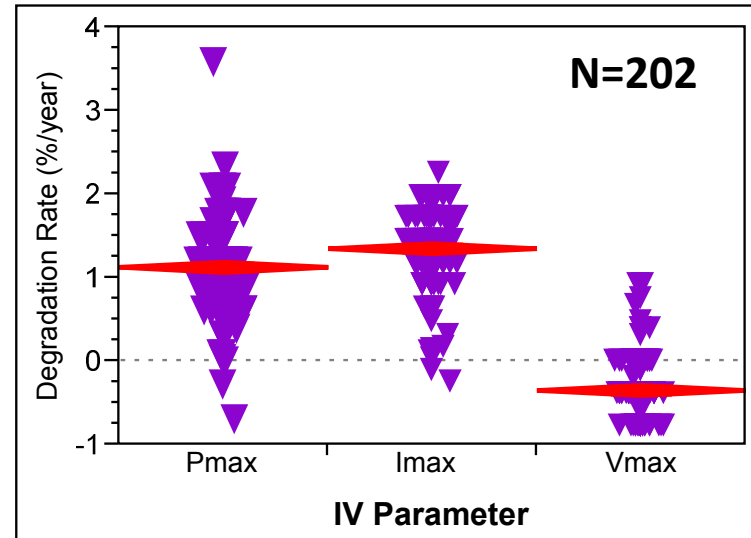
Thin-film technologies narrowed gap to c-Si in last 10 years
I-V parameter information for ca. 50% of all R_d

Pmax Degradation Partition

Mono-Si



Multi-Si



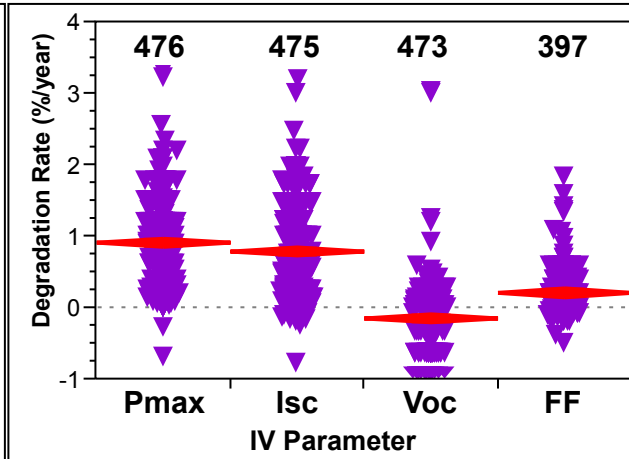
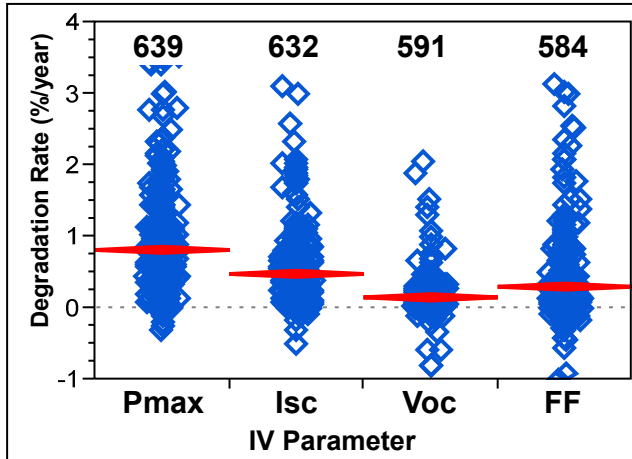
Important for proper inverter sizing

Statistically degradation in current not in voltage

I-V Parameters by Technology

Mono-Si

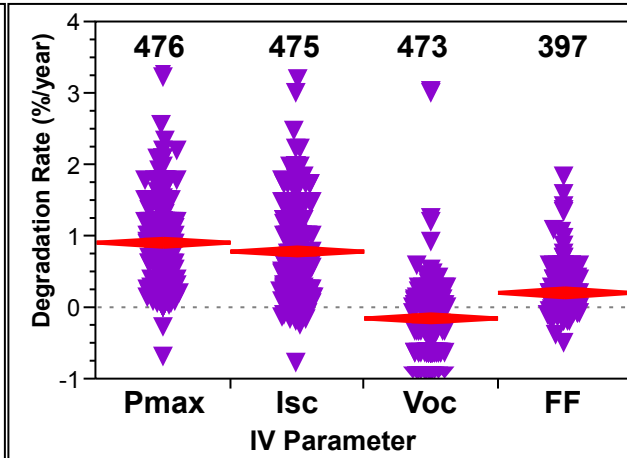
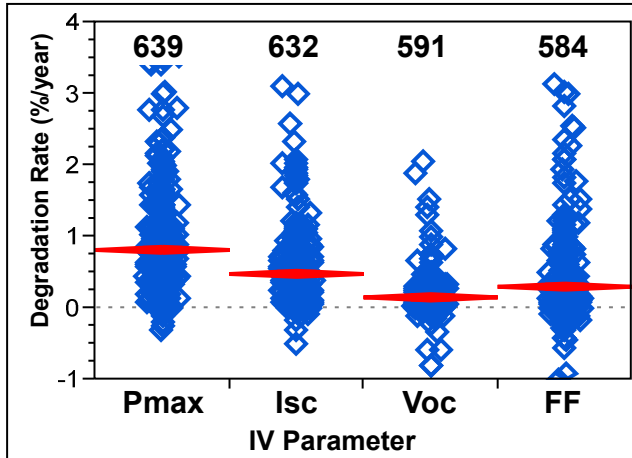
Multi-Si



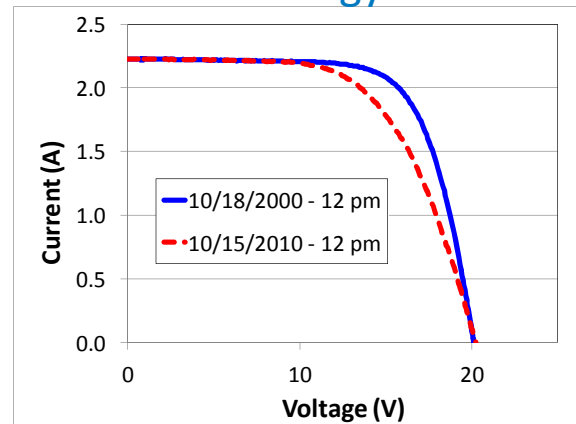
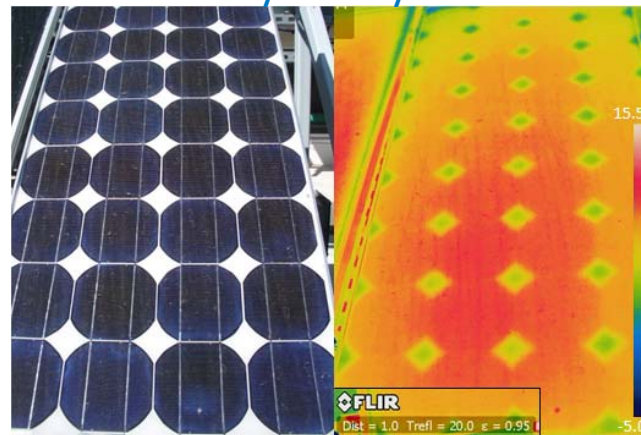
I-V Parameters by Technology

Mono-Si

Multi-Si



NREL study – May 2012 – World Renewable Energy Forum



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

Pmax correlated to Isc loss

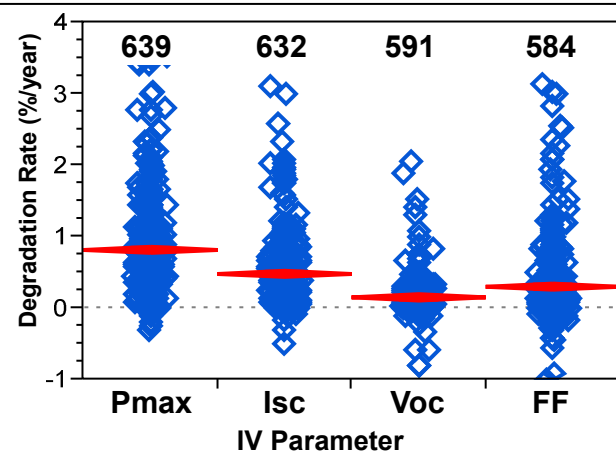
Pmax correlated to FF loss

9/12 modules

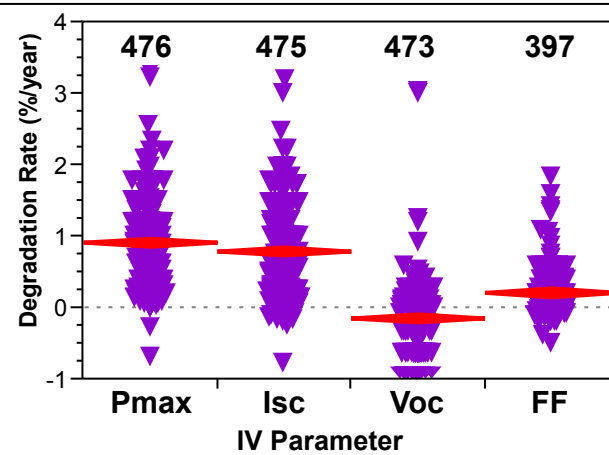
3/12 modules

I-V Parameters by Technology

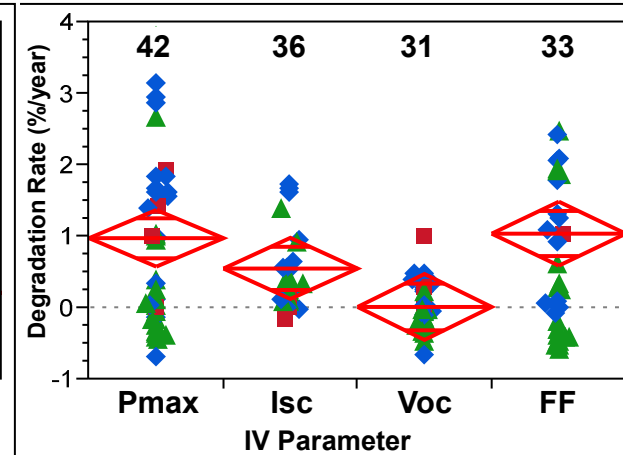
Mono-Si



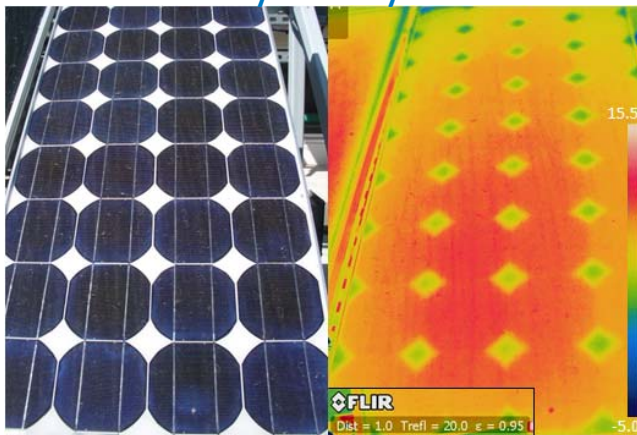
Multi-Si



Thin-film

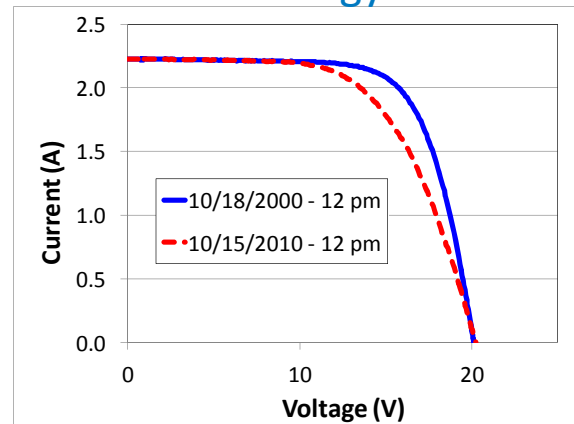


NREL study – May 2012 – World Renewable Energy Forum



Pmax correlated to Isc loss

9/12 modules



Pmax correlated to FF loss

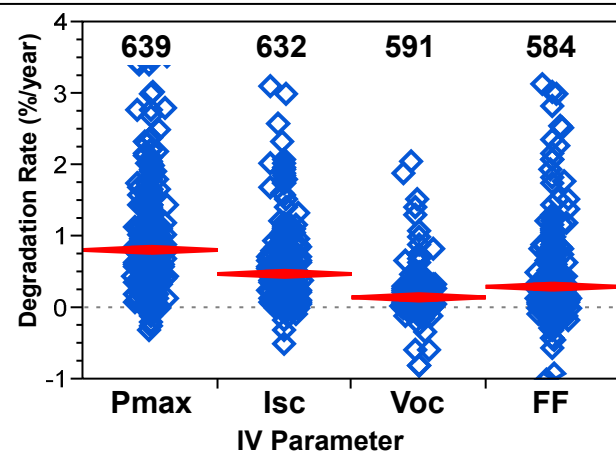
3/12 modules

- ◆ a-Si
- ▲ CIGS
- CdTe

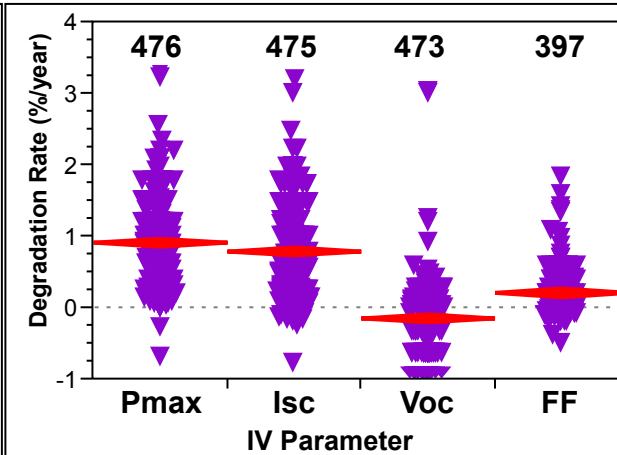
Smith et al., World Renewable Energy Forum, May 2012

