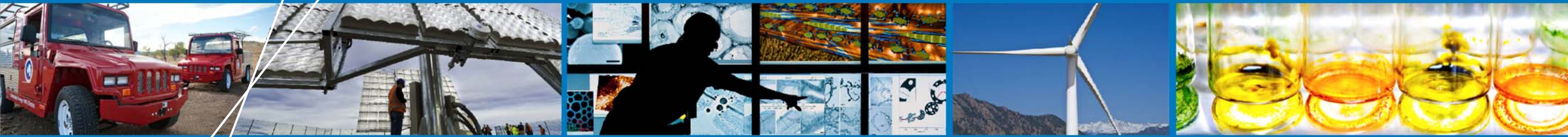
Technology and Climate Trends in PV Module Degradation



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 (Module 1) = 0.8 %/year
R_d (Module 2) = 0.8 %/year

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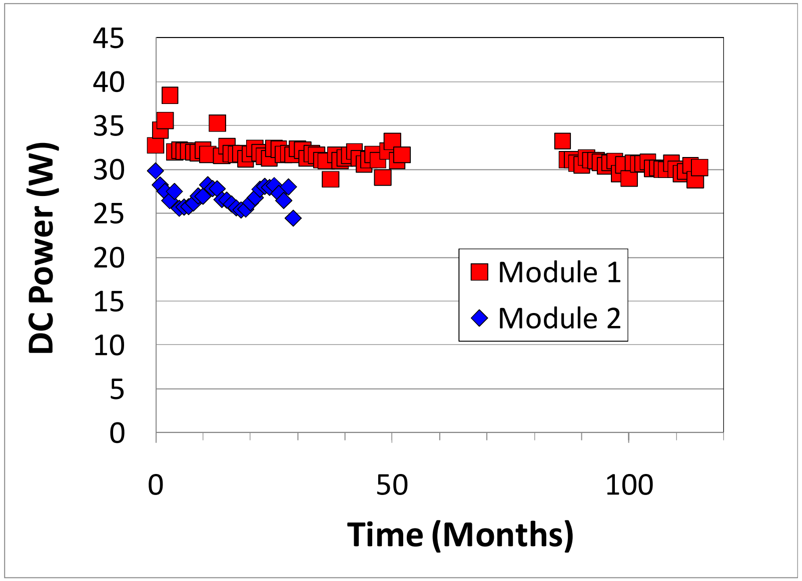

2 modules: Different observation lengths, seasonality etc.

R_d (Module 1) = 0.8 %/year

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Introduction- Degradation Rates (R_d)

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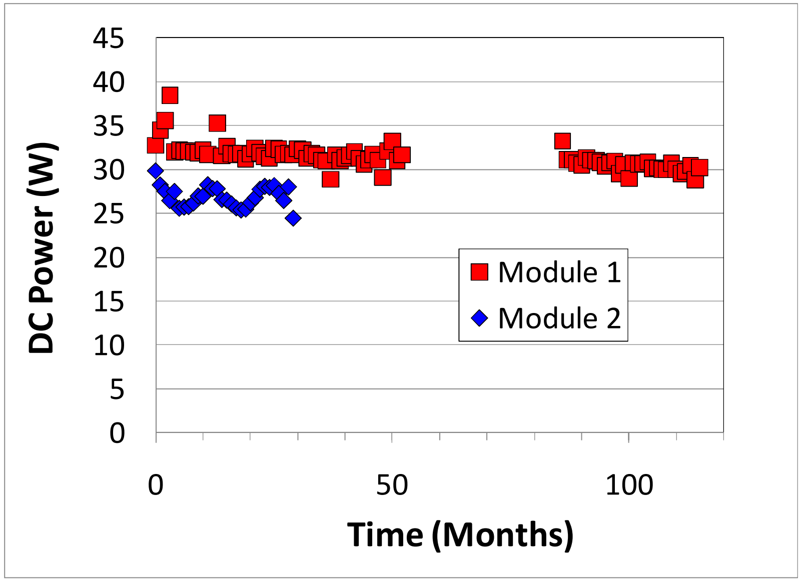


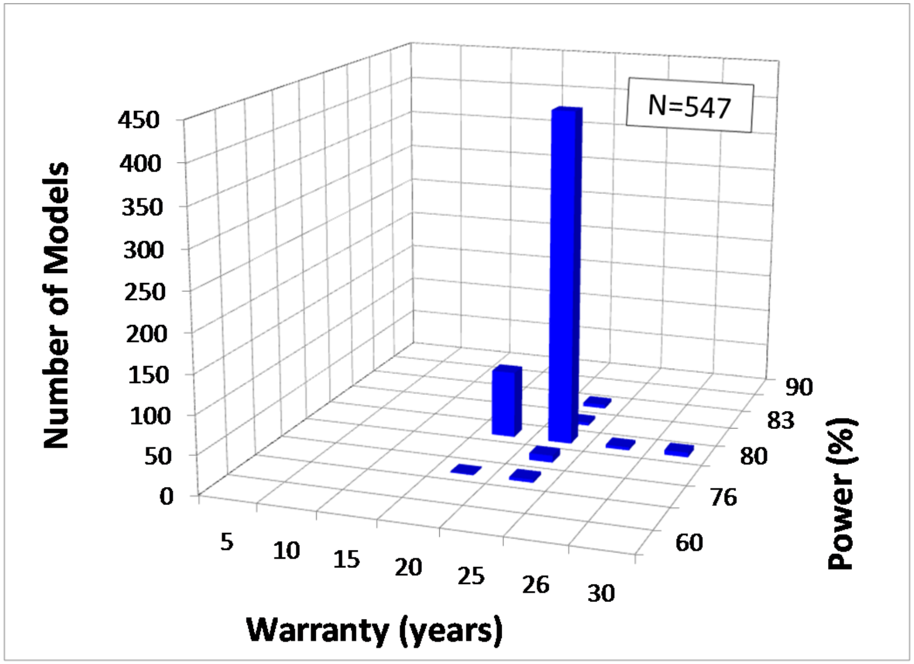
2 modules: Different observation lengths, seasonality etc.

R_d (Module 1) = (0.8 ±0.2) %/year
R_d (Module 2) = (0.8 ±1.0) %/year

Same degradation rate, different Uncertainty

R_D Uncertainty Impact on Warranty

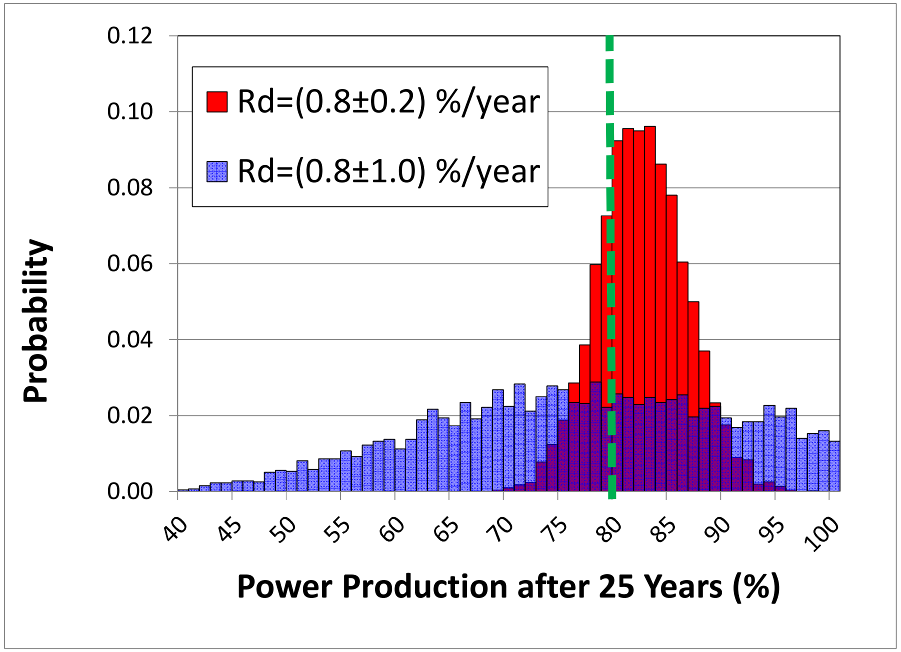
Maximum module warranty - 2010



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



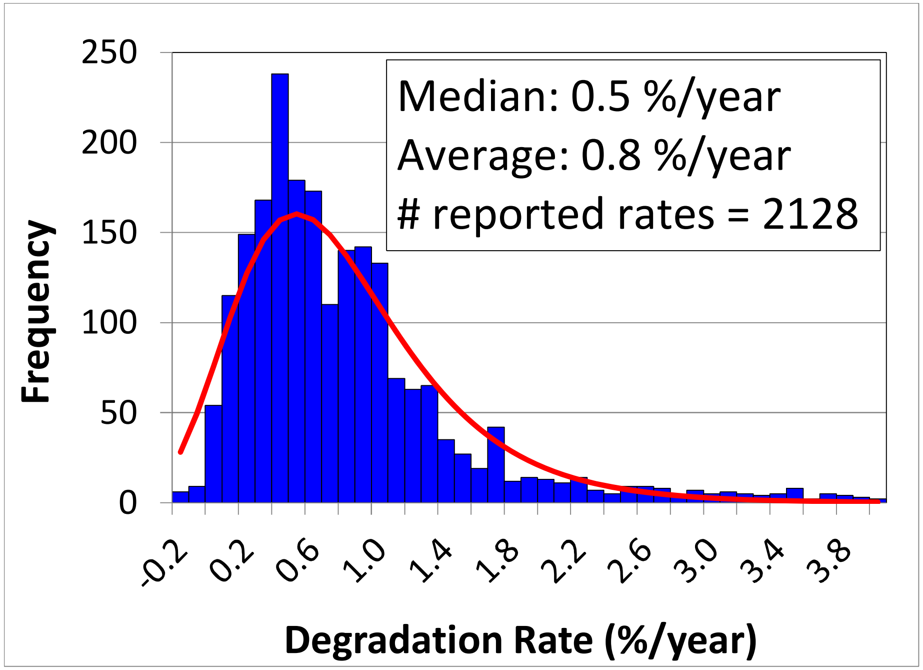
Probability to default on warranty:
Module 1: Probability = 24%
Module 2: Probability = 57%