I-V Parameters by Technology

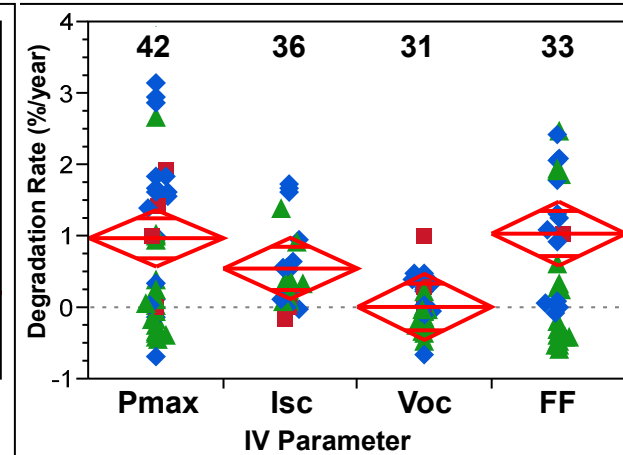
Mono-Si



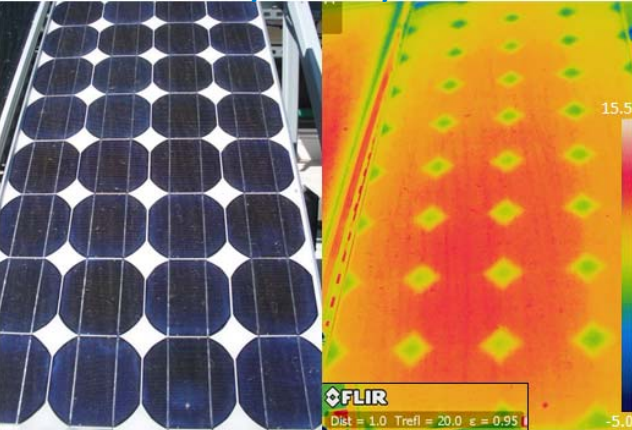
Multi-Si



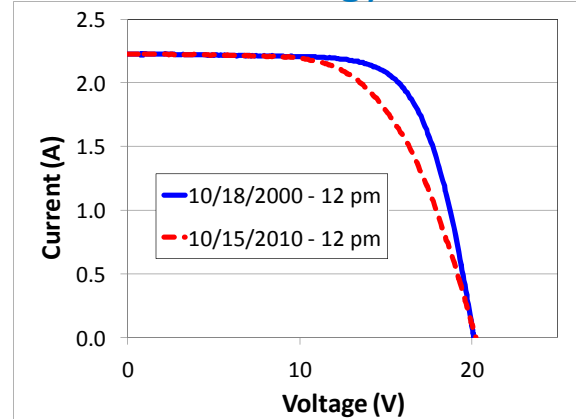
Thin-film



NREL study – May 2012 – World Renewable Energy Forum



Pmax correlated to Isc loss



Pmax correlated to FF loss

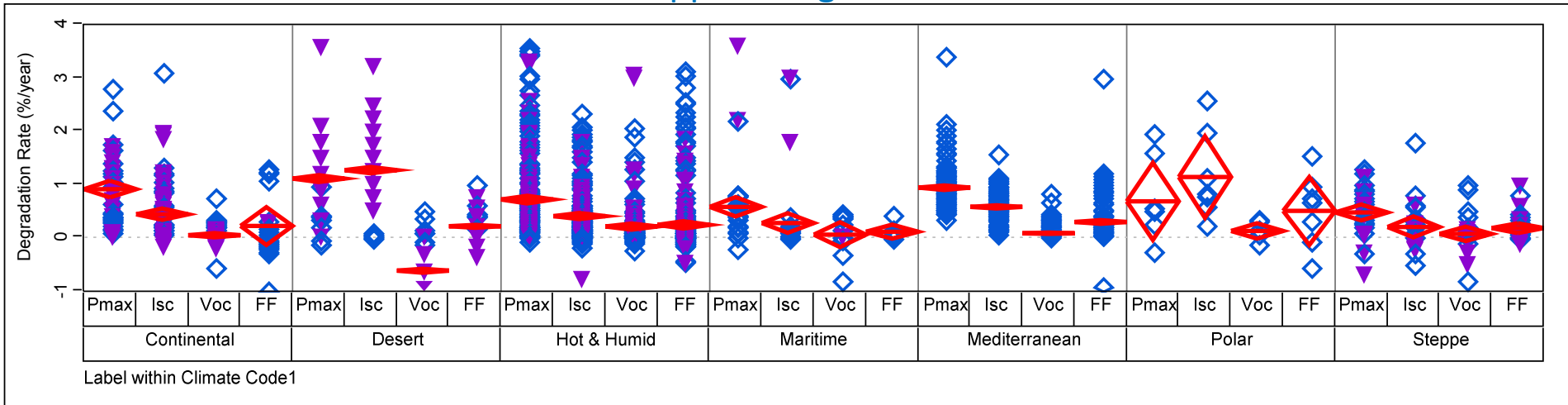
- ◆ a-Si
- ▲ CIGS
- CdTe

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

Degradation for c-Si Isc; Thin-film FF

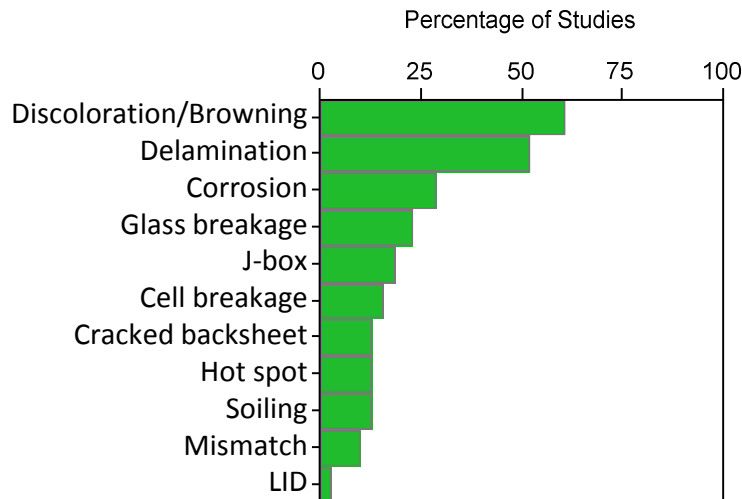
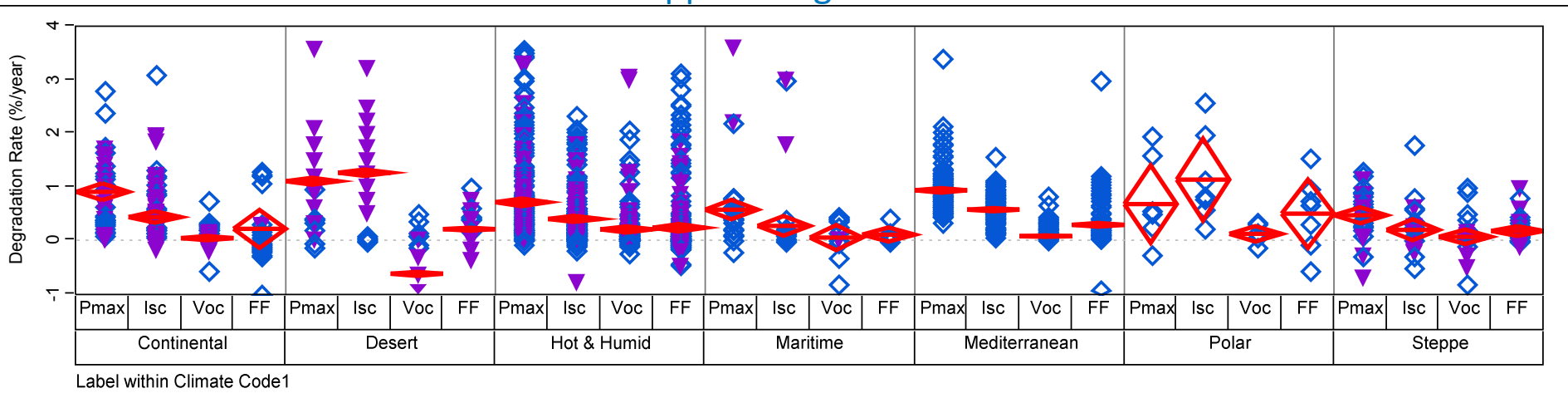
Climate Analysis

Based on Köppen-Geiger Classification



Climate Analysis

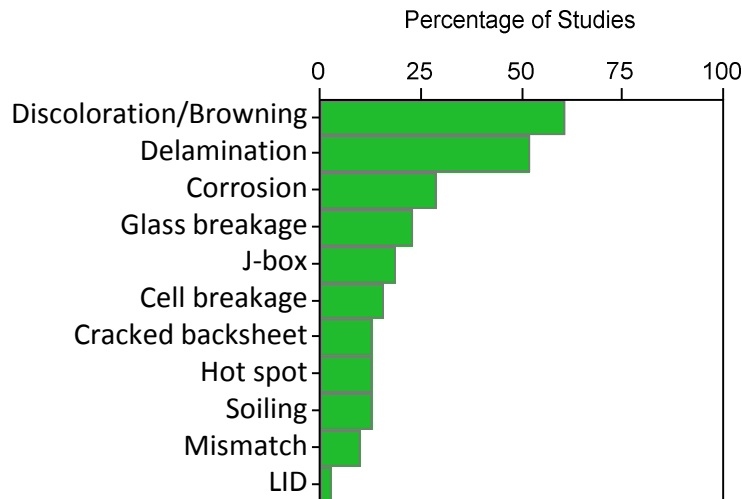
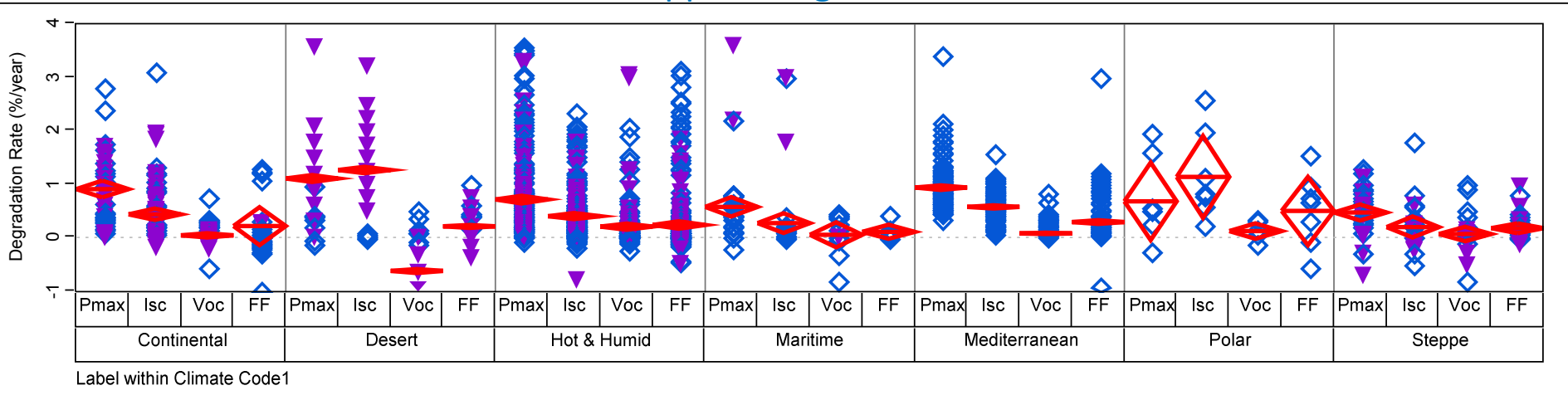
Based on Köppen-Geiger Classification



- Pmax most strongly correlated with Isc losses
- Isc losses: discoloration, soiling, delamination, light-induced degradation
- Majority of studies report discolor. & delam.
- No standard reporting of field failure mechanisms, C. Packard talk on Monday

Climate Analysis

Based on Köppen-Geiger Classification

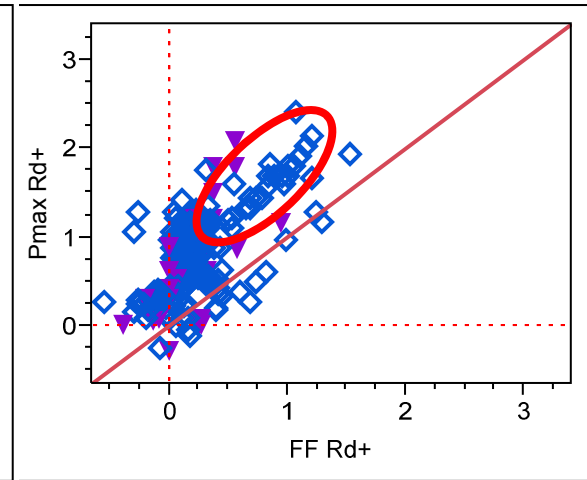
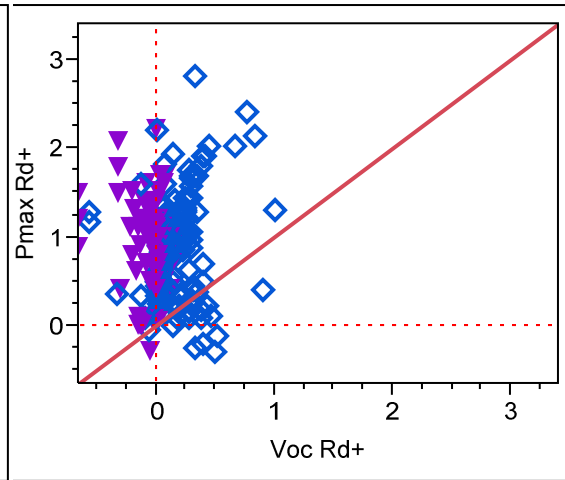
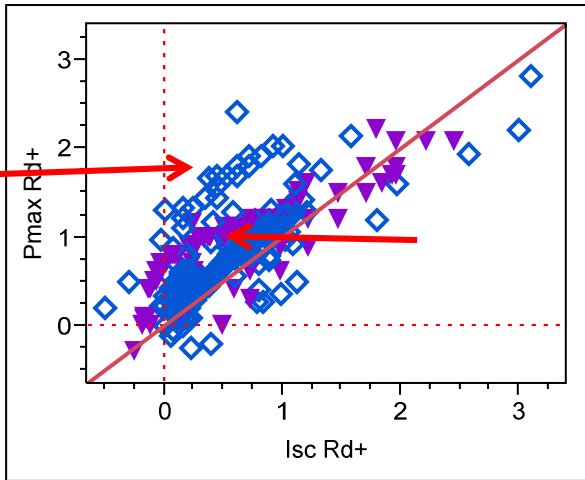


- Pmax most strongly correlated with Isc losses
- Isc losses: discoloration, soiling, delamination, light-induced degradation
- Majority of studies report discolor. & delam.
- No standard reporting of field failure mechanisms, C. Packard talk on Monday

Pmax correlated with Isc loss for most climates

I-V parameters for c-Si

Non
Hot &
Humid

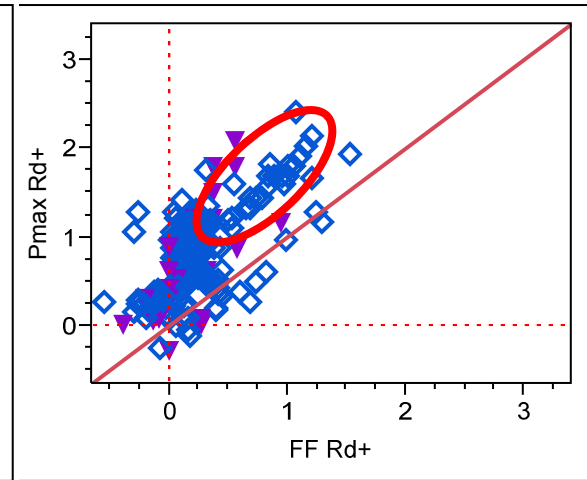
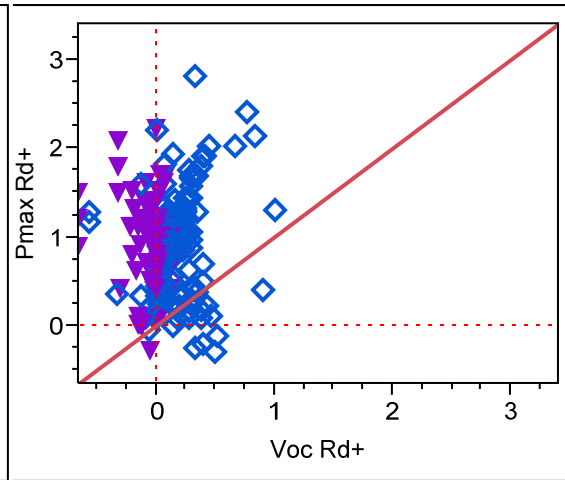
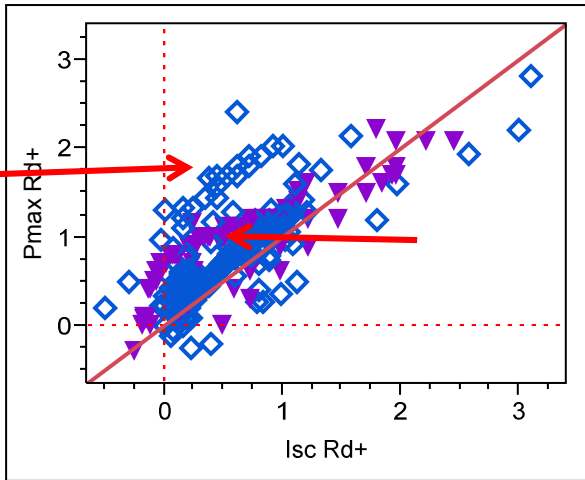


P_{max} degradation mostly correlated with I_{sc} loss
2 parallel lines – 1 measurement studies

Tail from study that
showed high corrosion

I-V parameters for c-Si

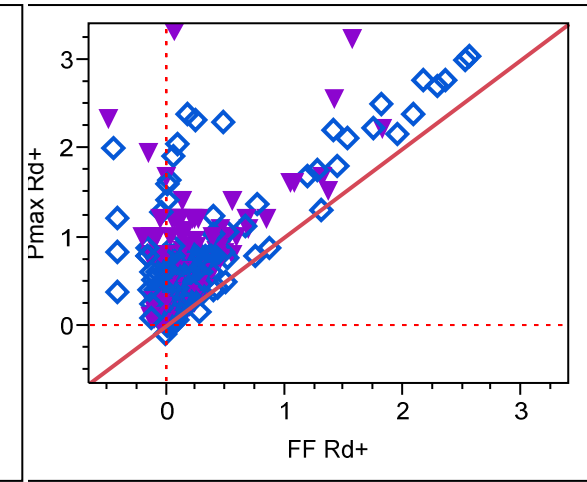
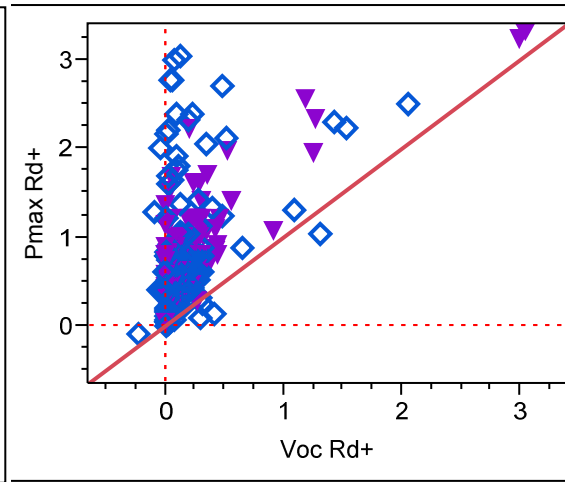
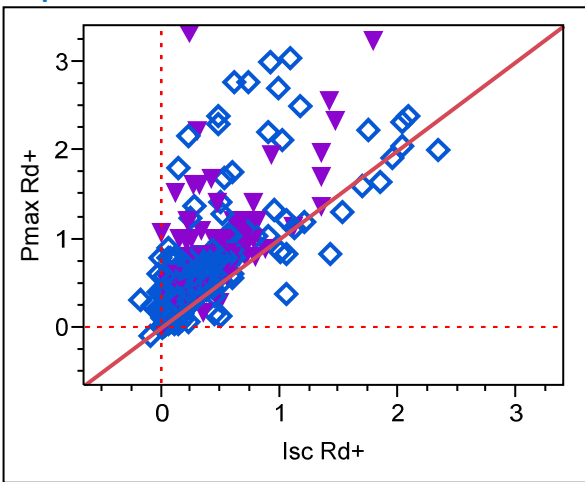
Non
Hot &
Humid



P_{max} degradation mostly correlated with I_{sc} loss
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Hot &
Humid



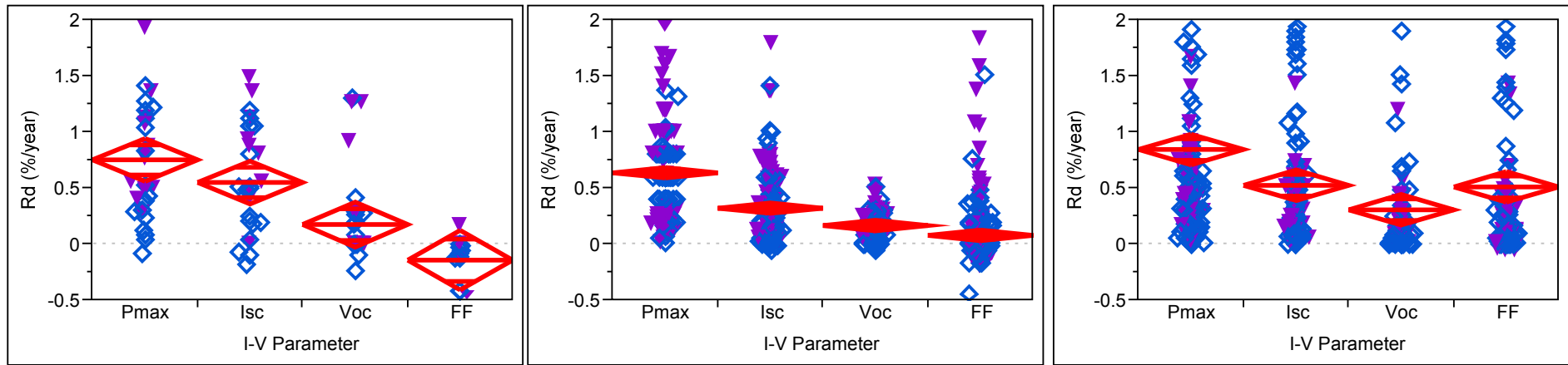
Hot & Humid shows mixture of degradation

Hot & Humid by Decade

Decade 1

Decade 2

Decade 3



◆ mono-Si
▼ multi-Si

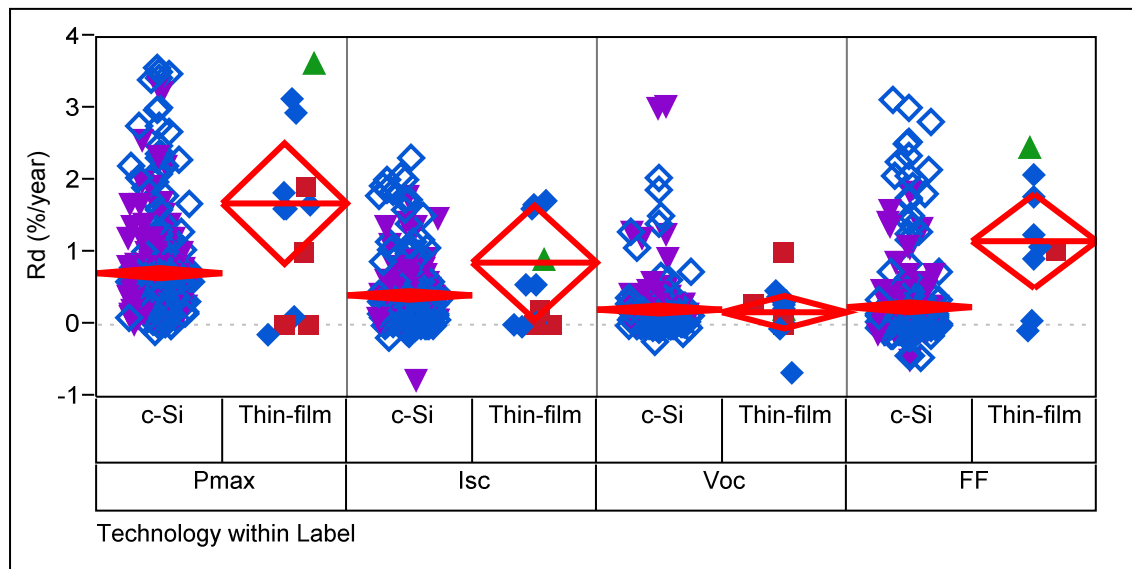
Very little FF degradation till in first 2 decades

Much higher FF degradation in studies longer than 20 years

Field failure mechanism may change with field exposure

c-Si – Thin-film Comparison

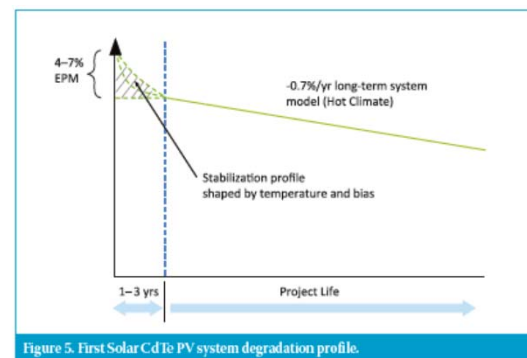
Hot & Humid Climate



- ◇ mono-Si
- ▼ multi-Si
- ◆ a-Si
- ▲ CIGS
- CdTe

Thin-film show high FF R_d in humid climates

First Solar



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

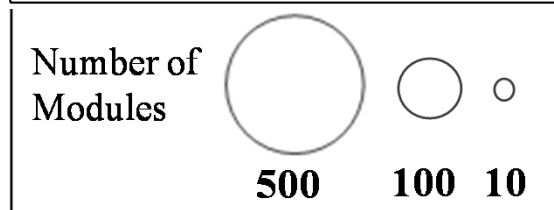
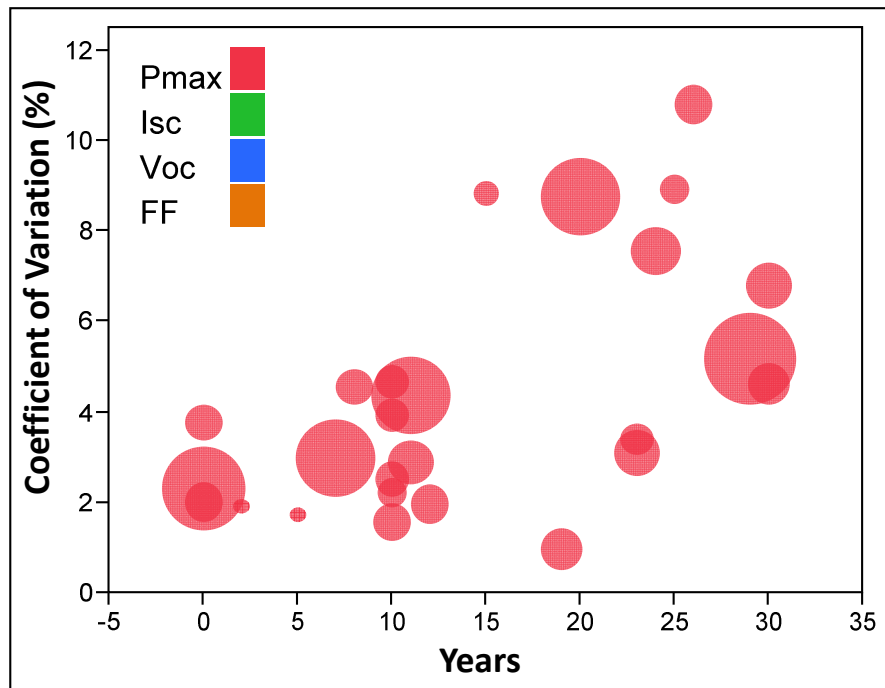
Different long-term performance recommendation based on climate

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

Different long-term recommendation based on climate

Module I-V Distribution

Distribution width



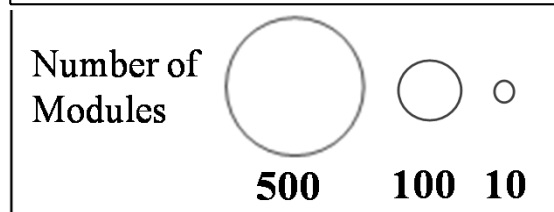
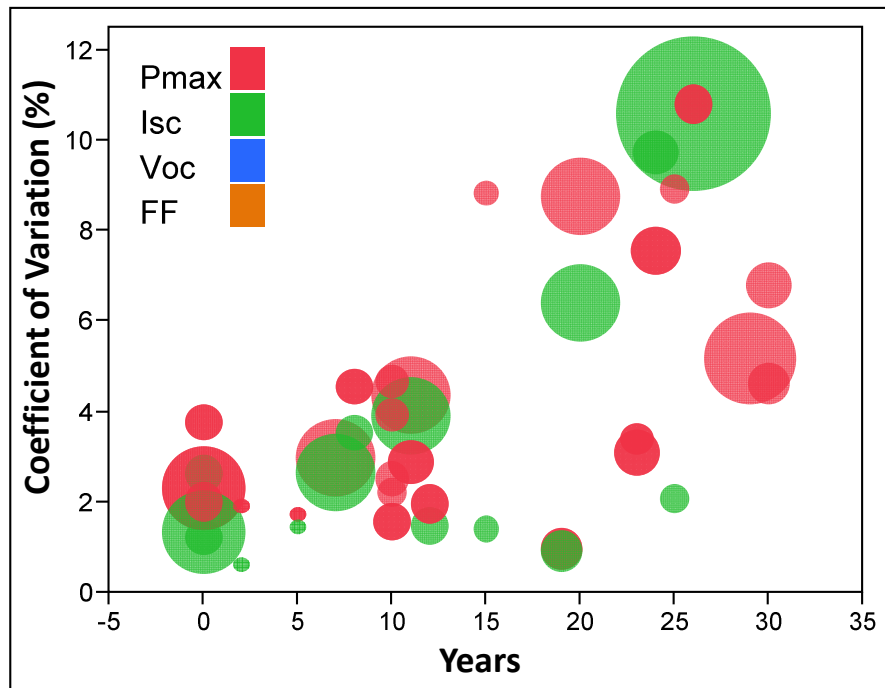
Color: I-V parameter

Size: Number of modules in study

Coefficient of Variation (CoV): Standard deviation/ Mean

Module I-V Distribution

Distribution width



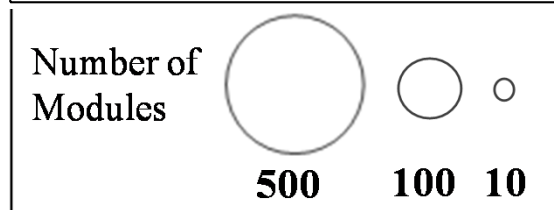
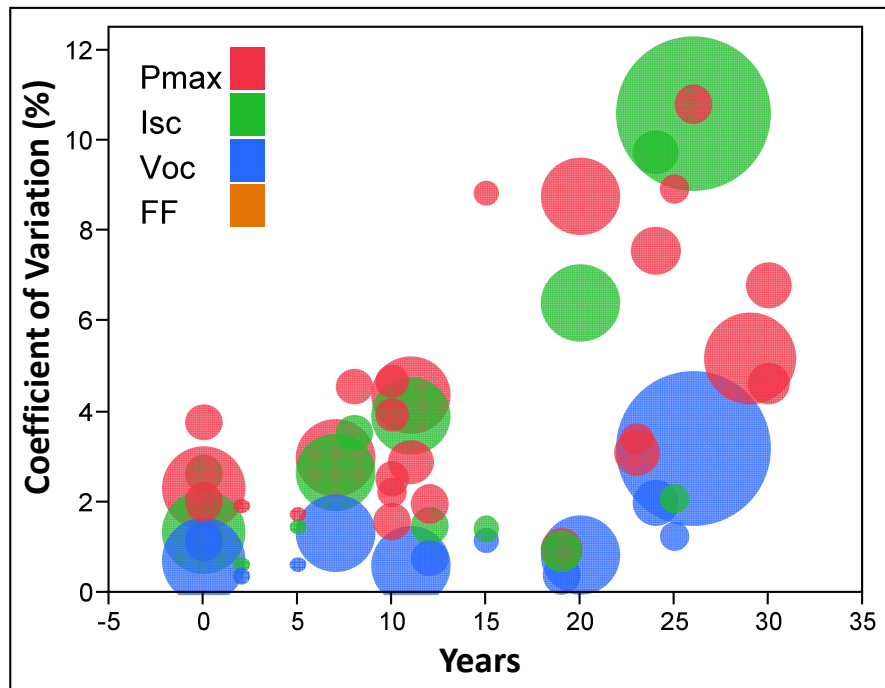
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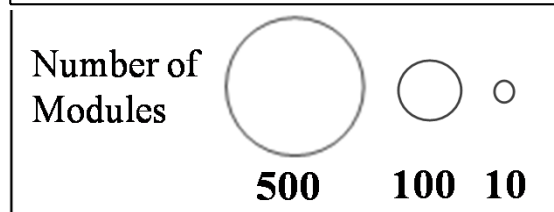
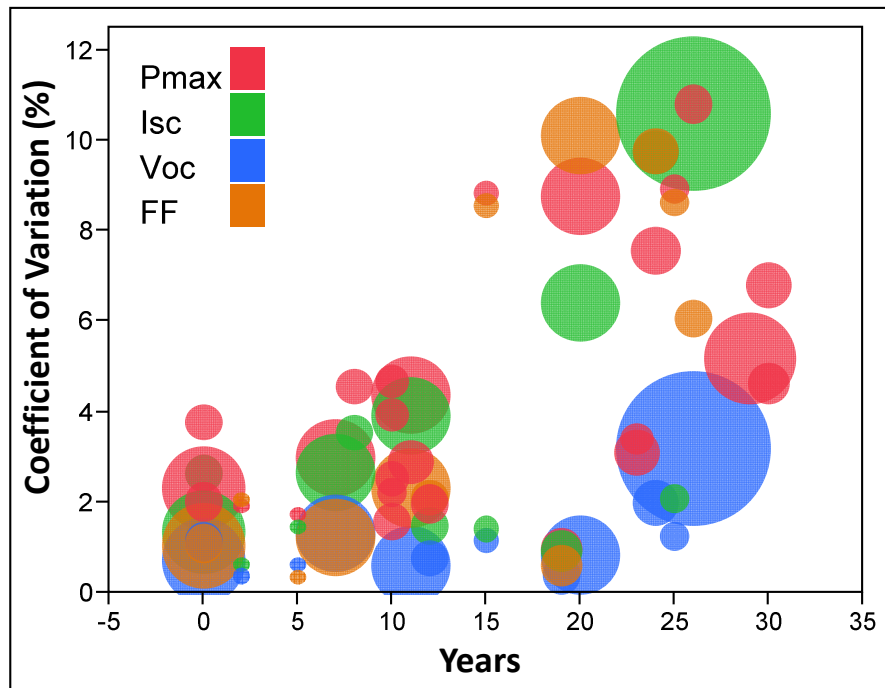
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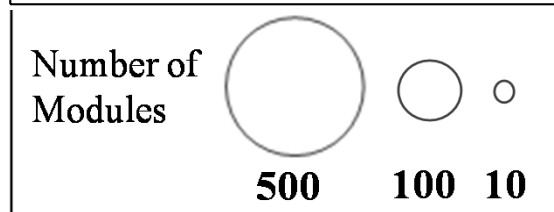
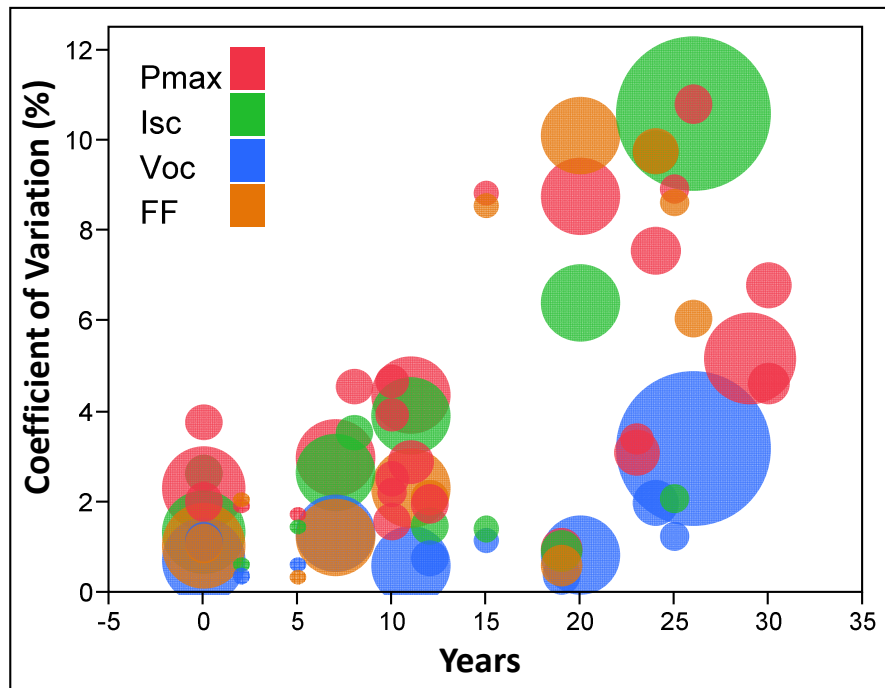
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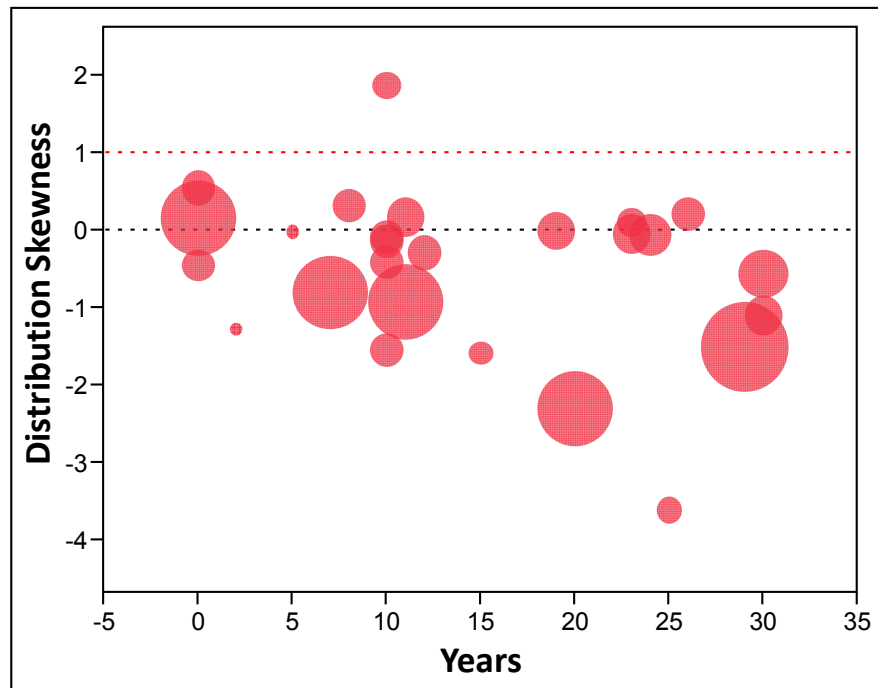
Coefficient of Variation (CoV): Standard deviation/ Mean