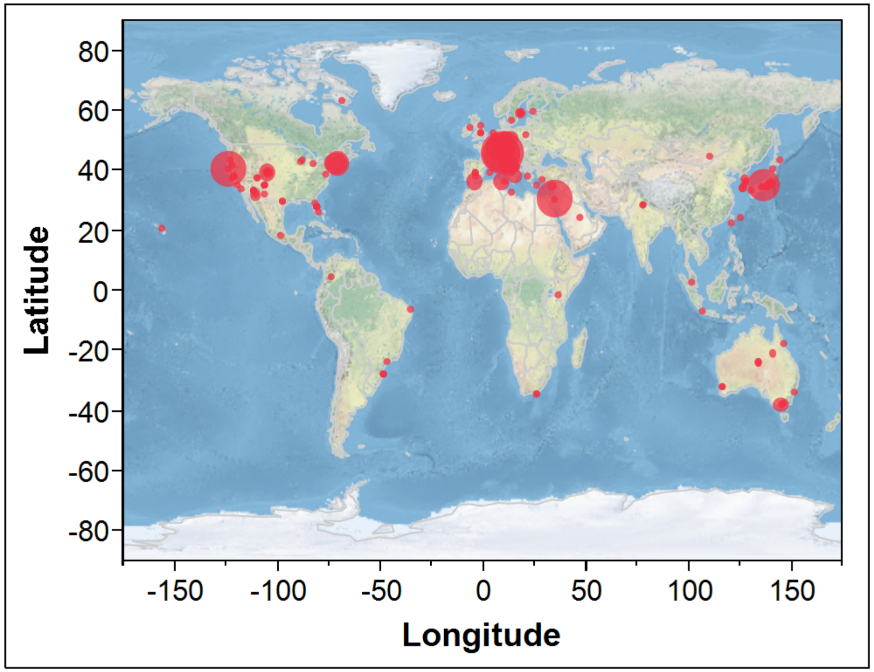
Need to determine R_d *accurately*

Degradation Rates – Literature Survey

Number of Degradation rates (R_d) from literature: 2128

> 100 publications from 32 countries





Technology, age, packaging, geographic location

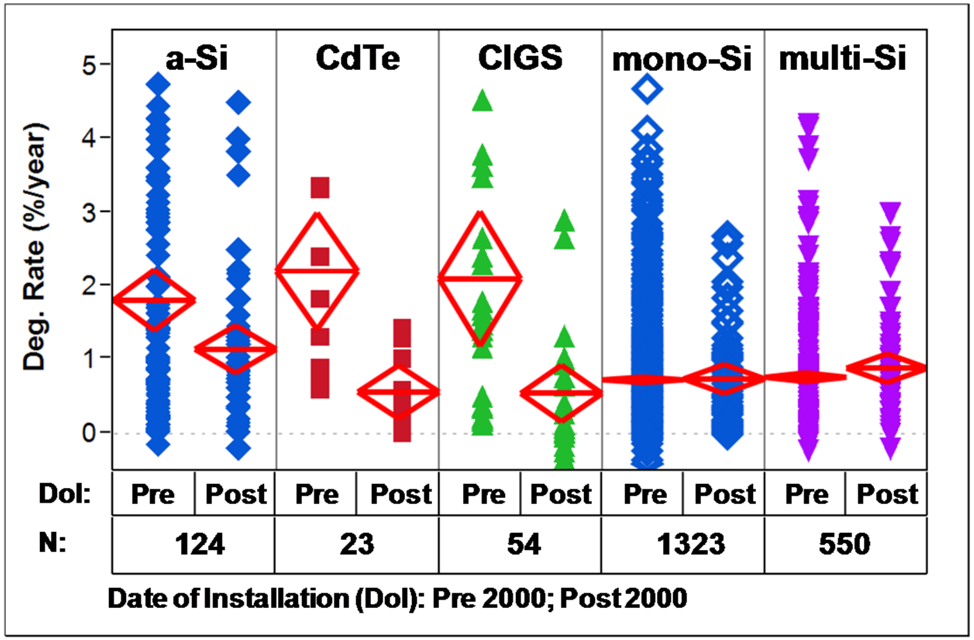
ca. 80% below 1%/year

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

Most modules degrade by ca. 0.5 %/year

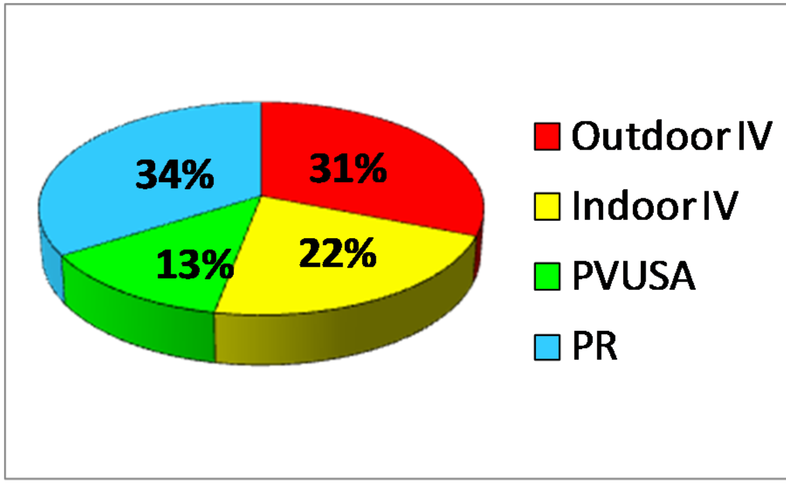
Jordan et al., "Degradation Rates – An Analytical Review", Progress in PV, 2011

Literature Degradation Rates



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

No standard to determine R_d



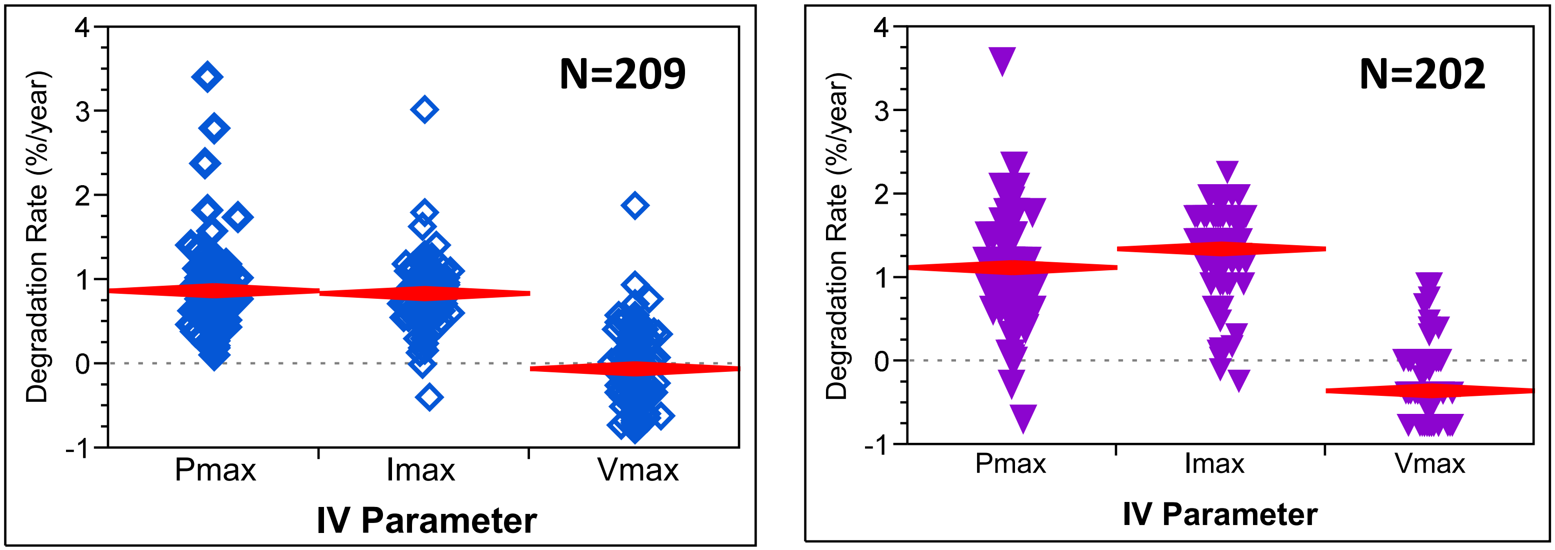
> 50% of Rd taken by I-V curves → Information on short-circuit current (Isc), open-circuit voltage (Voc), fill factor (FF), Imax, Vmax

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

Pmax Degradation Partition

Mono-Si

Multi-Si

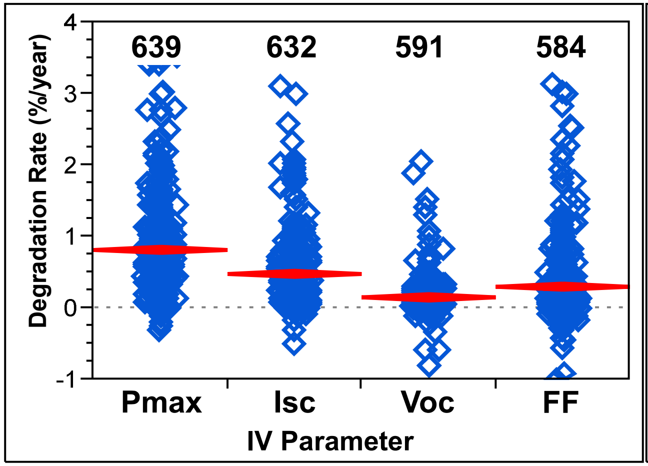


Important for proper inverter sizing

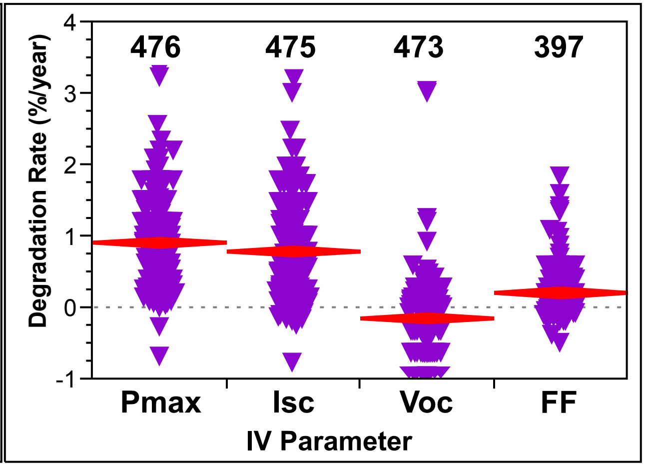
Statistically degradation in current not in voltage