Module I-V Distribution

Distribution width



Distribution symmetry



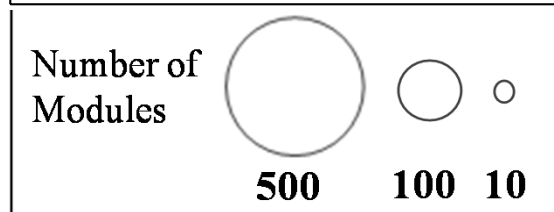
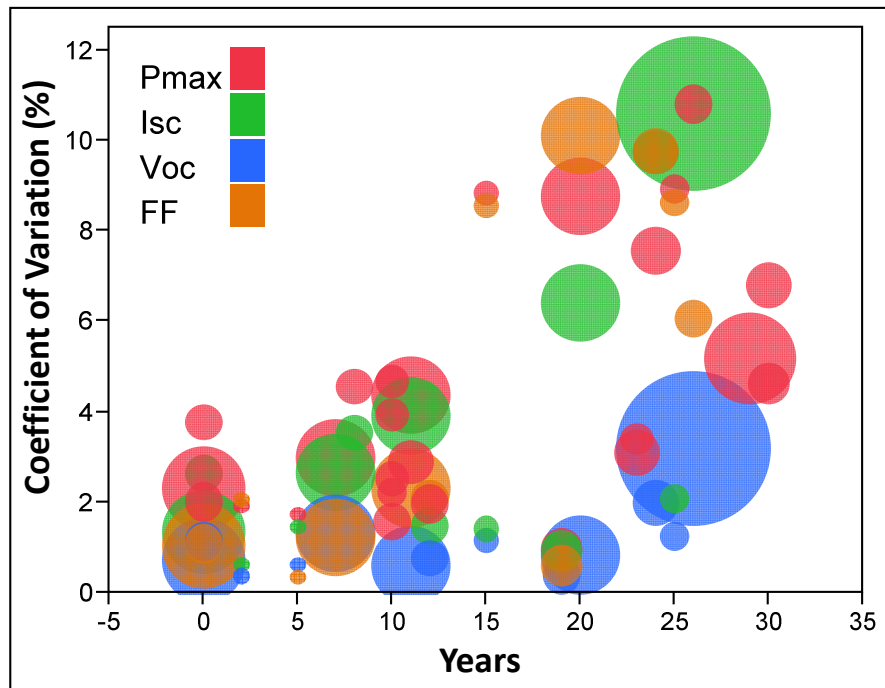
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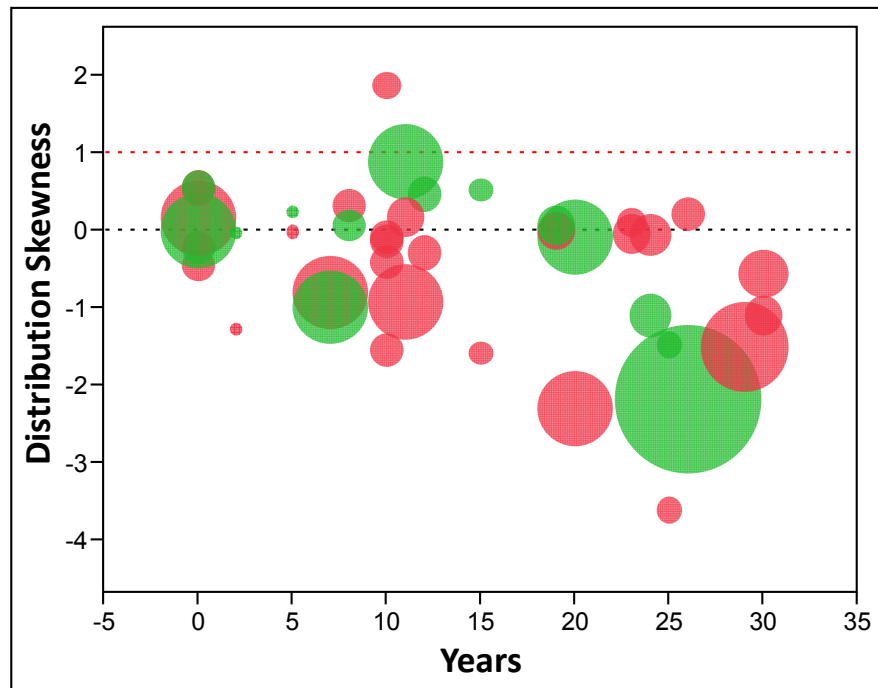
Coefficient of Variation (CoV): Standard deviation/ Mean

Module I-V Distribution

Distribution width



Distribution symmetry



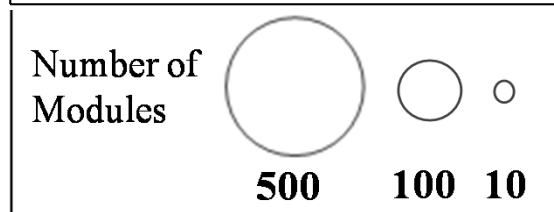
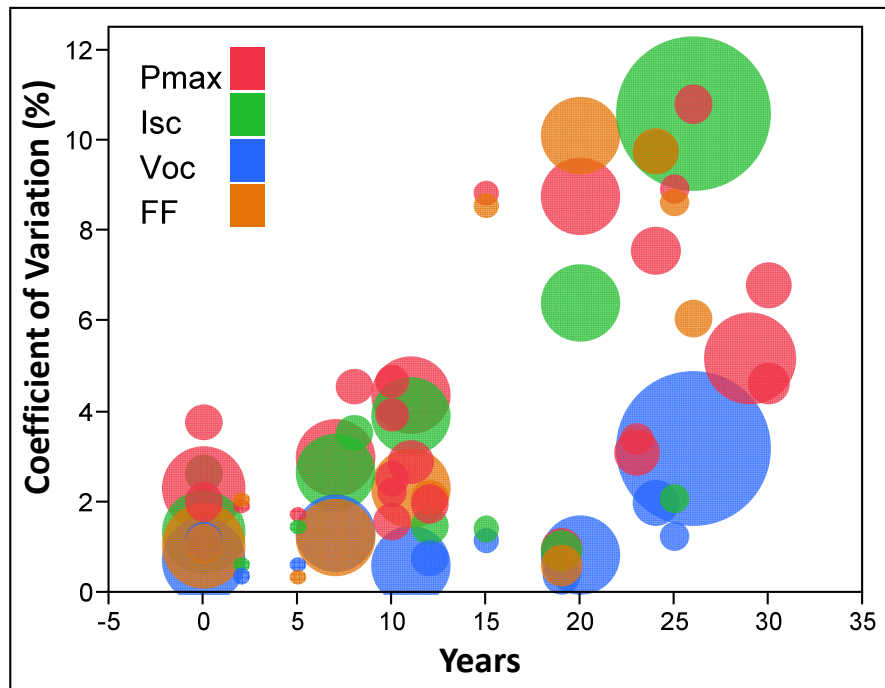
Color: I-V parameter

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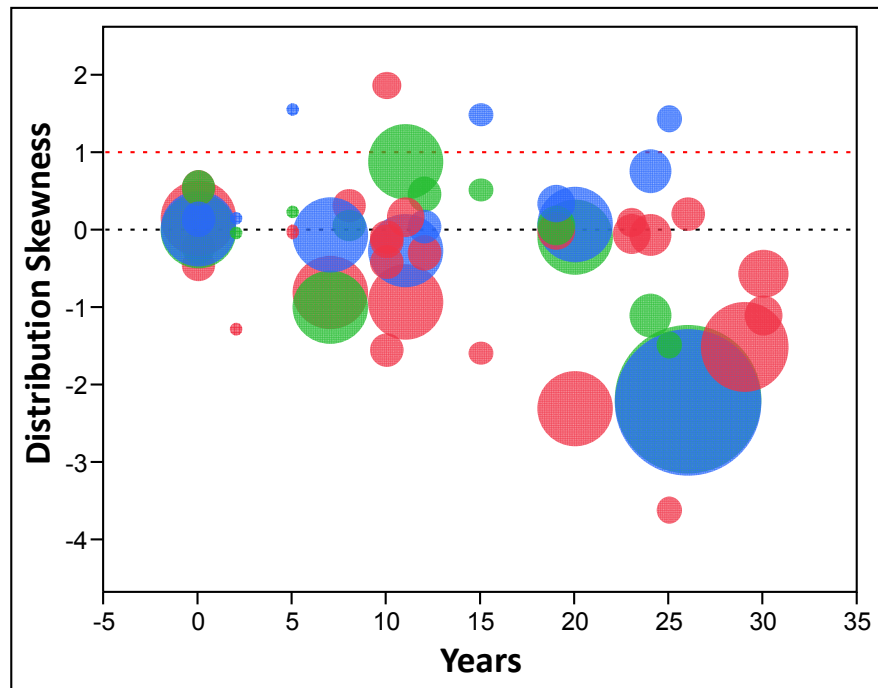
Coefficient of Variation (CoV): Standard deviation/ Mean

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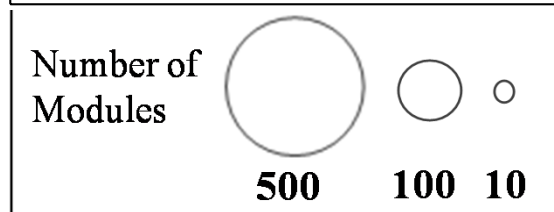
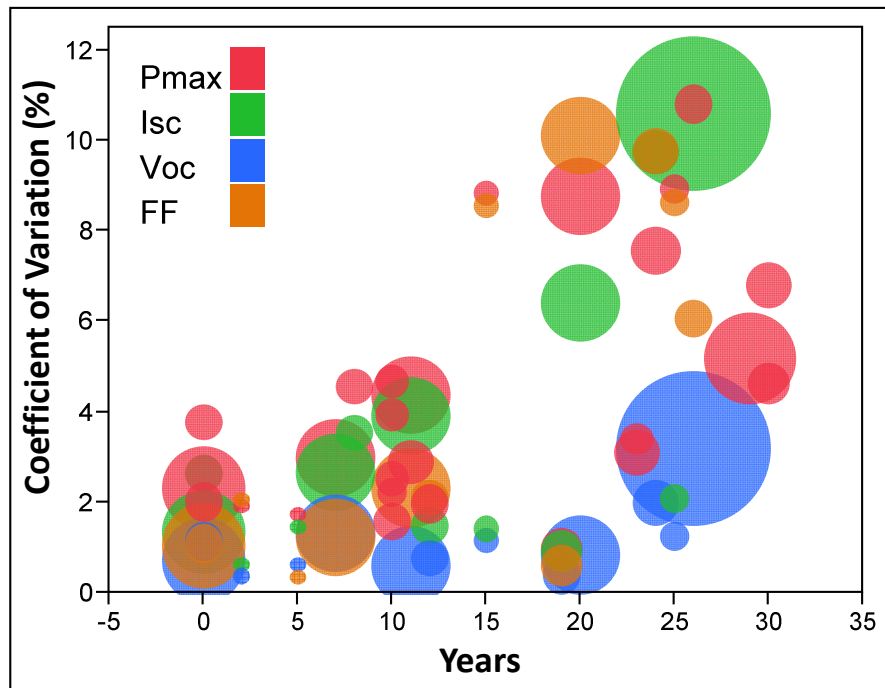
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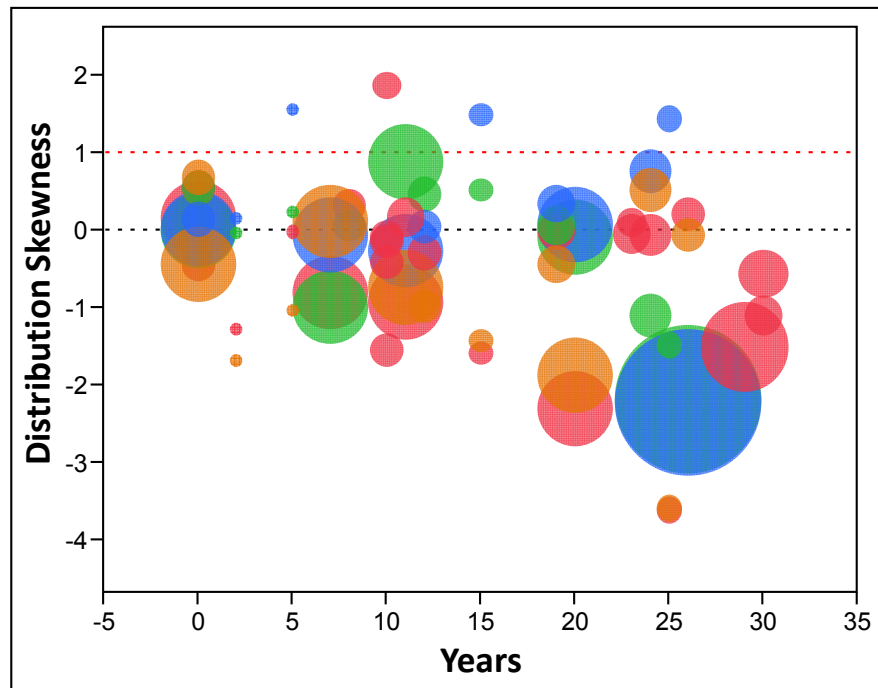
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Module I-V Distribution

Distribution width



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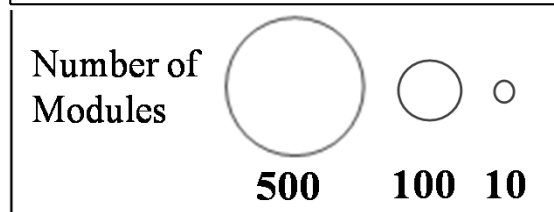
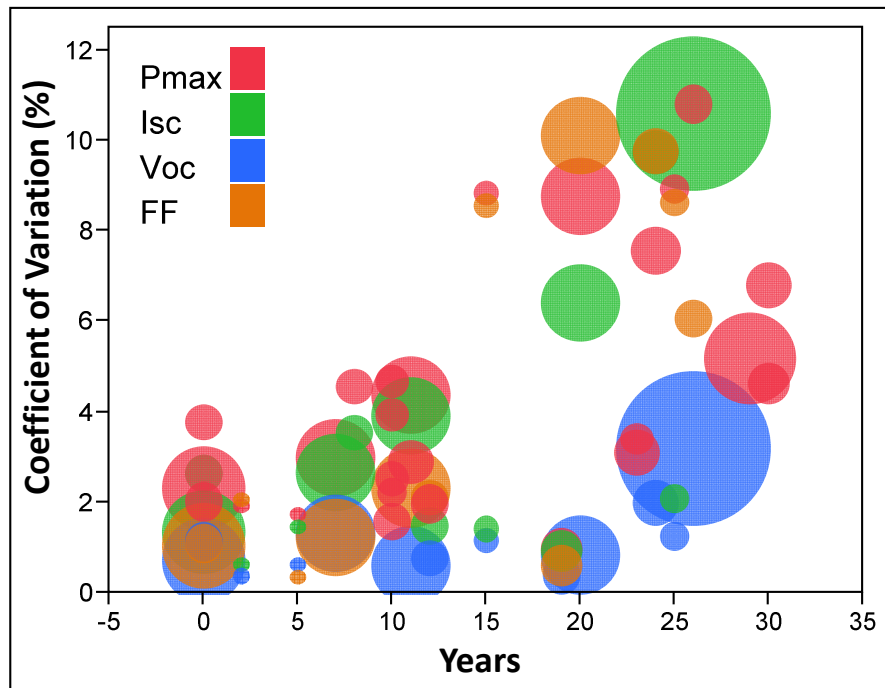
Color: I-V parameter

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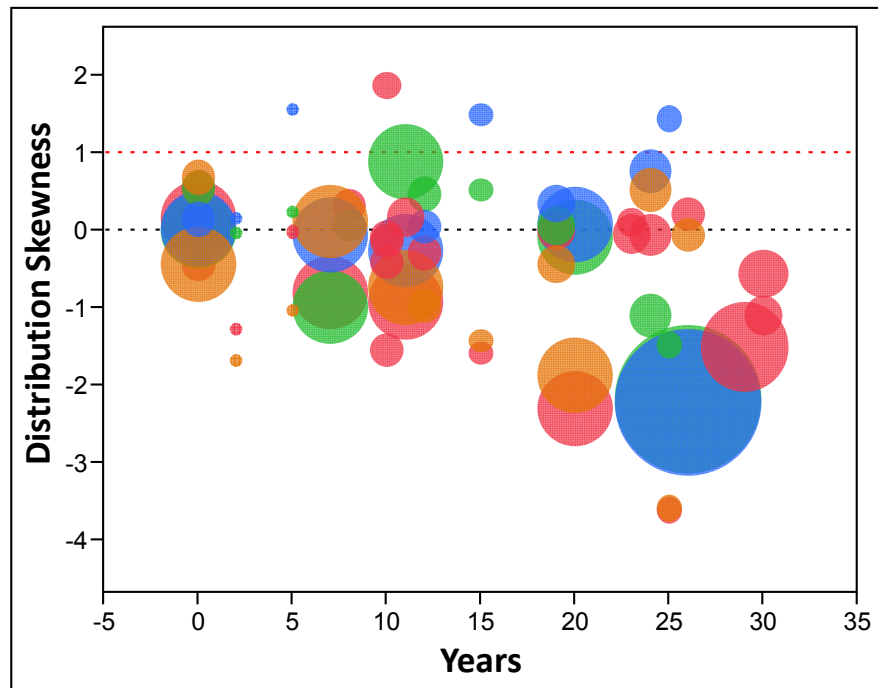
Coefficient of Variation (CoV): Standard deviation/ Mean

Module I-V Distribution

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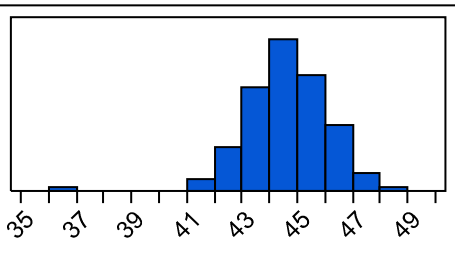
Size: Number of modules in study

Coefficient of Variation (CoV): Standard deviation/ Mean

Distributions widen and skew with field exposure

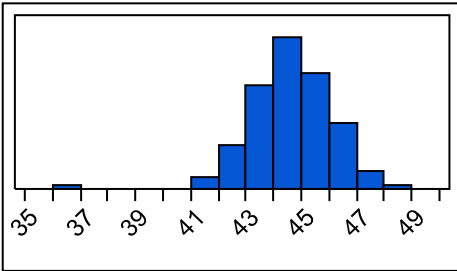
I-V Distributions

Israel – 1995 – 7 years

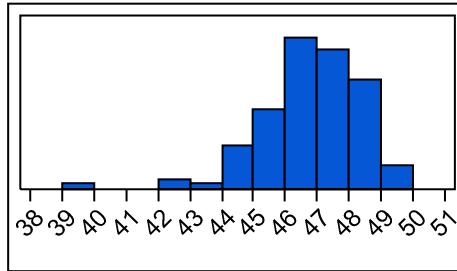


I-V Distributions

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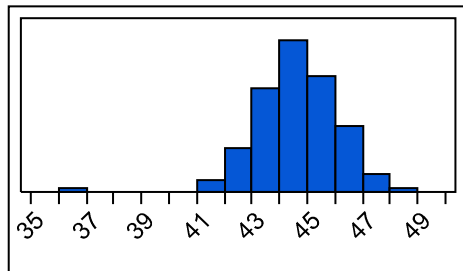