I-V Parameters by Technology

Mono-Si



Multi-Si



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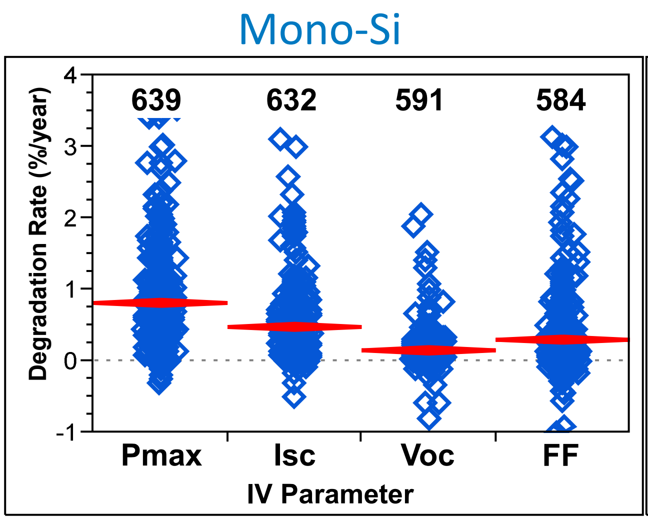
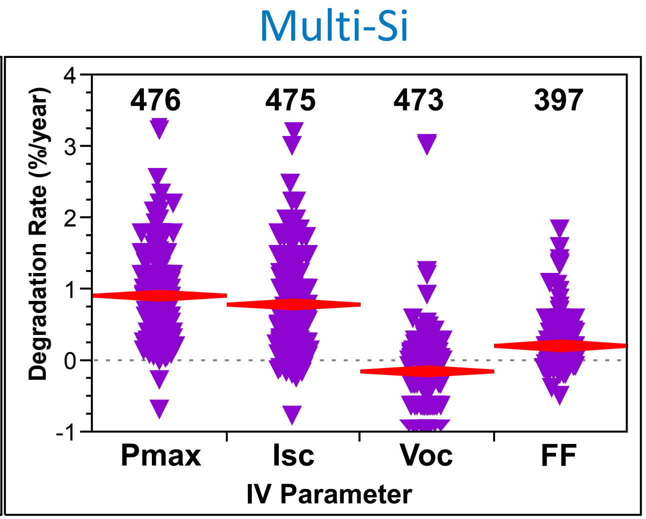
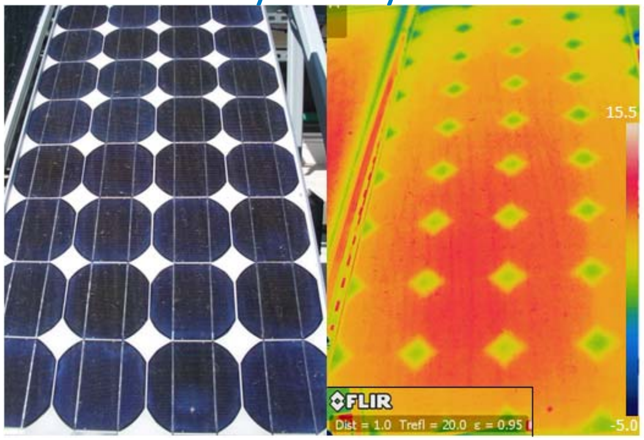
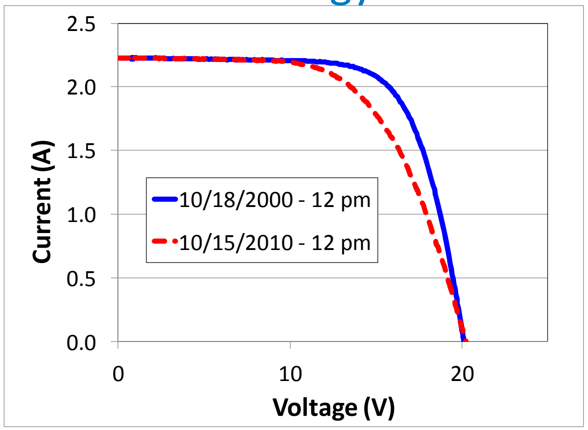




NREL study – May 2012 – World Renewable Energy Forum





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

Pmax correlated to Isc loss

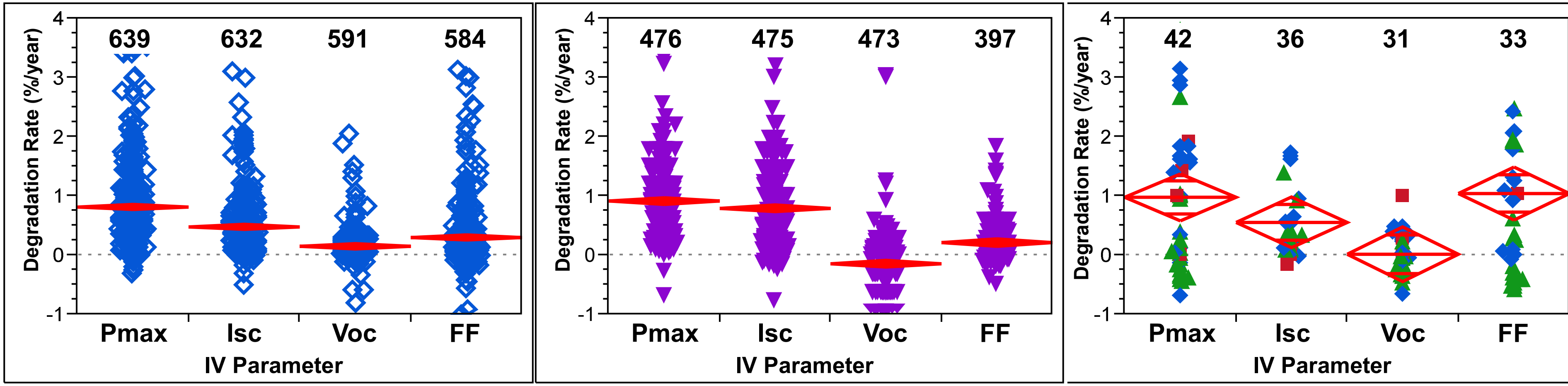
9/12 modules

Pmax correlated to FF loss

3/12 modules

I-V Parameters by Technology

Mono-Si Multi-Si Thin-film



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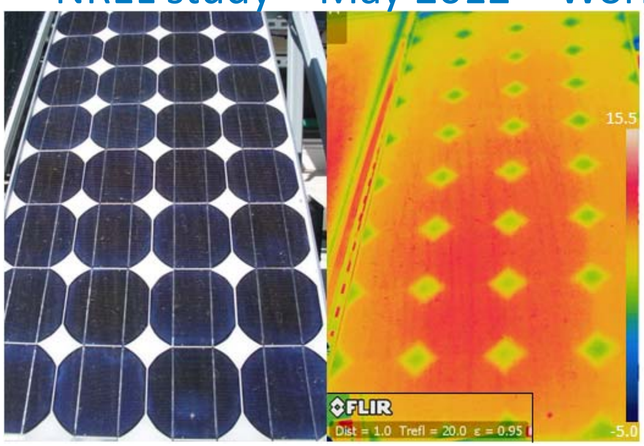

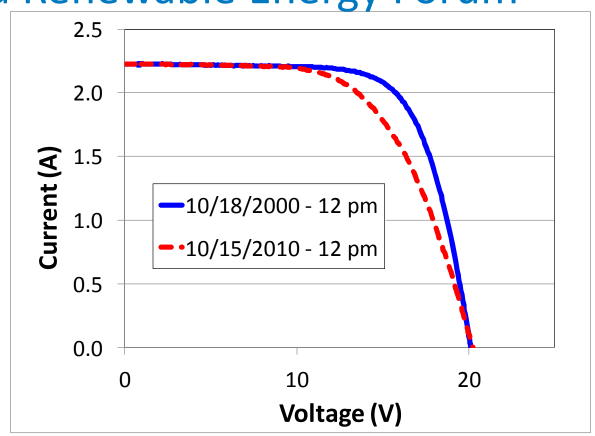

a-Si
CIGS
CdTe

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

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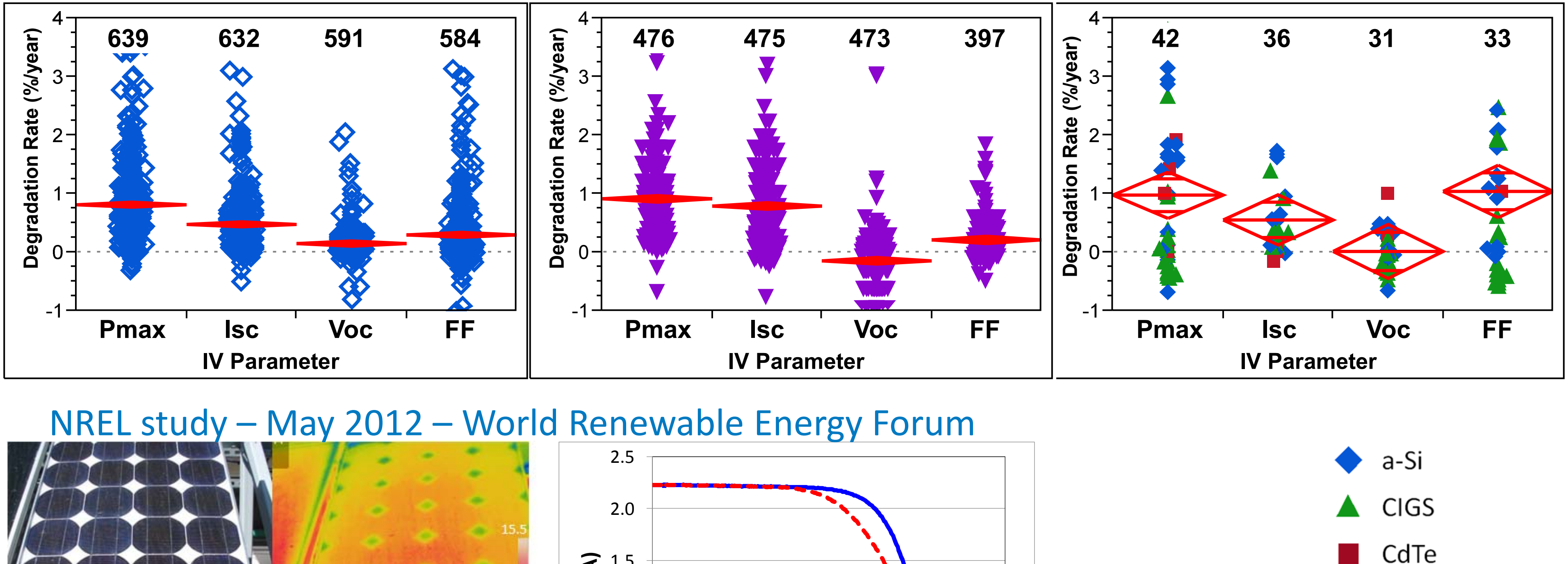

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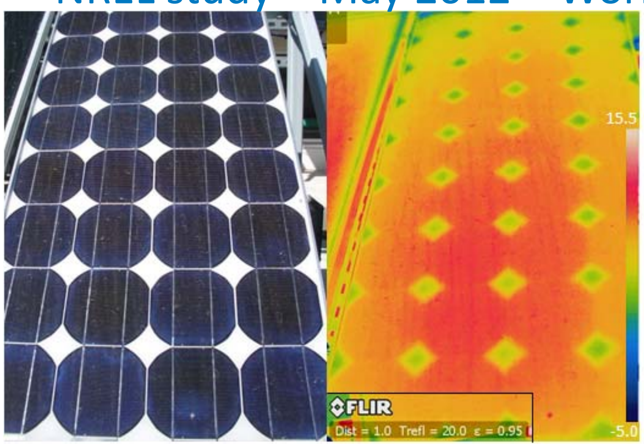
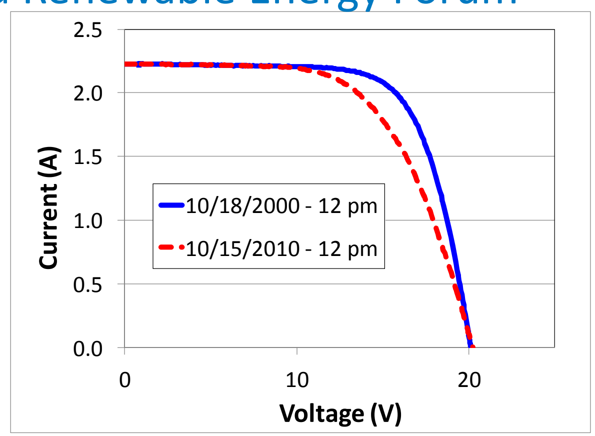