Japan – 2003 – 10 years

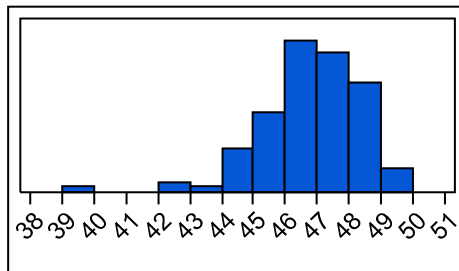


I-V Distributions

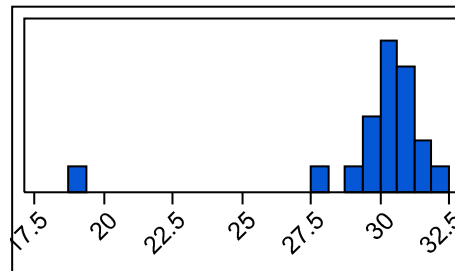
Israel – 1995 – 7 years



Japan – 2003 – 10 years

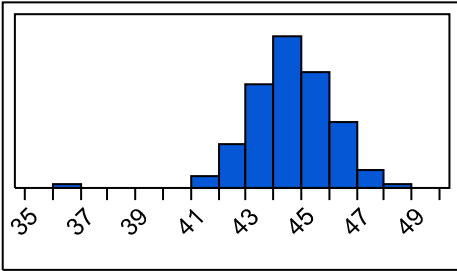


Sweden – 2006 – 25 years

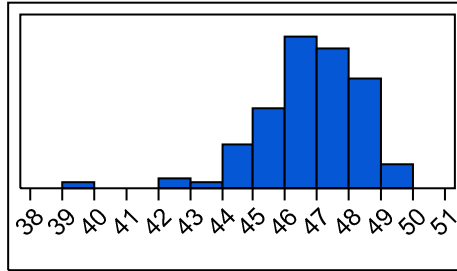


I-V Distributions

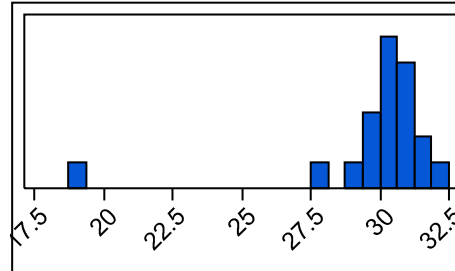
Israel – 1995 – 7 years



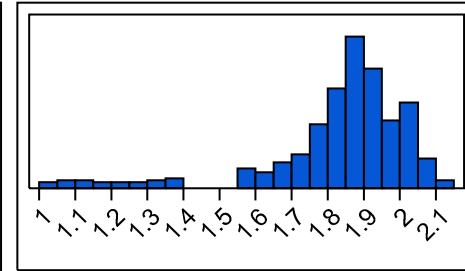
Japan – 2003 – 10 years



Sweden – 2006 – 25 years

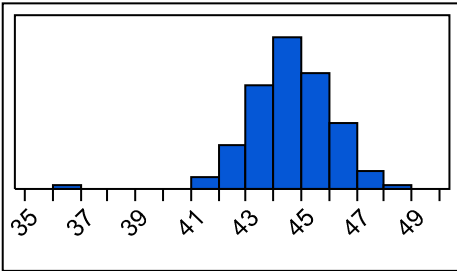


Tunisia – 2008 – 25 years

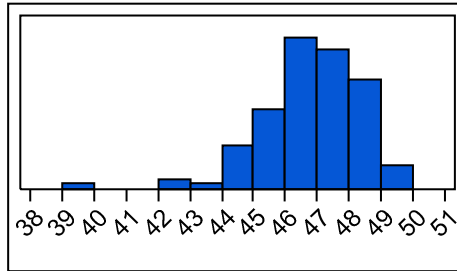


I-V Distributions

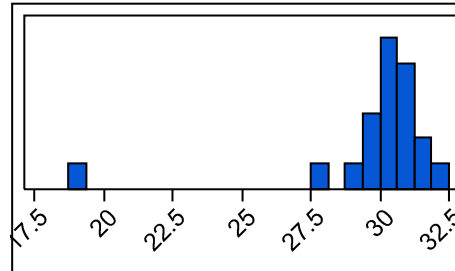
Israel – 1995 – 7 years



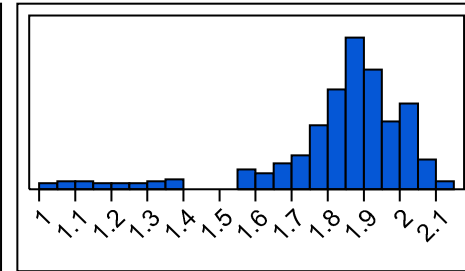
Japan – 2003 – 10 years



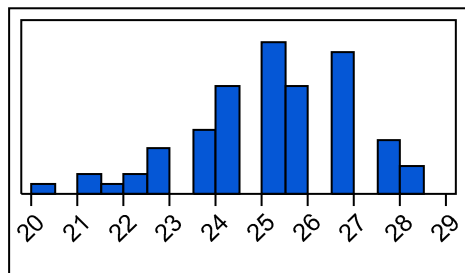
Sweden – 2006 – 25 years



Tunisia – 2008 – 25 years

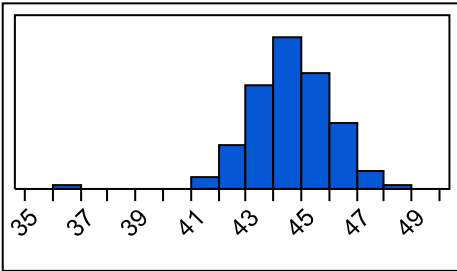


MA – 2010 – 30 years

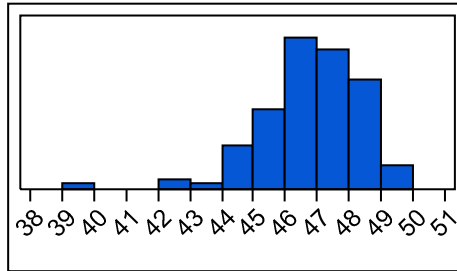


I-V Distributions

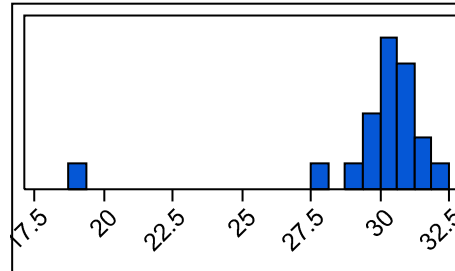
Israel – 1995 – 7 years



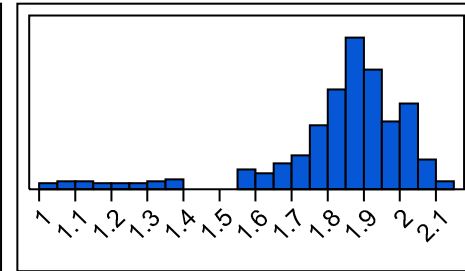
Japan – 2003 – 10 years



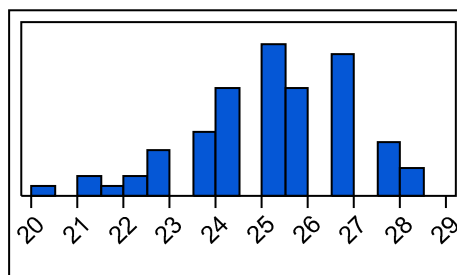
Sweden – 2006 – 25 years



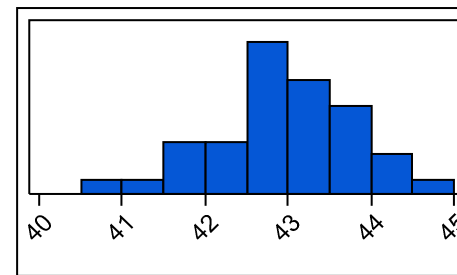
Tunisia – 2008 – 25 years



MA – 2010 – 30 years

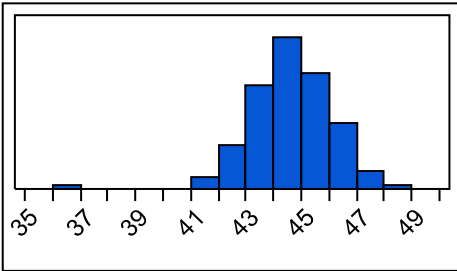


Spain – 2011 – 12 years

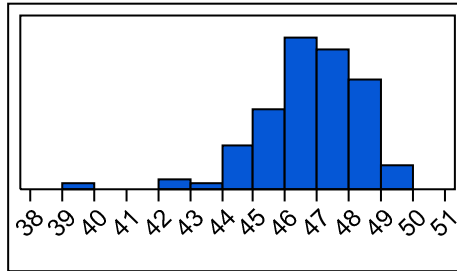


I-V Distributions

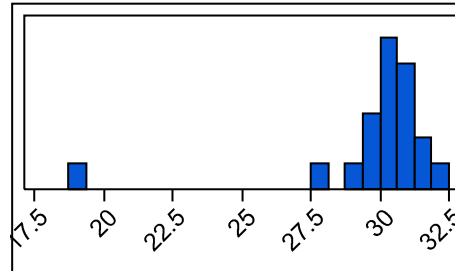
Israel – 1995 – 7 years



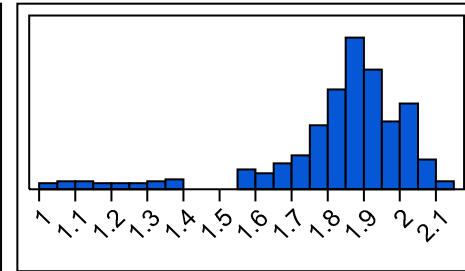
Japan – 2003 – 10 years



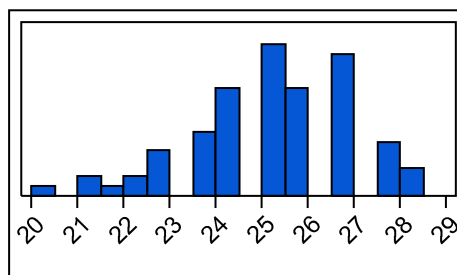
Sweden – 2006 – 25 years



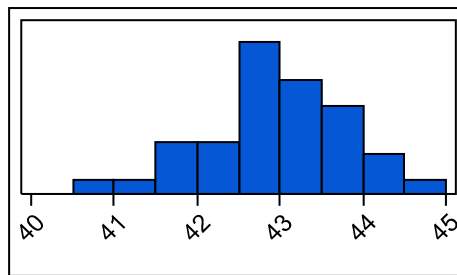
Tunisia – 2008 – 25 years



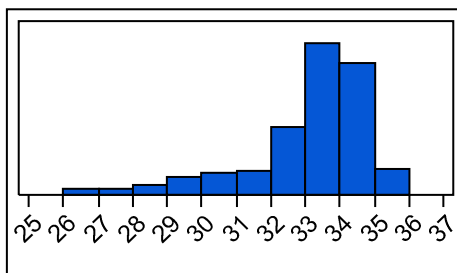
MA – 2010 – 30 years



Spain – 2011 – 12 years

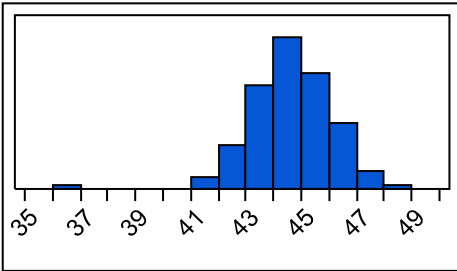


Switzerland – 2010 -20 years

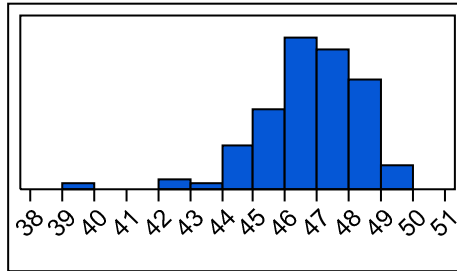


I-V Distributions

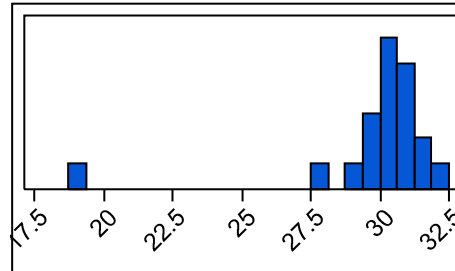
Israel – 1995 – 7 years



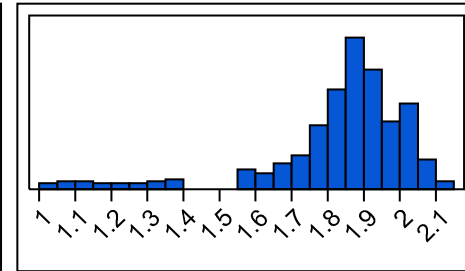
Japan – 2003 – 10 years



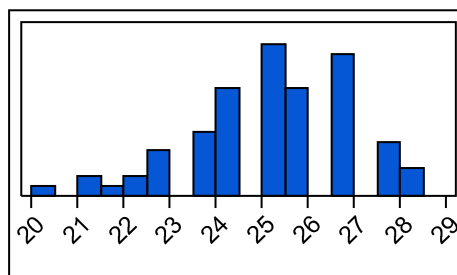
Sweden – 2006 – 25 years



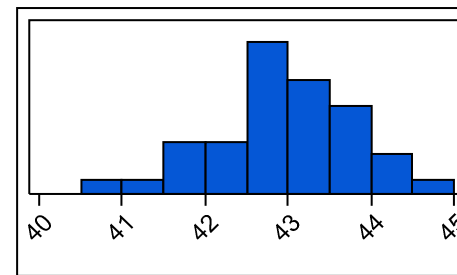
Tunisia – 2008 – 25 years



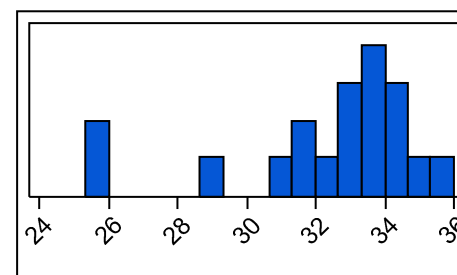
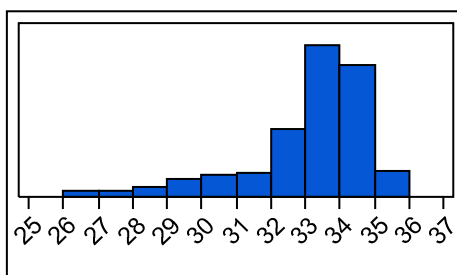
MA – 2010 – 30 years



Spain – 2011 – 12 years

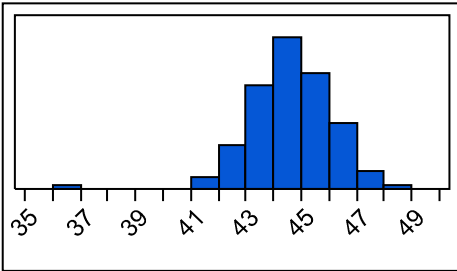


Switzerland – 2010 -20 years CO – 2012 – 15 years

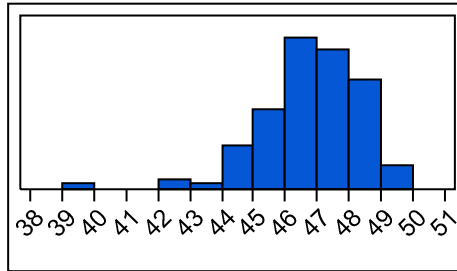


I-V Distributions

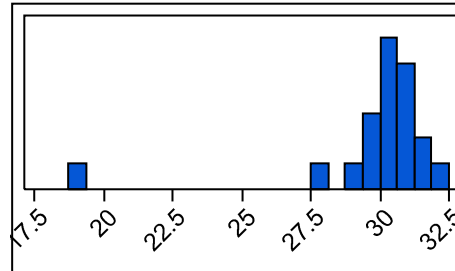
Israel – 1995 – 7 years



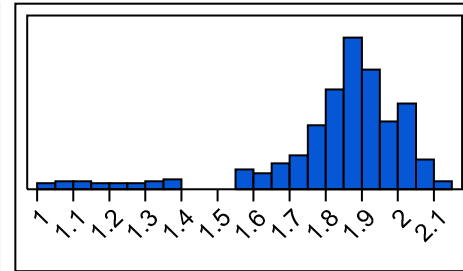
Japan – 2003 – 10 years



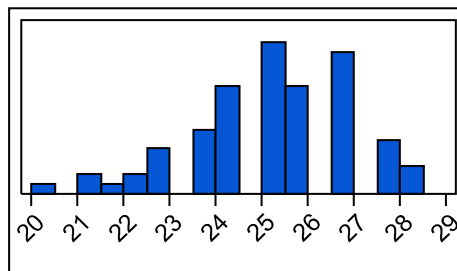
Sweden – 2006 – 25 years



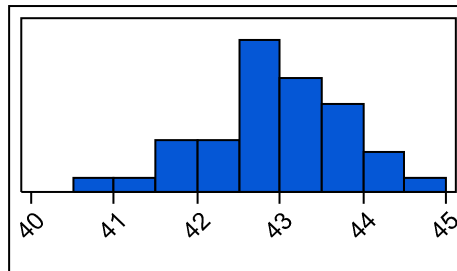
Tunisia – 2008 – 25 years



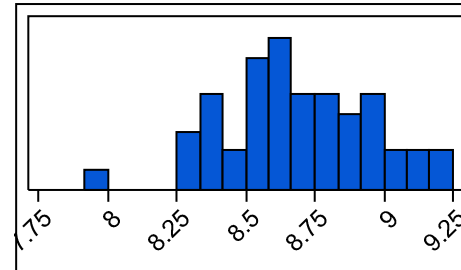
MA – 2010 – 30 years



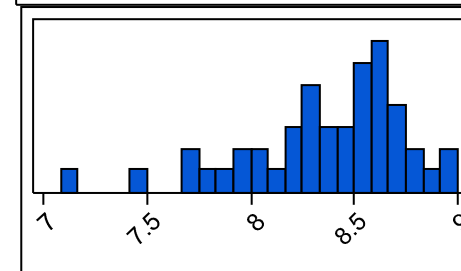
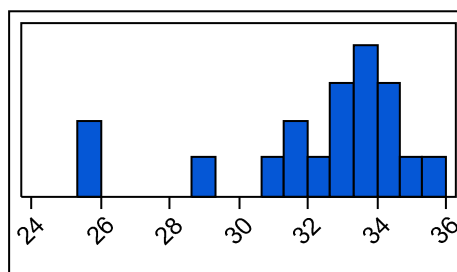
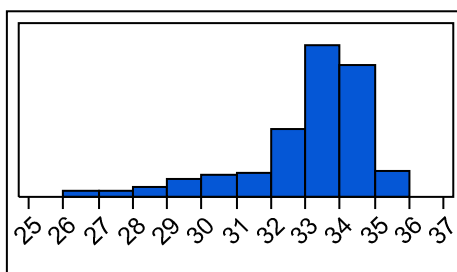
Spain – 2011 – 12 years



Italy – 2010 –
23 & 30 years

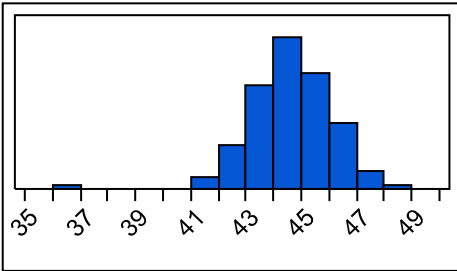


Switzerland – 2010 -20 years CO – 2012 – 15 years

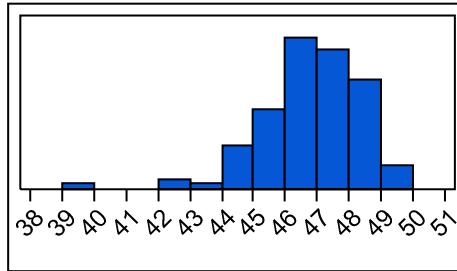


I-V Distributions

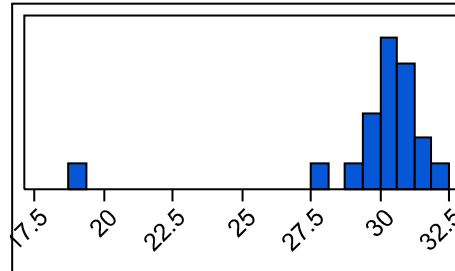
Israel – 1995 – 7 years



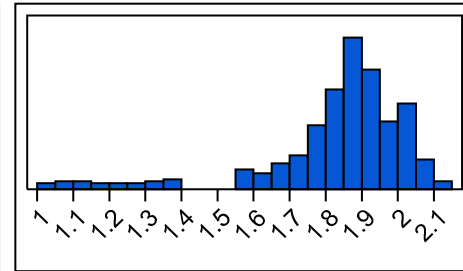
Japan – 2003 – 10 years



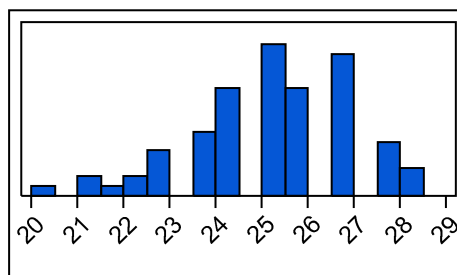
Sweden – 2006 – 25 years



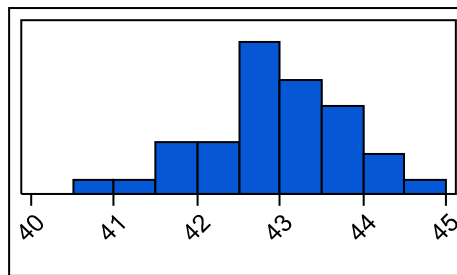
Tunisia – 2008 – 25 years



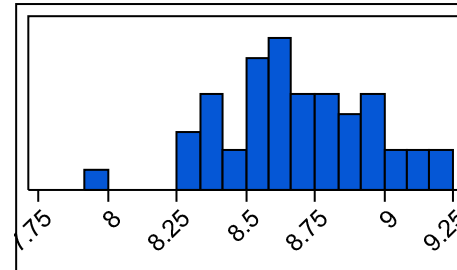
MA – 2010 – 30 years



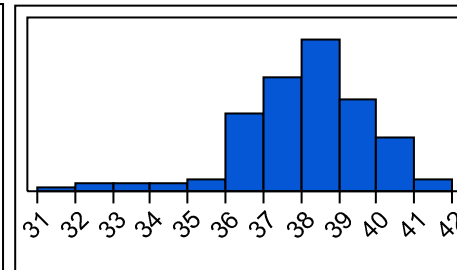
Spain – 2011 – 12 years



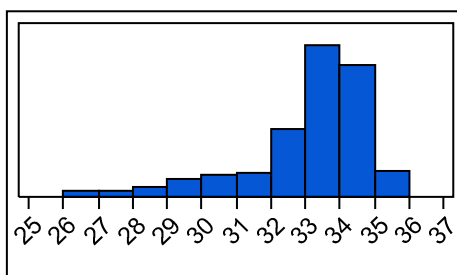
Italy – 2010 –
23 & 30 years



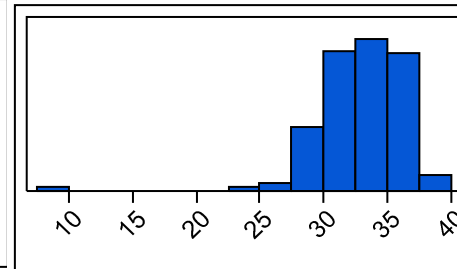
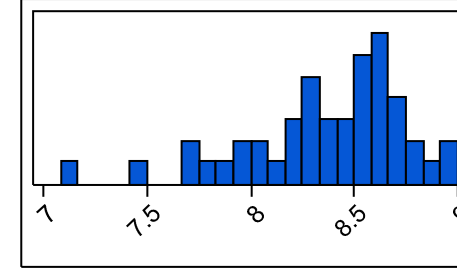
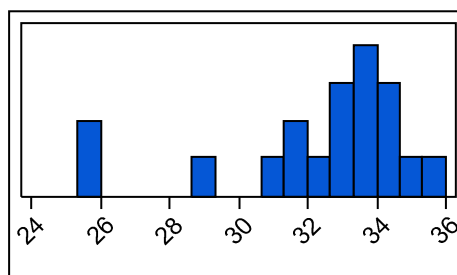
CA – 2011 –
11 & 20 years



Switzerland – 2010 -20 years

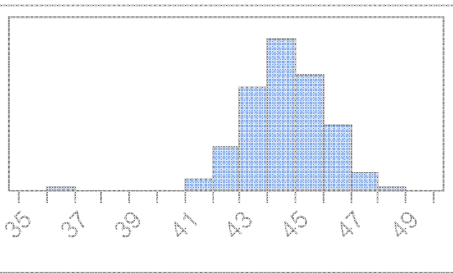


CO – 2012 – 15 years

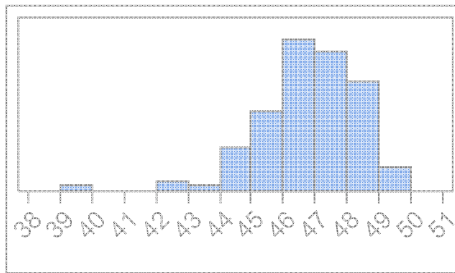


I-V Distributions

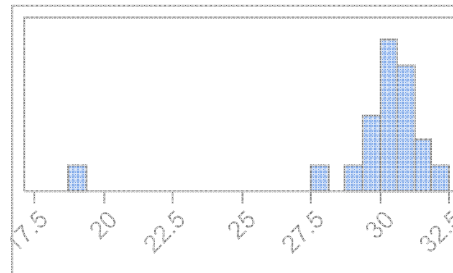
Israel – 1995 – 7 years



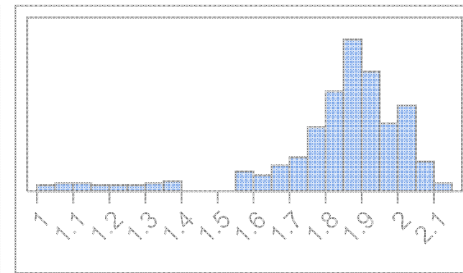
Japan – 2003 – 10 years



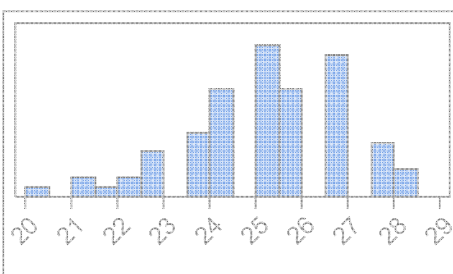
Sweden – 2006 – 25 years



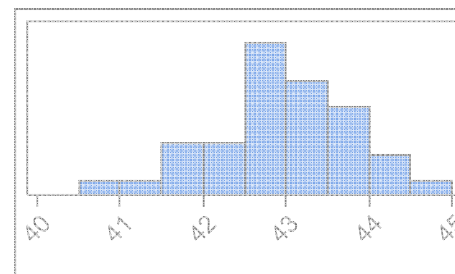
Tunisia – 2008 – 25 years



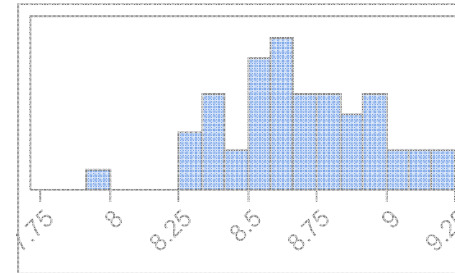
MA – 2010 – 30 years



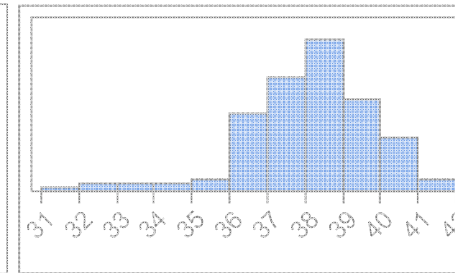
Spain – 2011 – 12 years



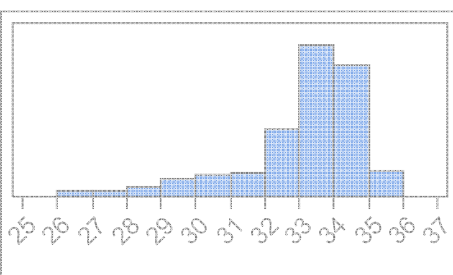
Italy – 2010 –
23 & 30 years



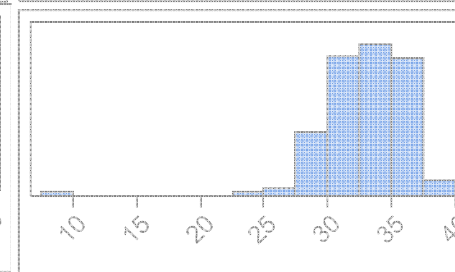
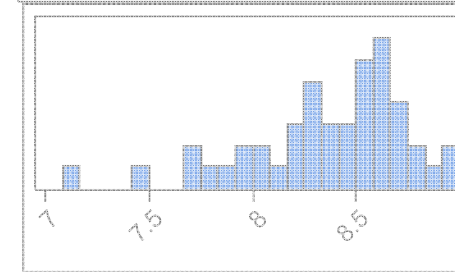
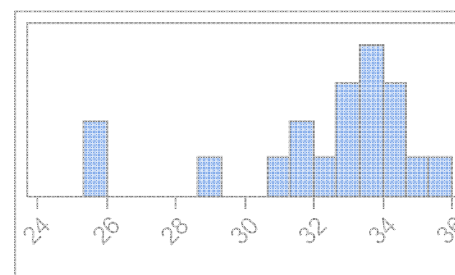
CA – 2011 –
11 & 20 years