Smith et al., World Renewable Energy Forum, May 2012

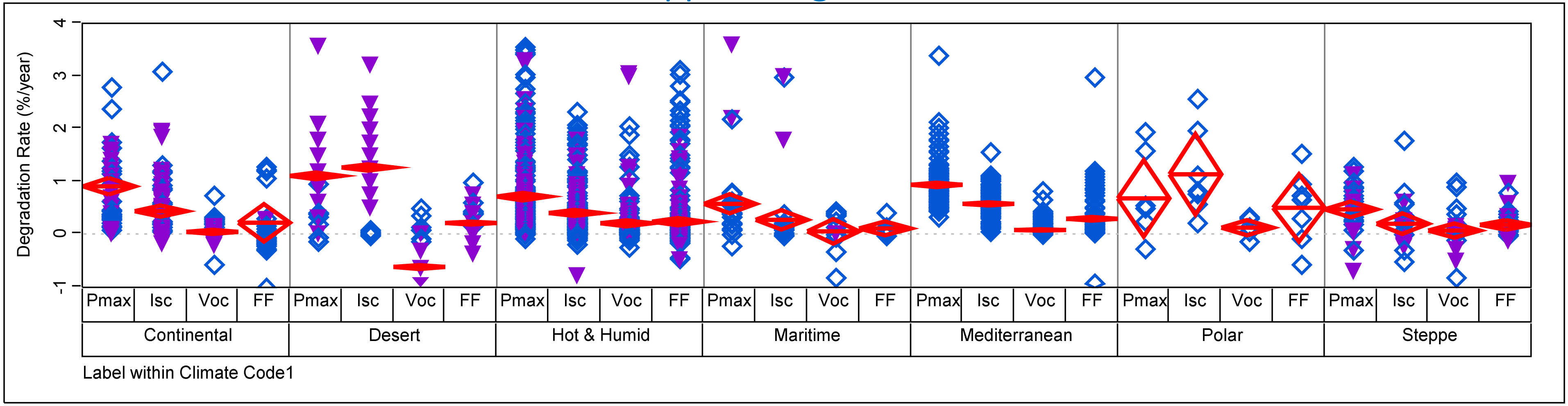
Pmax correlated to Isc loss

Pmax correlated to FF loss

Degradation for c-Si Isc; Thin-film FF

Climate Analysis

Based on Köppen-Geiger Classification



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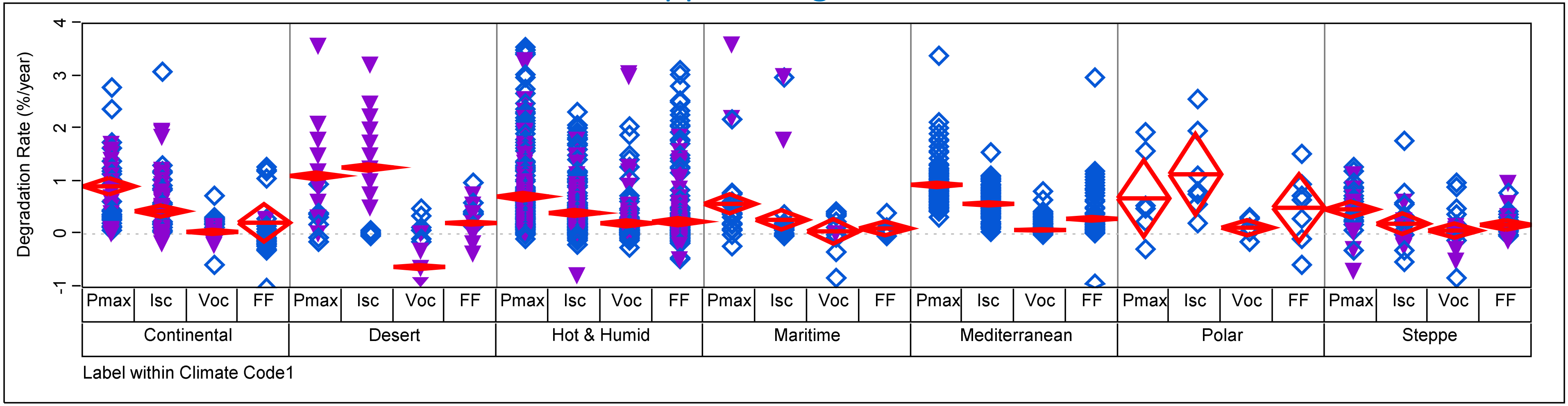

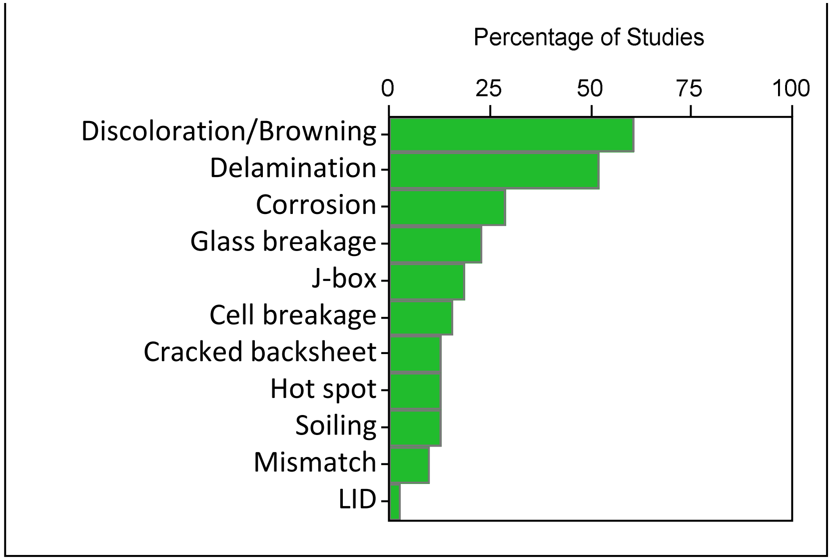

- Pmax most strongly correlated with Isc losses
- Isc losses: discoloration, soiling, delamination, light-induced degradation
- Majority of studies report discolor. & delam.
- No standard reporting of field failure mechanisms, C. Packard talk on Monday

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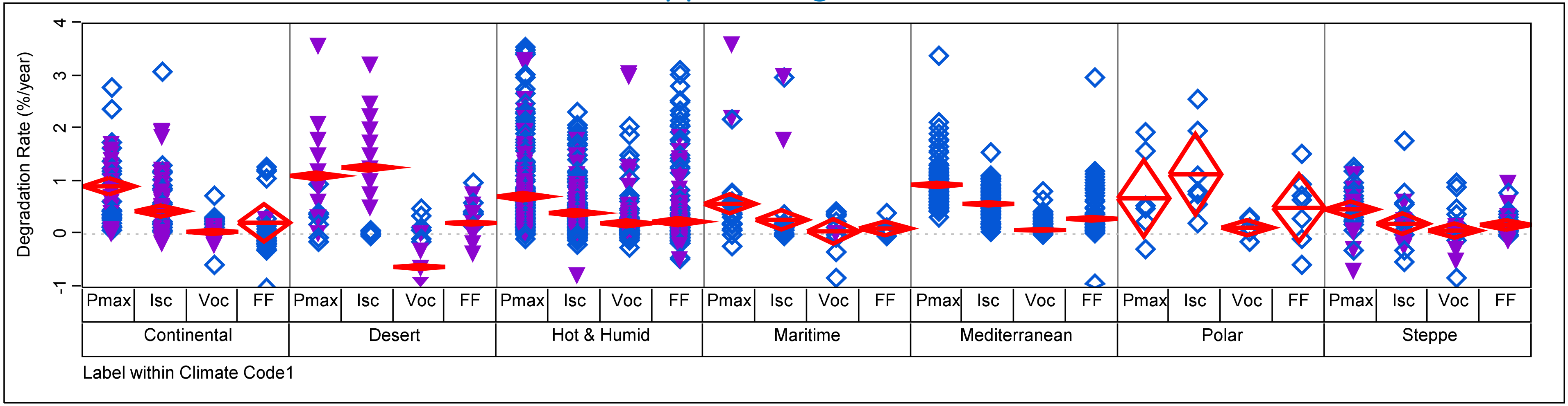

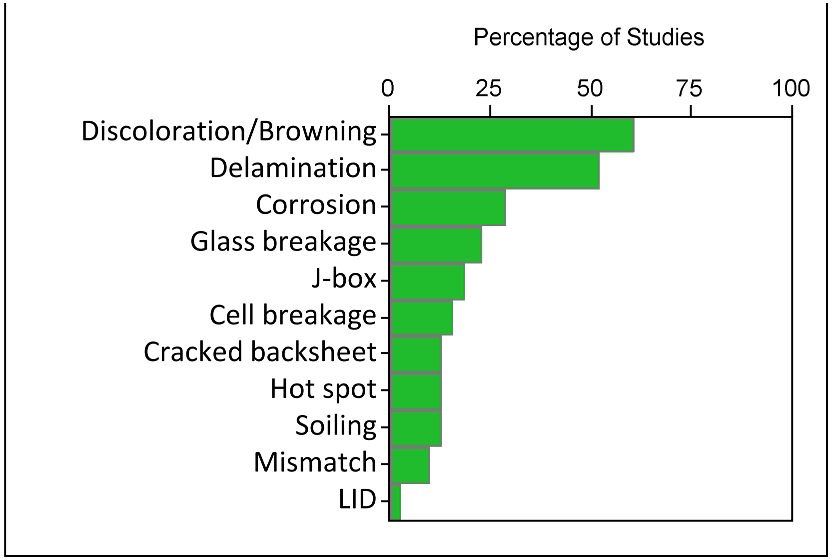

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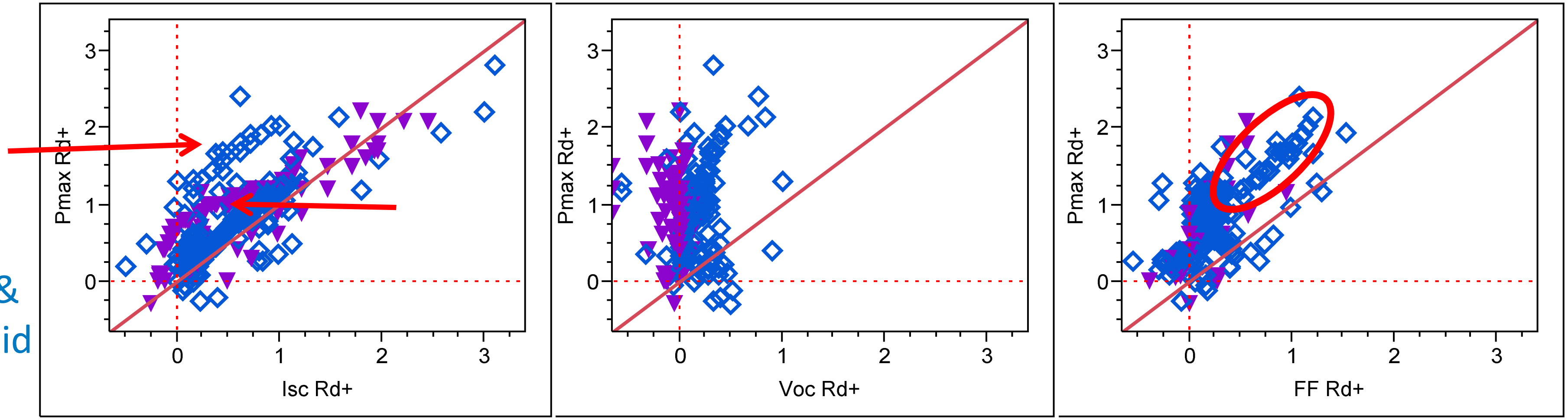
Pmax correlated with Isc loss for most climates

I-V parameters for c-Si

Non Hot & Humid



Pmax degradation mostly correlated with Isc loss
2 parallel lines – 1 measurement studies