Switzerland – 2010 -20 years

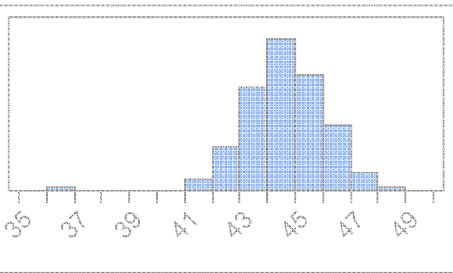


CO – 2012 – 15 years

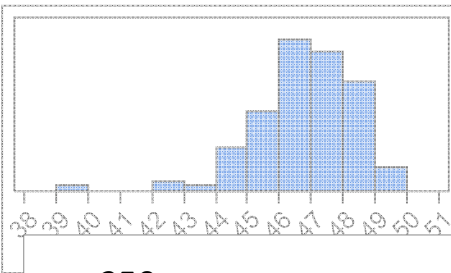


I-V Distributions

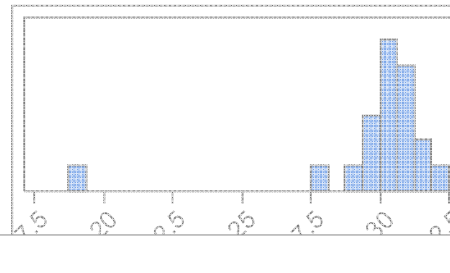
Israel – 1995 – 7 years



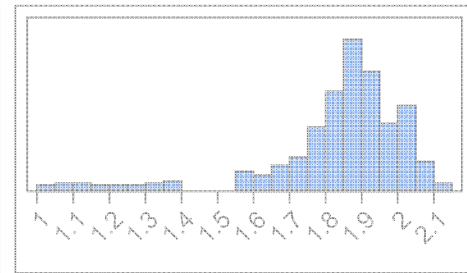
Japan – 2003 – 10 years



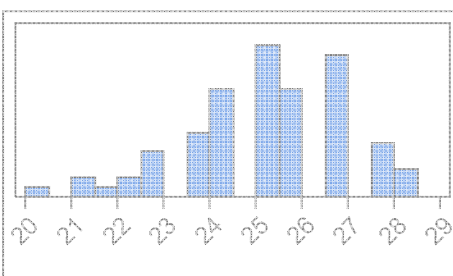
Sweden – 2006 – 25 years



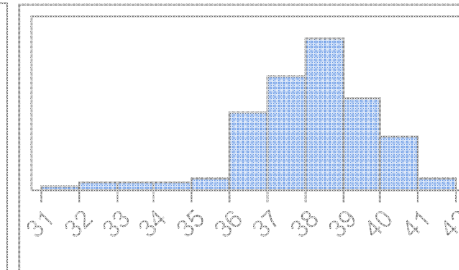
Tunisia – 2008 – 25 years



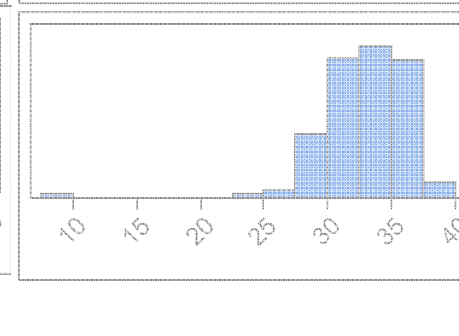
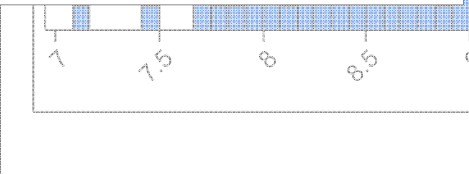
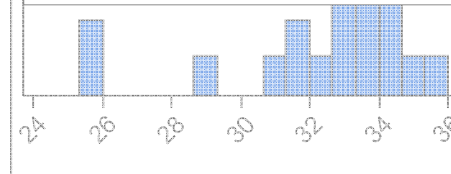
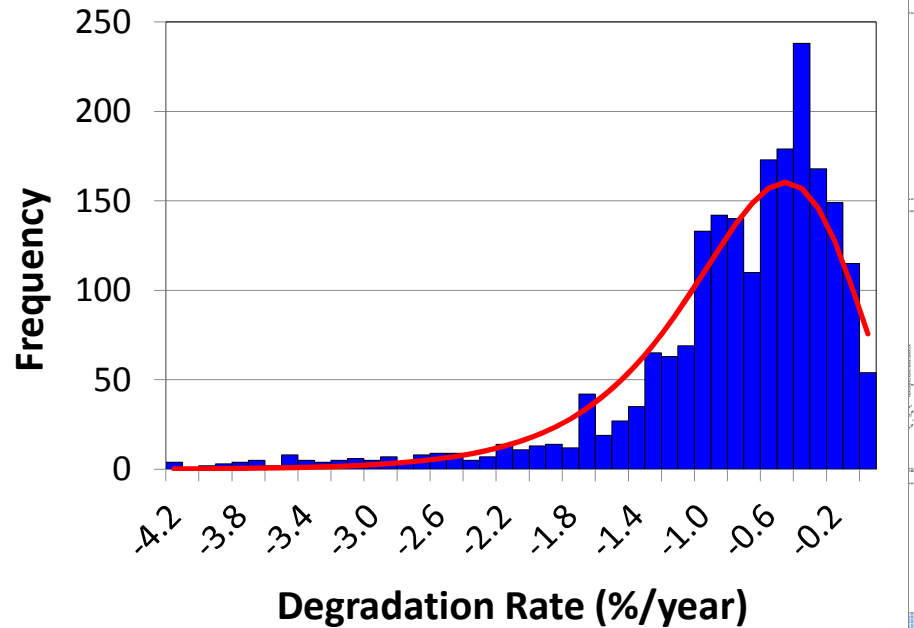
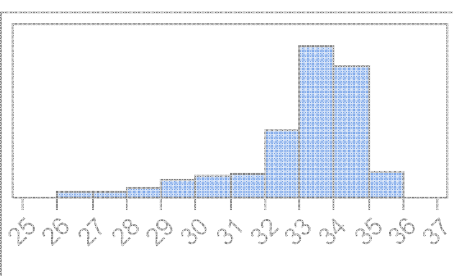
MA – 2010 – 30 years



CA – 2011 –
11 & 20 years

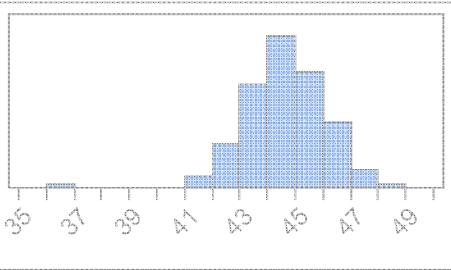


Switzerland – 2010 -20 years

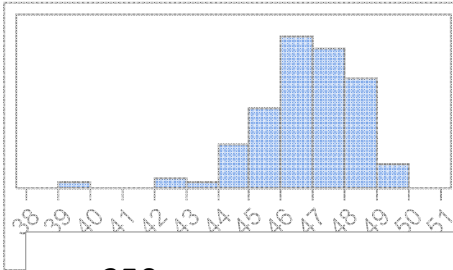


I-V Distributions

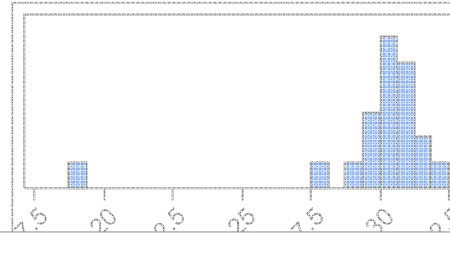
Israel – 1995 – 7 years



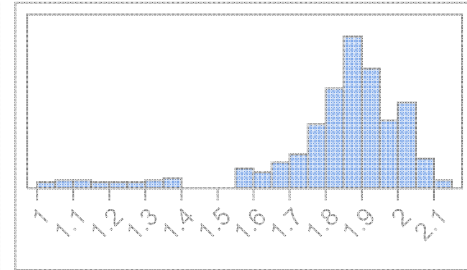
Japan – 2003 – 10 years



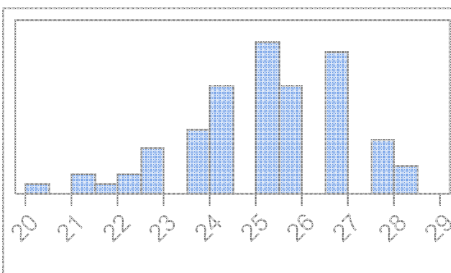
Sweden – 2006 – 25 years



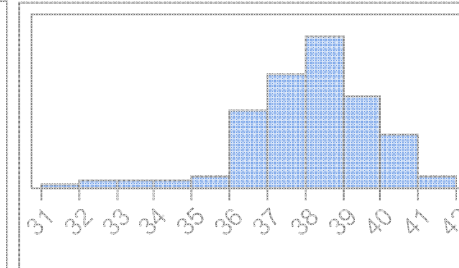
Tunisia – 2008 – 25 years



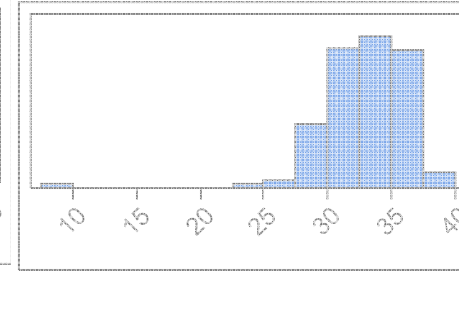
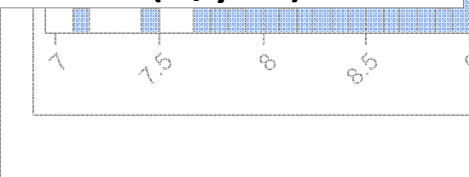
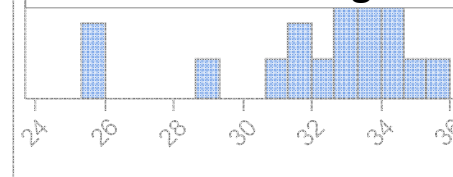
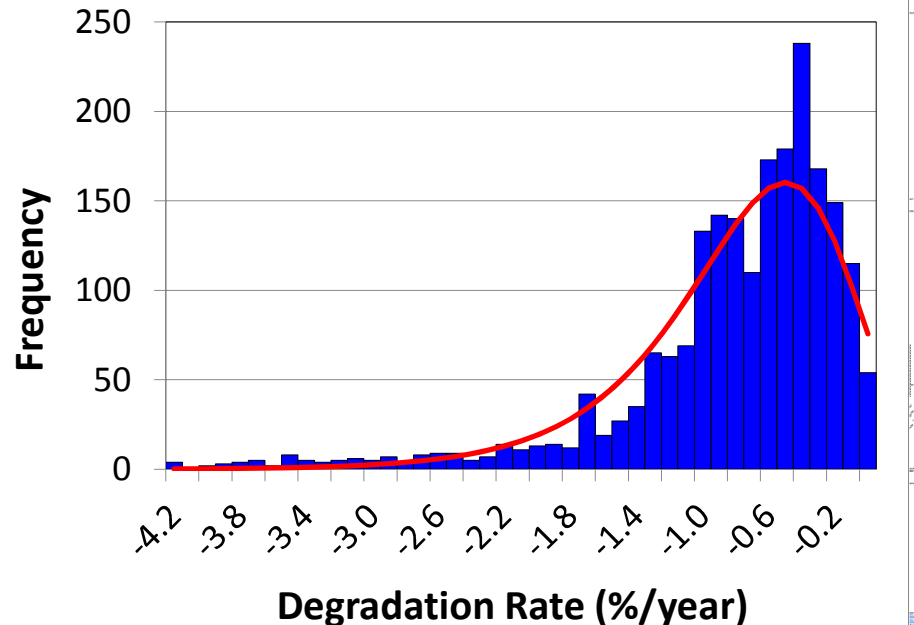
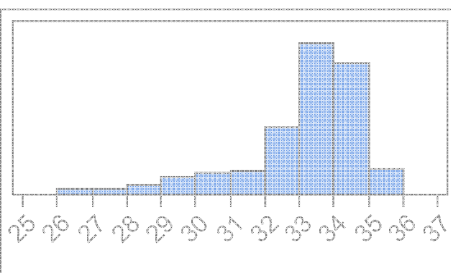
MA – 2010 – 30 years



CA – 2001 –
11 & 20 years



Switzerland – 2010 -20 years



Module Parameter Distributions similar to R_d Distribution

Module Failure Mechanisms

TABLE 1
Common Failure Modes for Crystalline Silicon Modules

<i>Failure Modes</i>
Broken Interconnects
Broken Cells
Corrosion
Delamination of Encapsulant
Encapsulant loss of Elasticity or Adhesion
Encapsulant Discoloration
Solder Bond Failure
Broken Glass
Hot Spots
Ground Faults
Junction Box Failures
Connection Failures
Structural Failures
Bypass Diode Failures
Open circuits leading to arcing

Wohlgemuth et al., IEEE International Reliability Physics Symposium, Monterey, CA, USA, 2011.

Extreme value theory: situation where many independent processes can lead to failure

Situation often modeled by (Maximum or Minimum) Extreme Value Distribution

Also known as the “Weakest link distribution”

Module may be modeled by Extreme Value Distribution

Extreme Weather

Extreme events can be modeled by Extreme Value Distribution

Drought - Current

Hurricane Katrina 2005

Tornado 1995

Wildfire 2010



Photos from University Corporation for Atmospheric Research

Hailstone Nebraska 2003



500 year flood Midwest 1993



Photos from University Corporation for Atmospheric Research

President Truman's Water Commission (1950):

"However big floods get, there will always be a bigger one coming; so says one theory of extremes, and experience suggests it is true."

Emil Gumbel:

"It seems that the rivers know the theory. It only remains to convince the engineers of the validity of this analysis."