Tail from study that showed high corrosion

I-V parameters for c-Si

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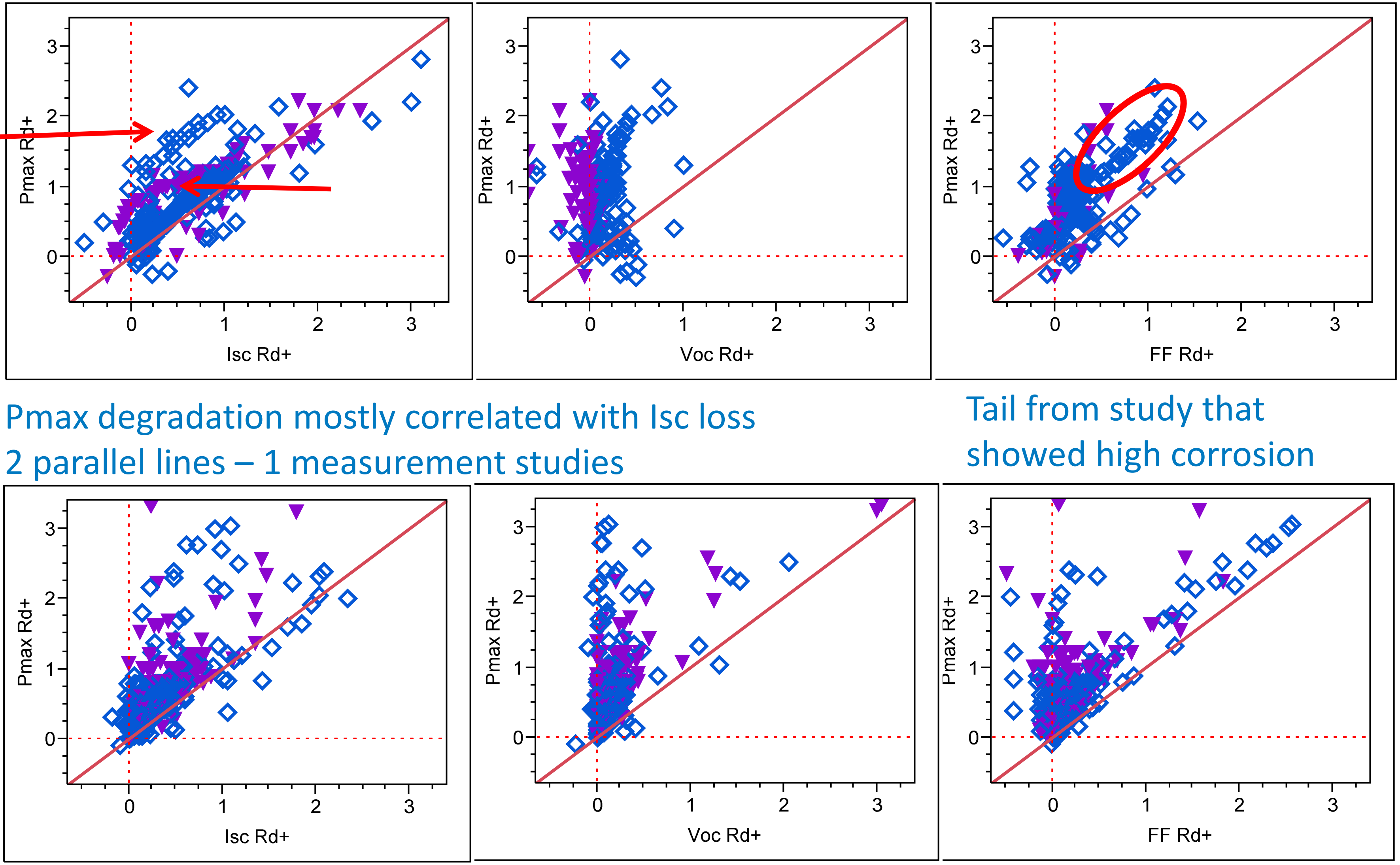

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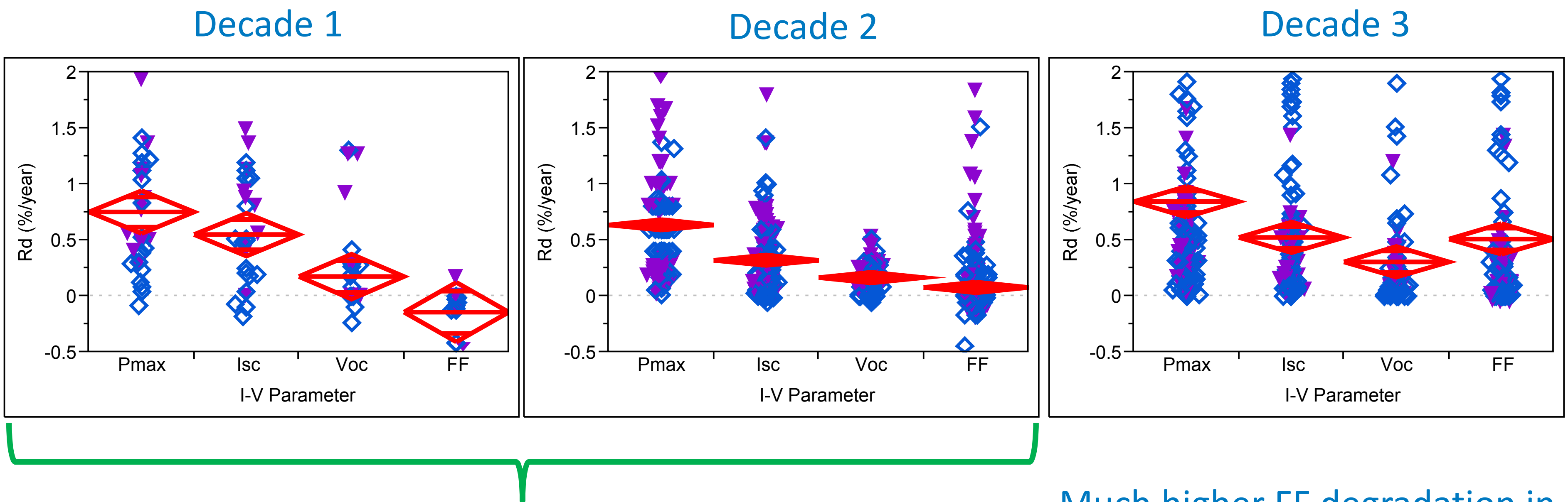
Hot & Humid

Hot & Humid shows mixture of degradation

Hot & Humid by Decade



mono-Si
multi-Si

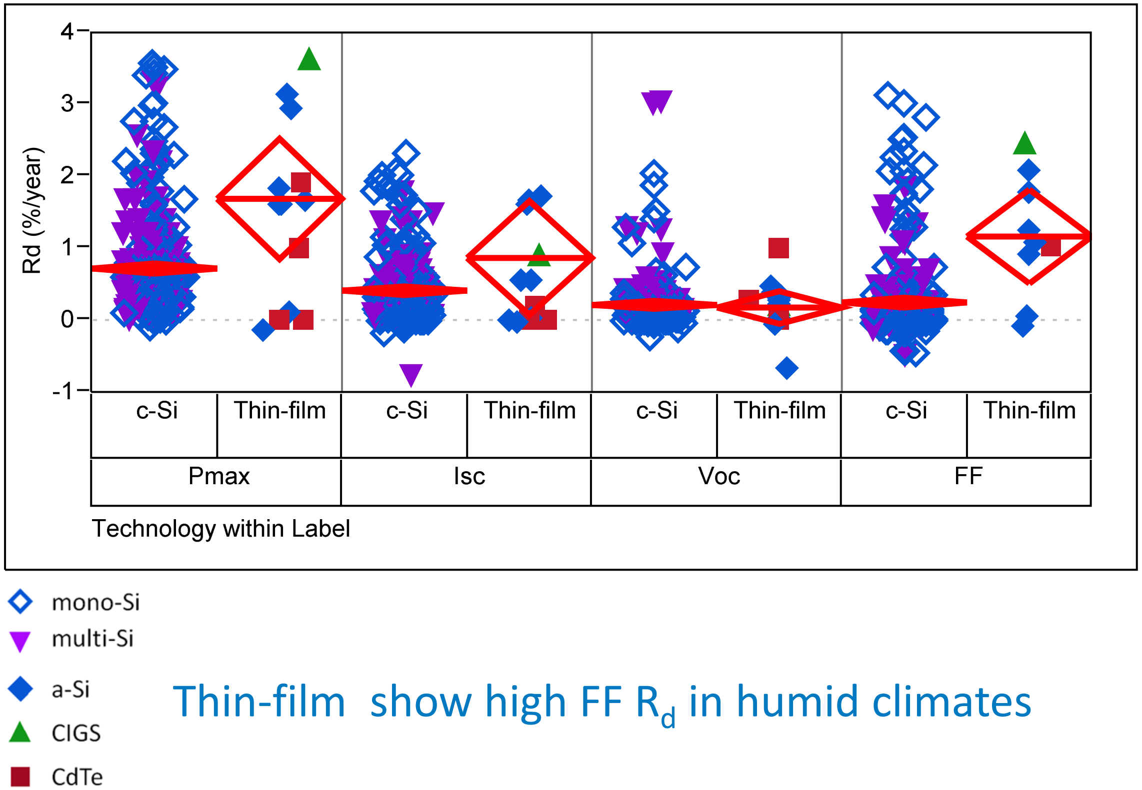
Very little FF degradation till in first 2 decades

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



Thin-film show high FF R_d in humid climates

First Solar

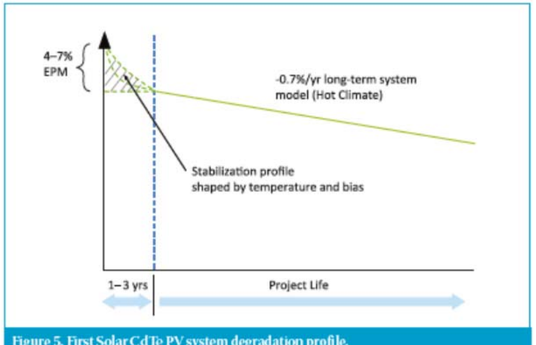


Figure 5. First Solar CdTe PV system degradation profile.

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

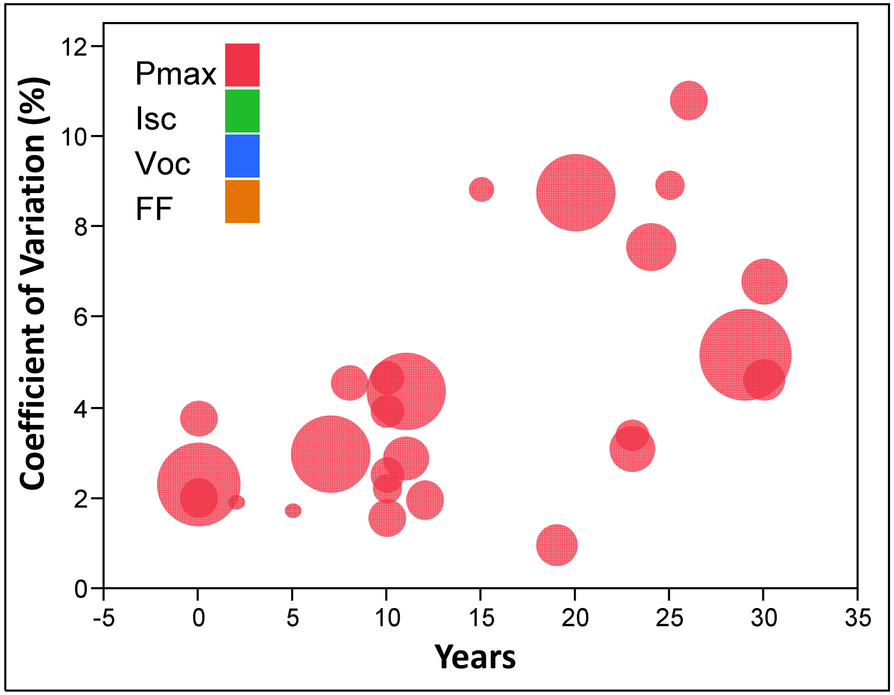
Different long-term performance recommendation based on climate

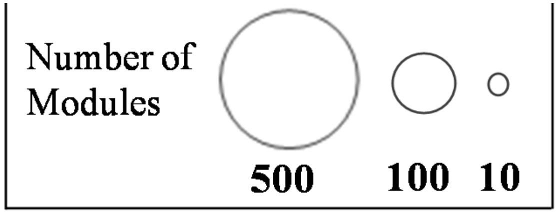
Strevel et al., 17th edition Journal Photovoltaics International, 2012

Different long-term recommendation based on climate

Module I-V Distribution

Distribution width





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

Coefficient of Variation (CoV): Standard deviation/ Mean

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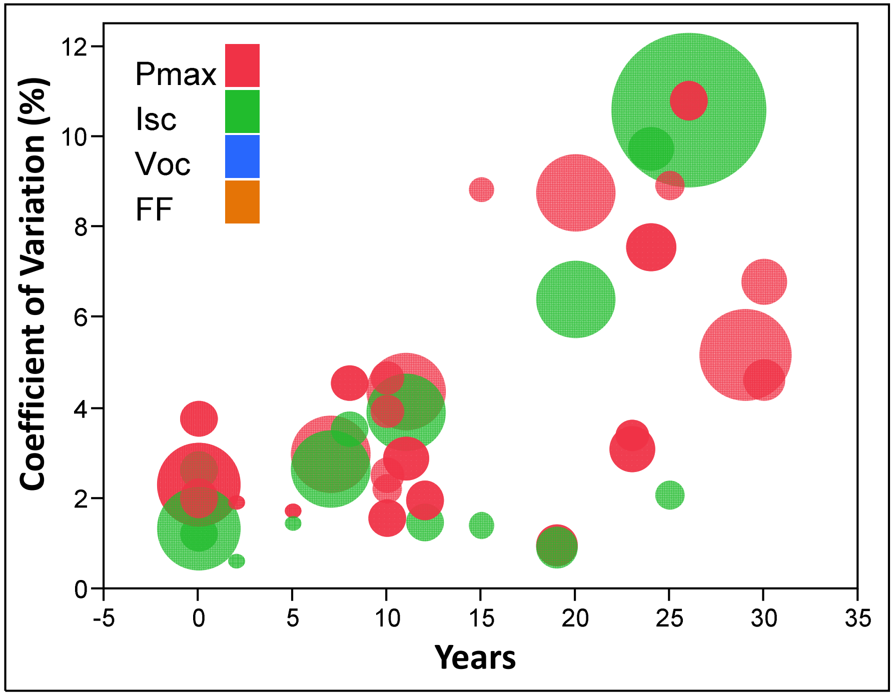

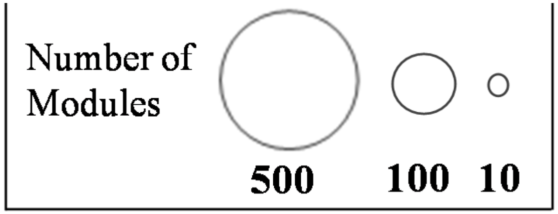

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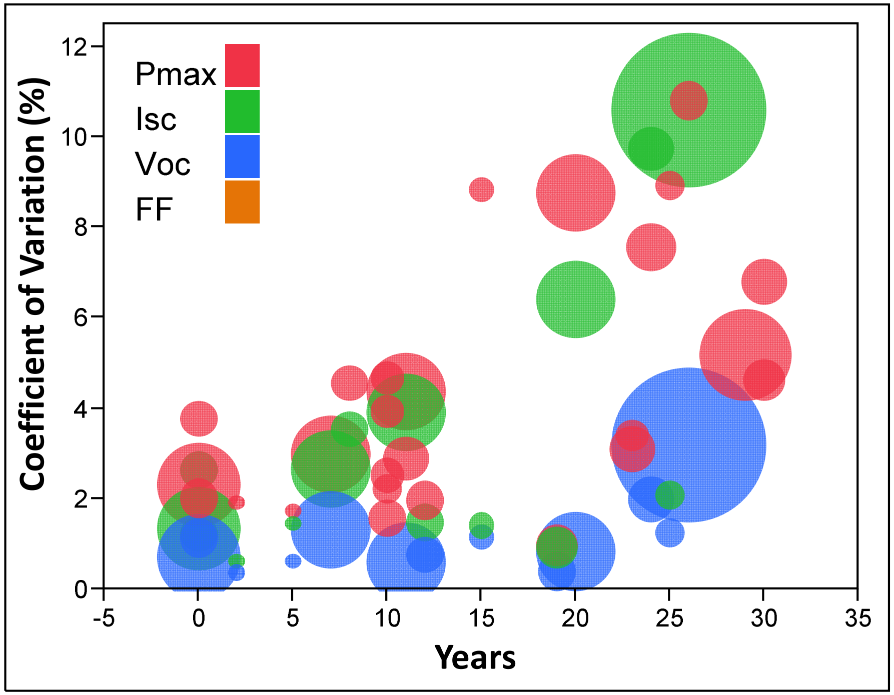

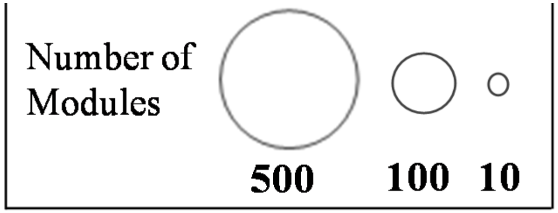

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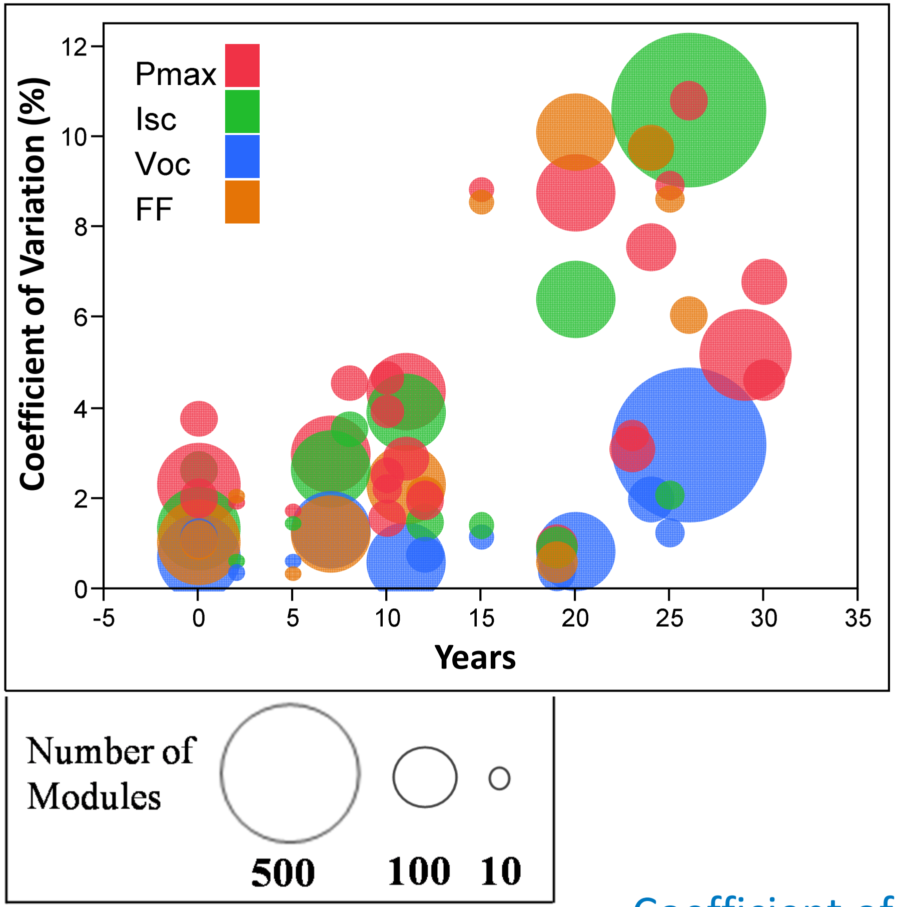

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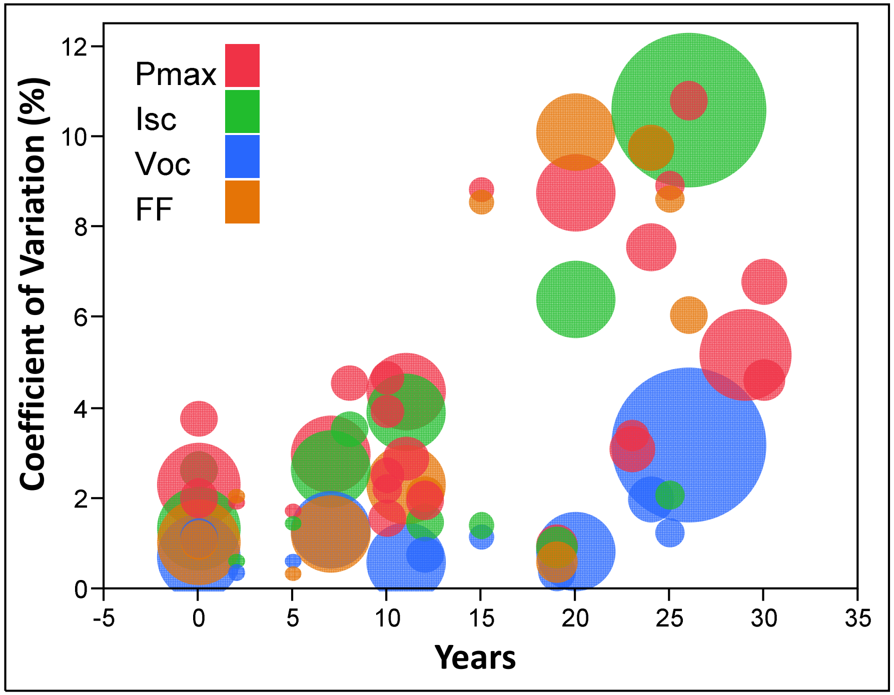
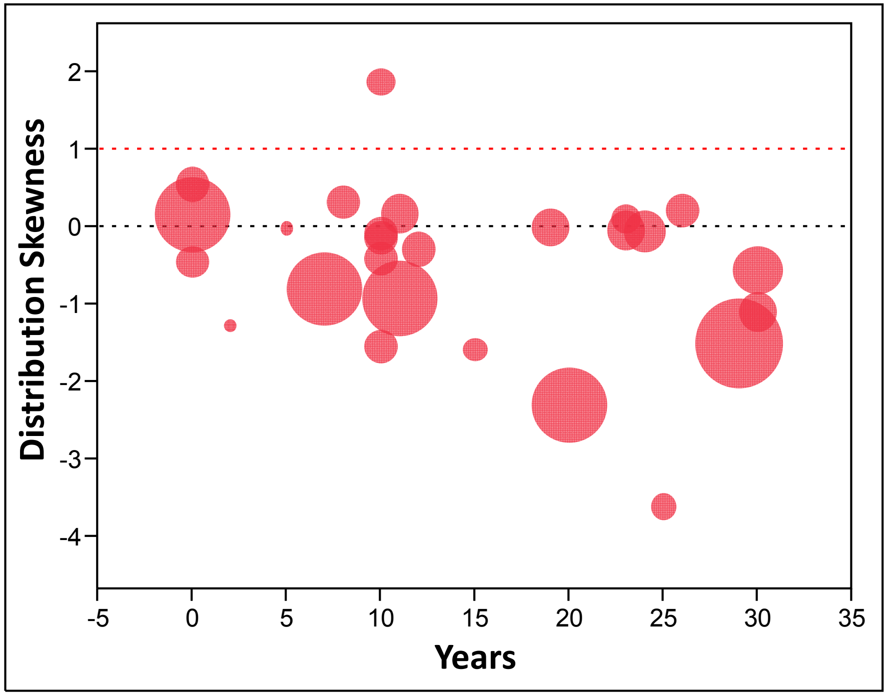
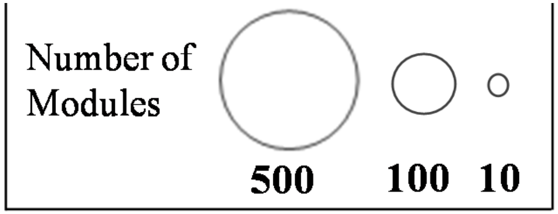