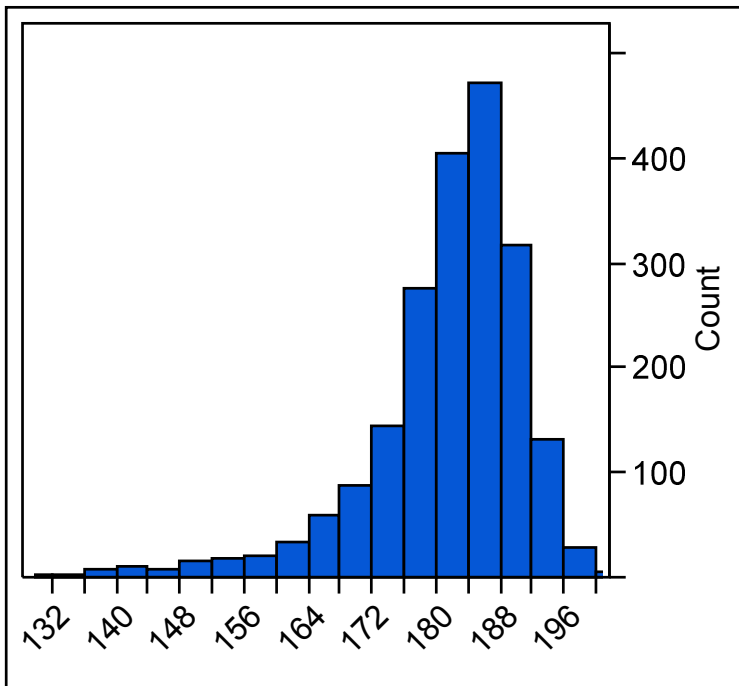
System Performance

10 normal distributions, take the smallest value

Repeat 2000 times -->Smallest Extreme Value Distribution

Very few studies investigate that many modules

--> take 50 random sample



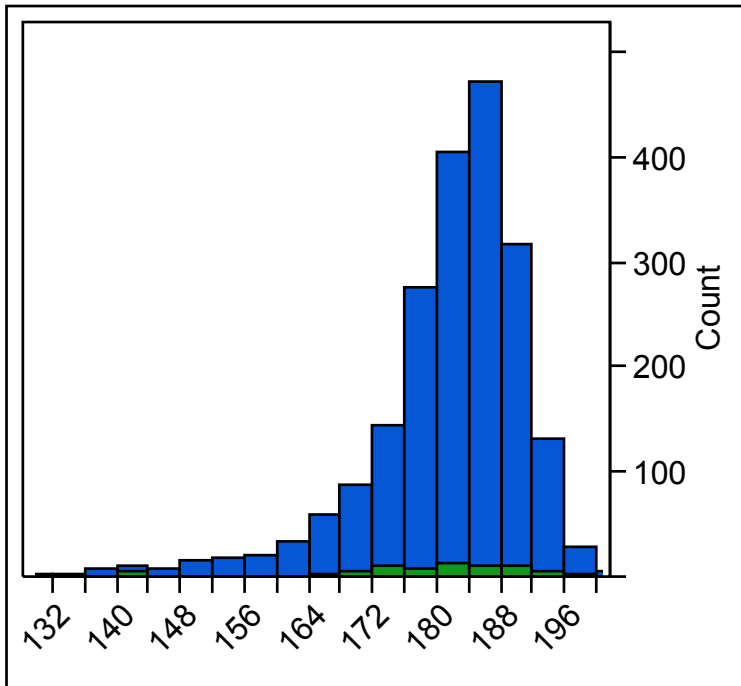
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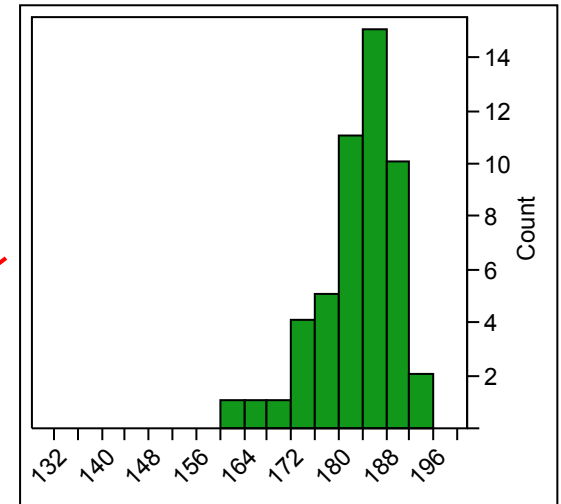
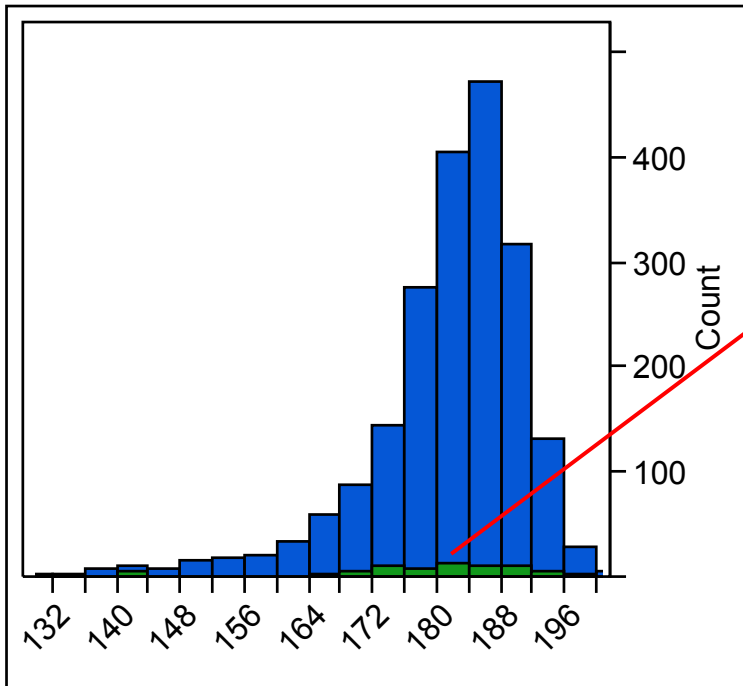
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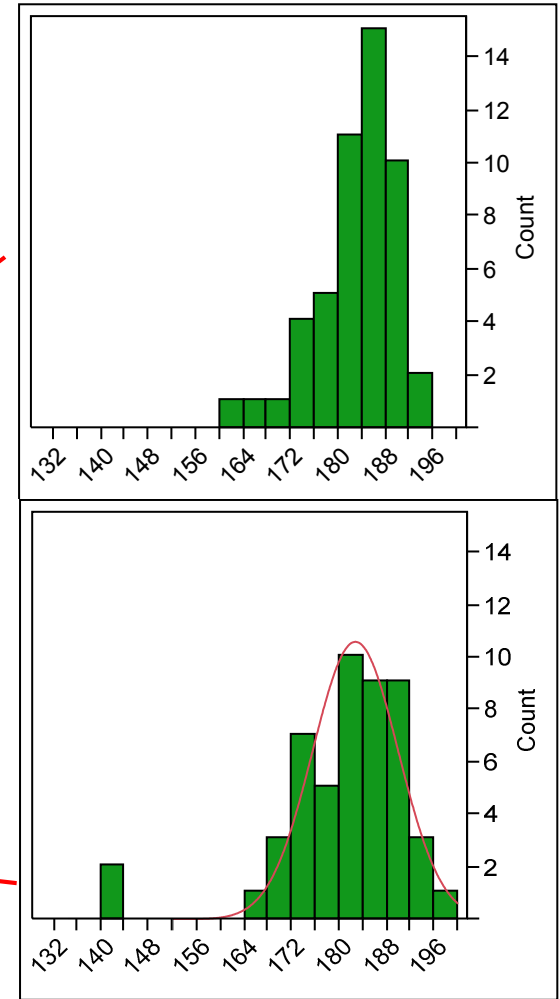
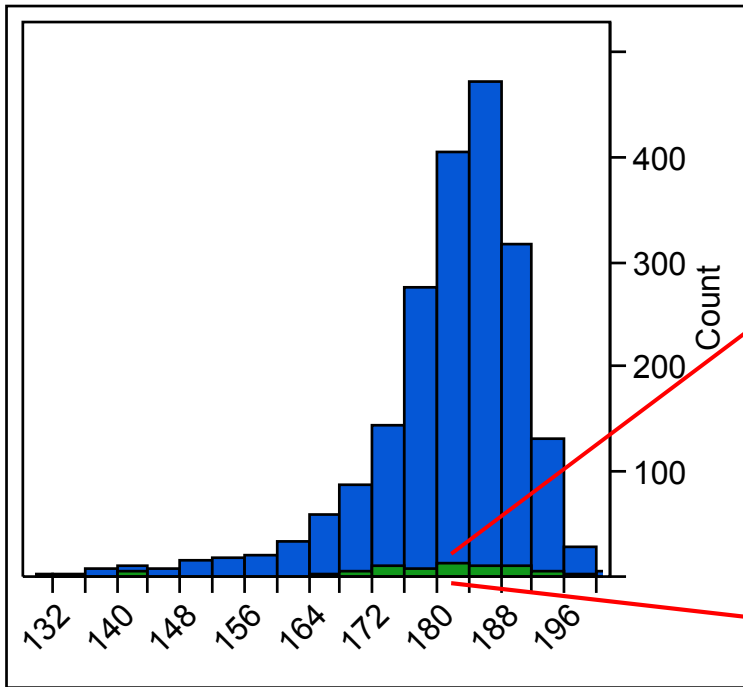
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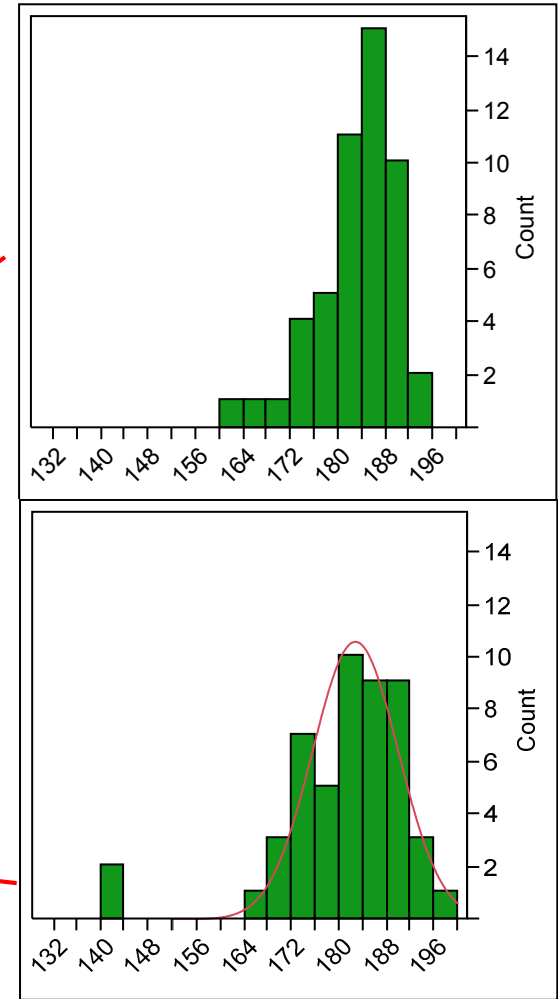
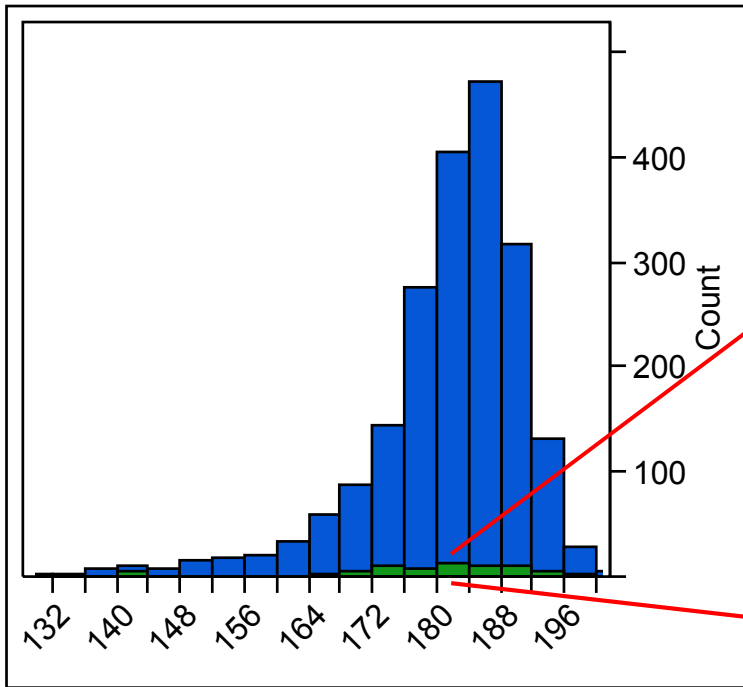
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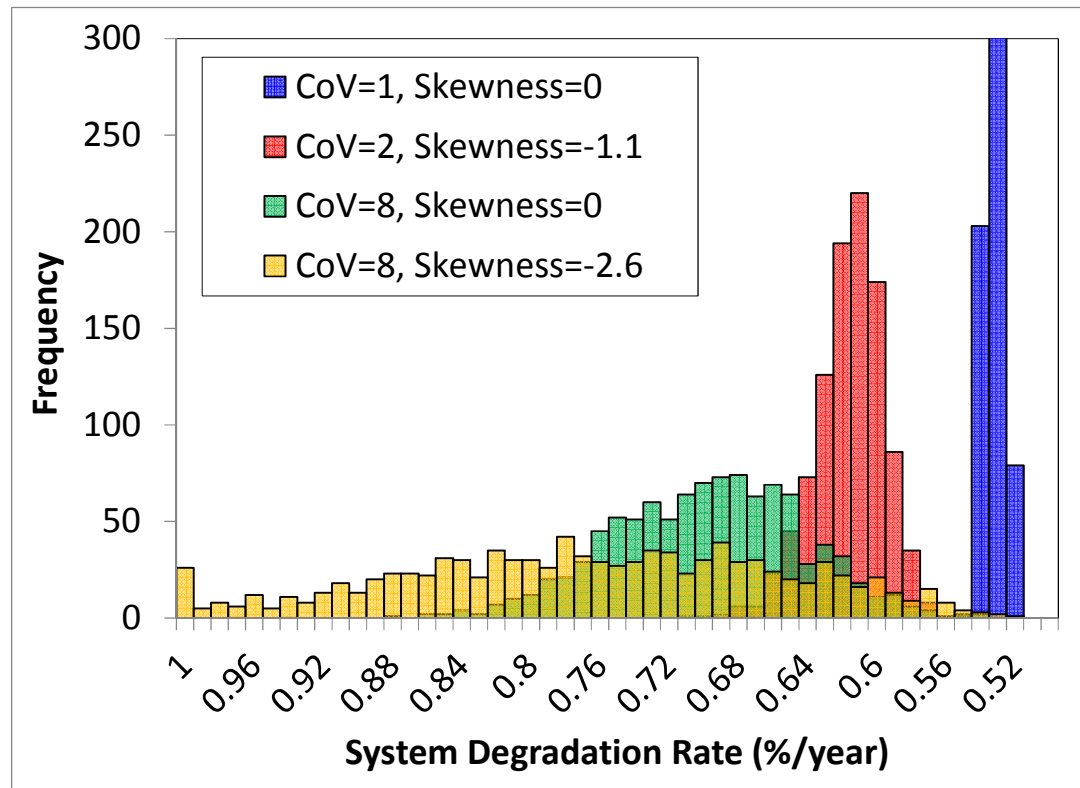
Outlier may be indicative of skewed distribution
Takes sufficient field exposure & sample size to see it

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

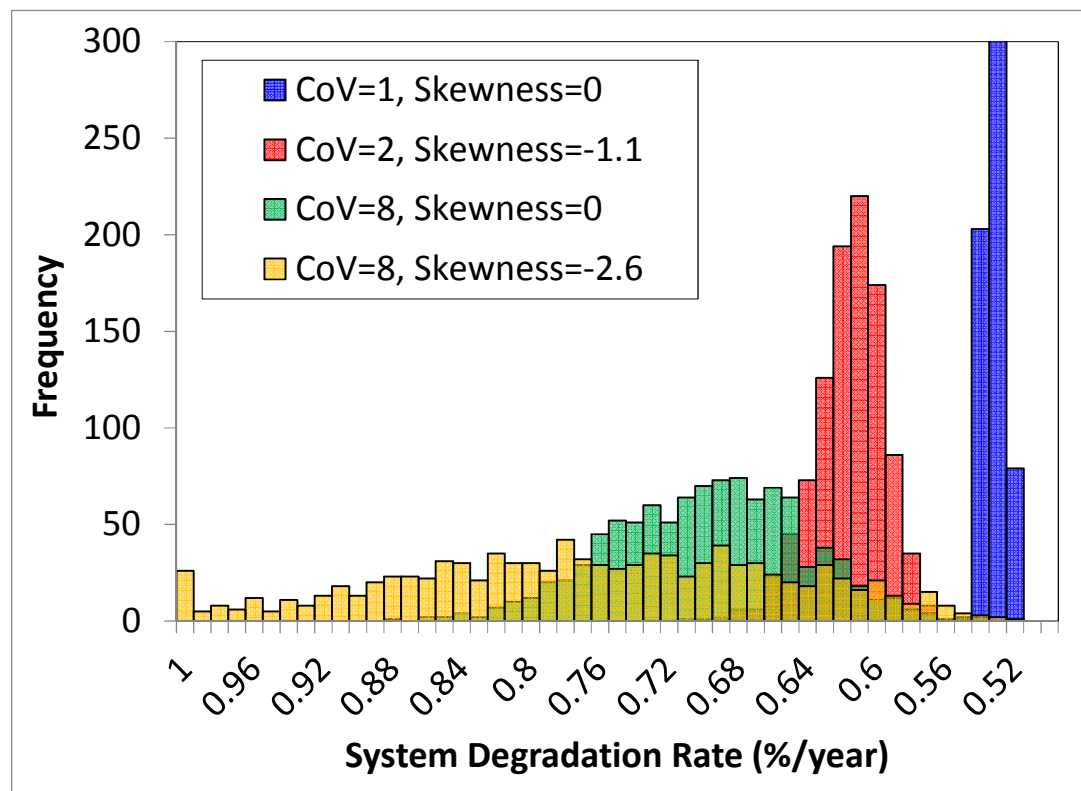


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Distribution of module degradation affects system degradation

Summary

1. Individual trends

- c-Si Pmax decline is most strongly correlated with I_{sc} , less FF
- Hot & humid climate show mixture with higher FF degradation
- 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

2. Big Picture

- IEC 61215: Infant mortality test ↔ No lifetime test, International Quality Assurance Task Force
- Can help in prioritizing failure mechanisms & used to develop accelerated tests for lifetime in c-Si.

Acknowledgments

Thank you for your attention

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National Renewable Energy Laboratory
15013 Denver West Parkway, MS 3411
Golden, CO 80401, USA
dirk.jordan@nrel.gov

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