Distribution symmetry





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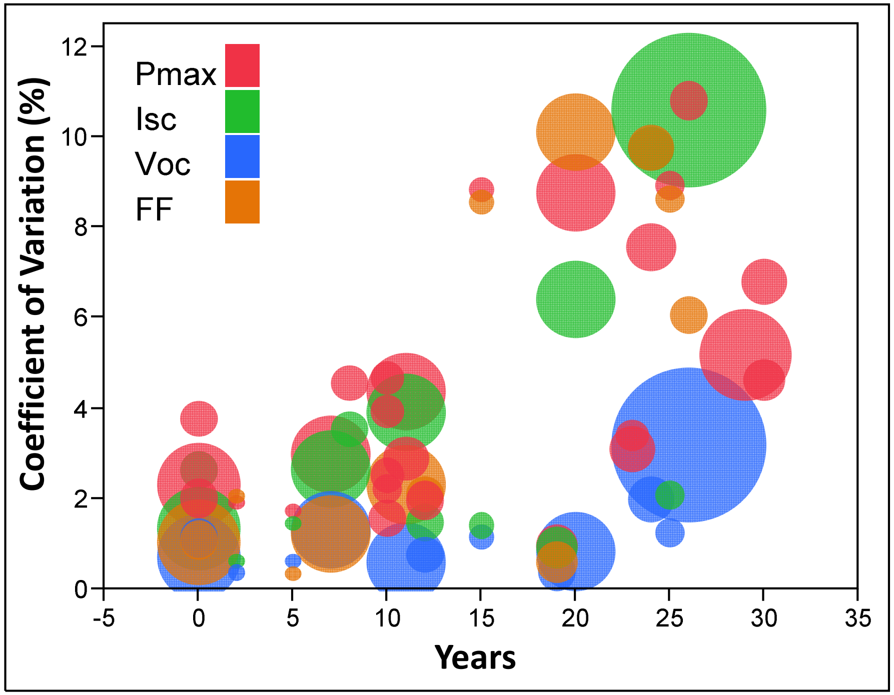

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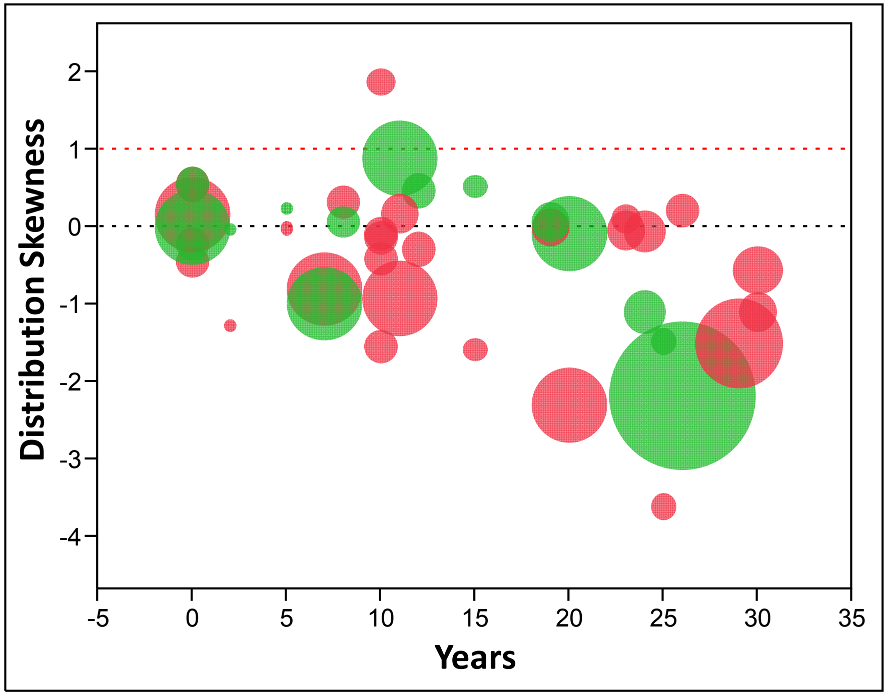

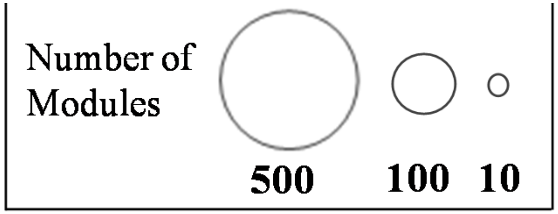

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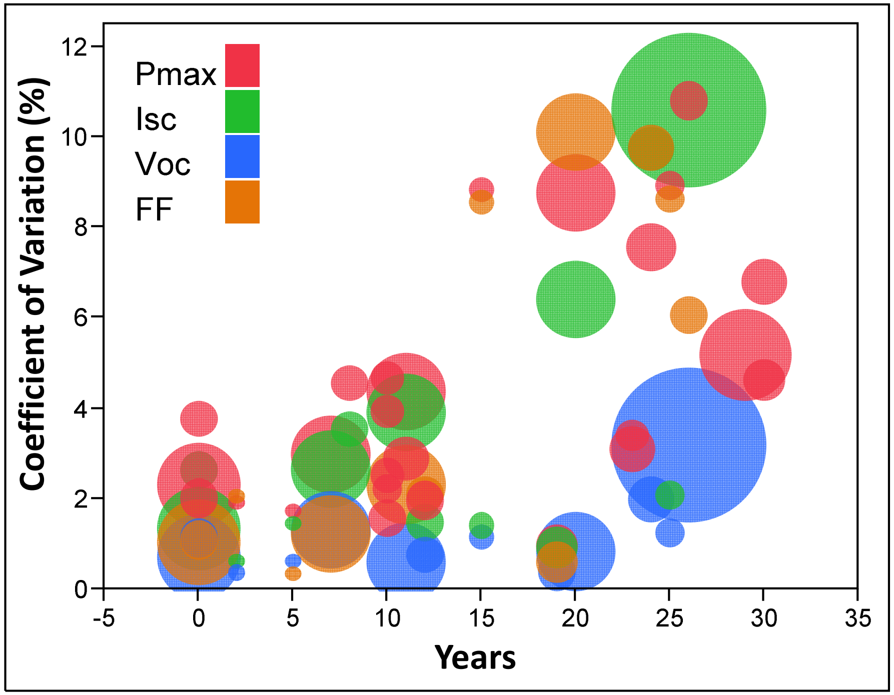

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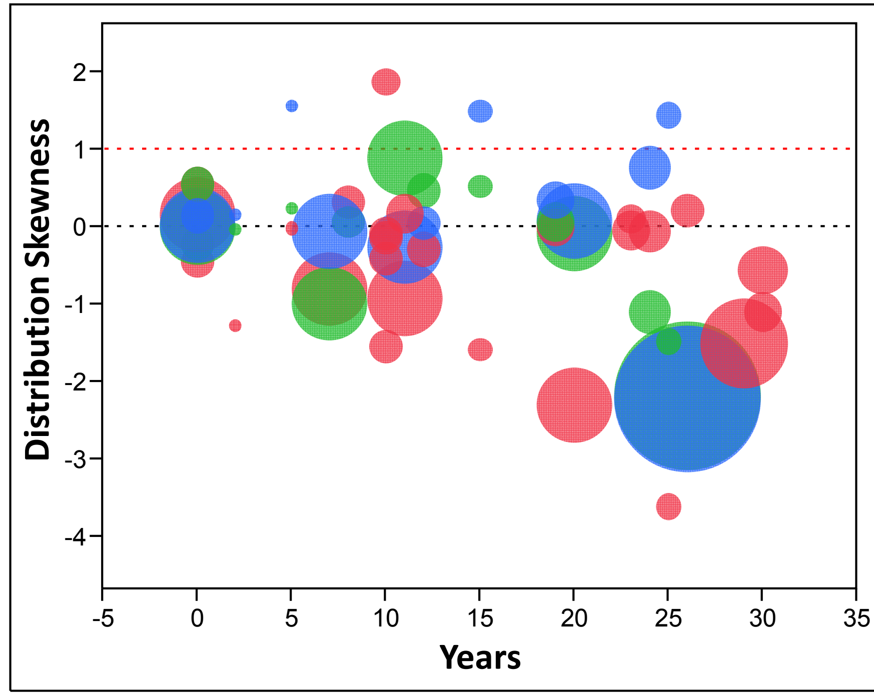

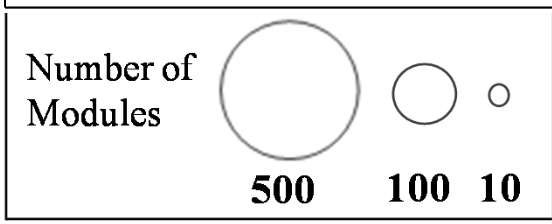

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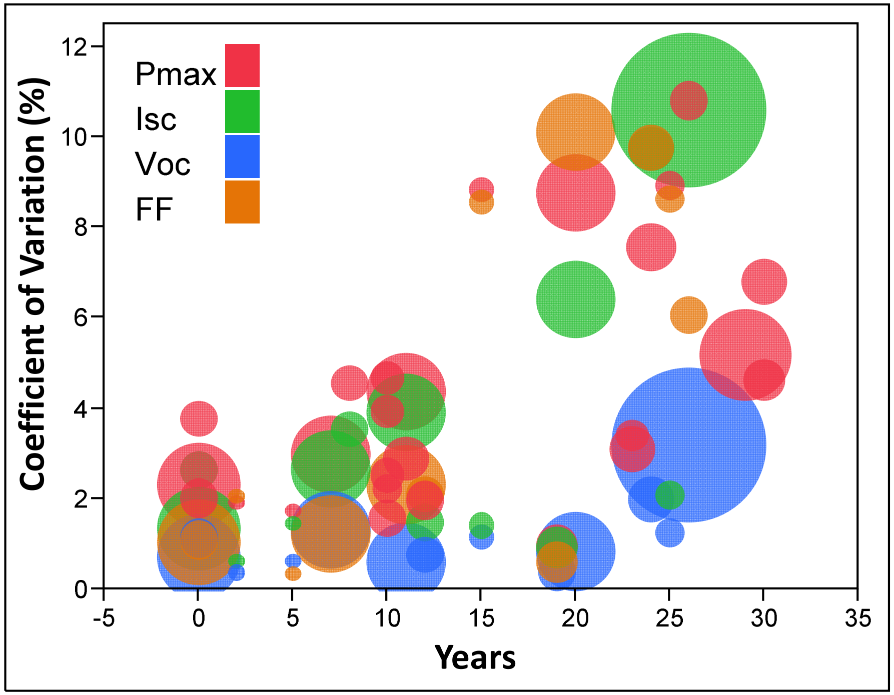

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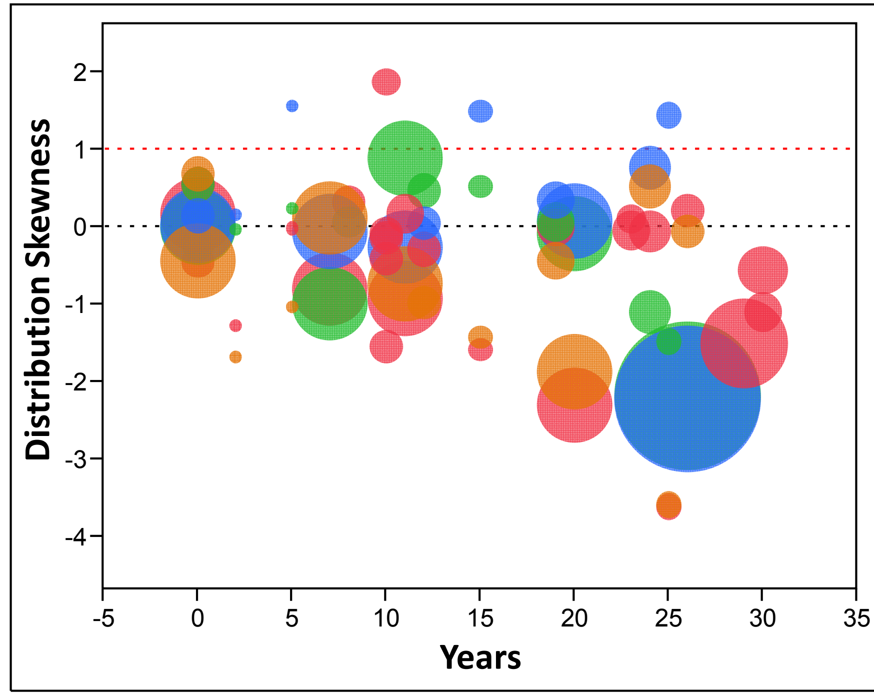

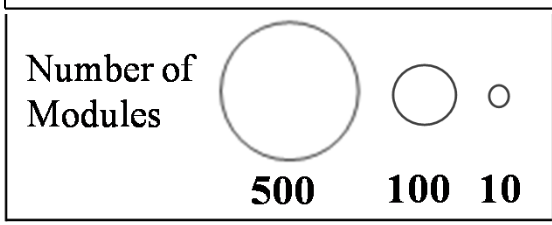

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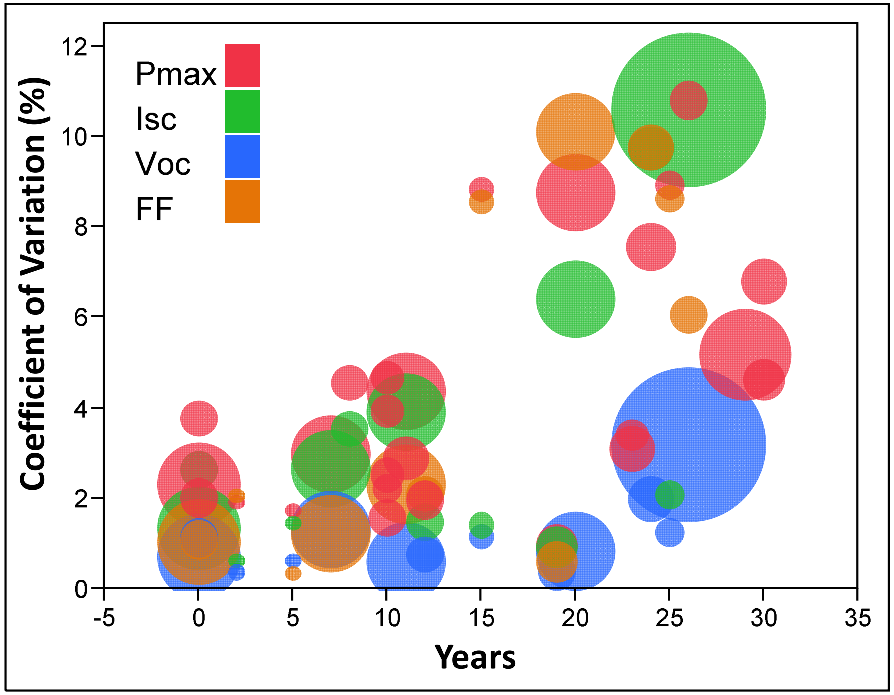

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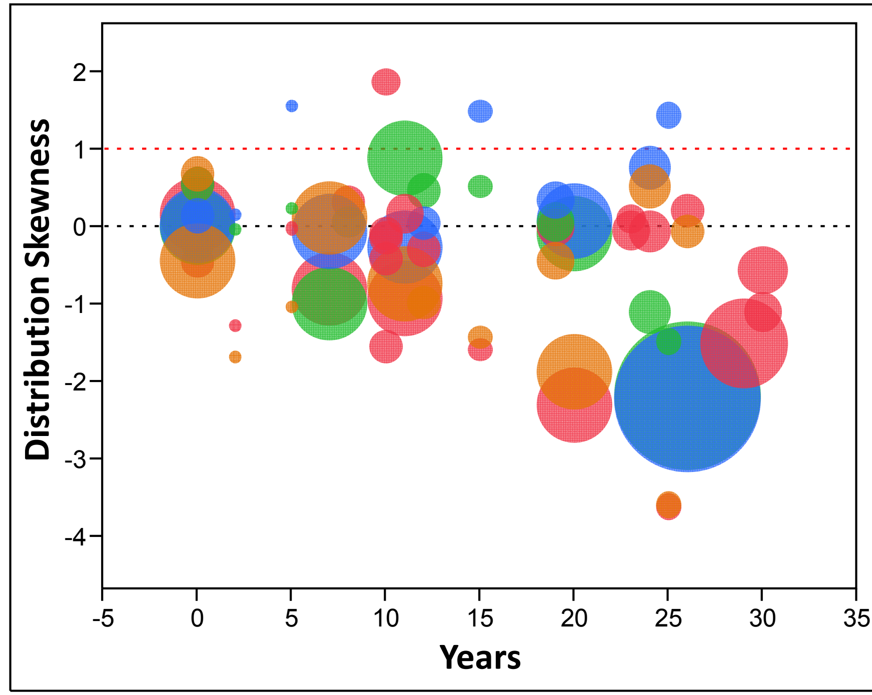

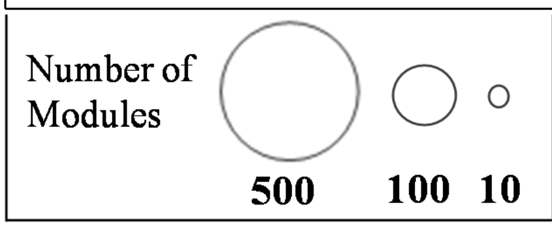

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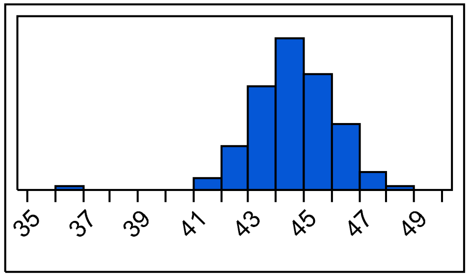
Distributions widen and skew with field exposure

I-V Distributions

Israel – 1995 – 7 years



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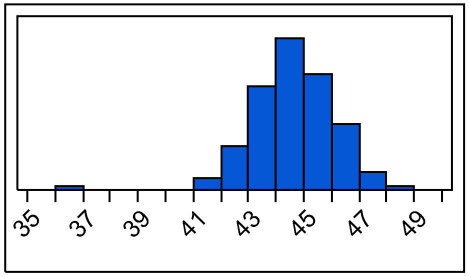
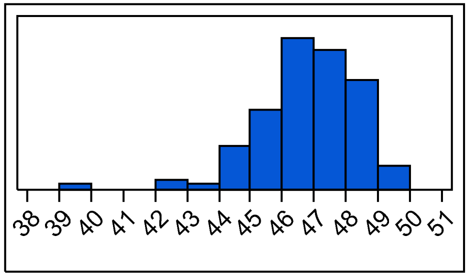


Japan – 2003 – 10 years



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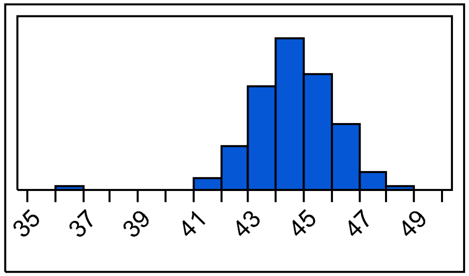

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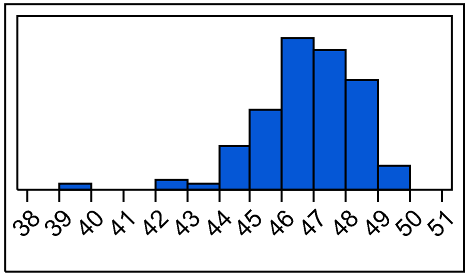
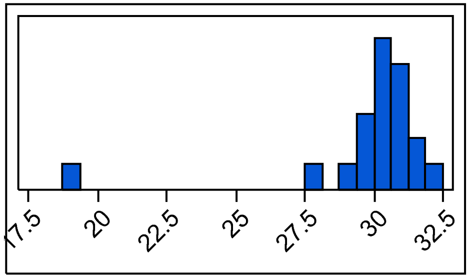
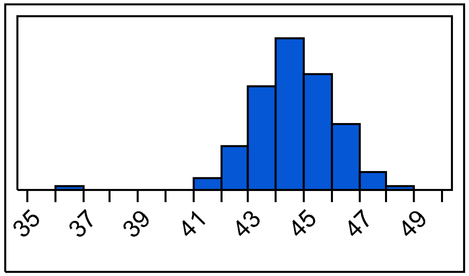


Sweden – 2006 – 25 years

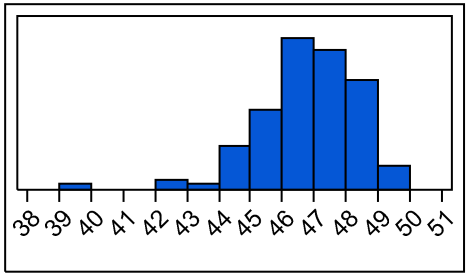


I-V Distributions

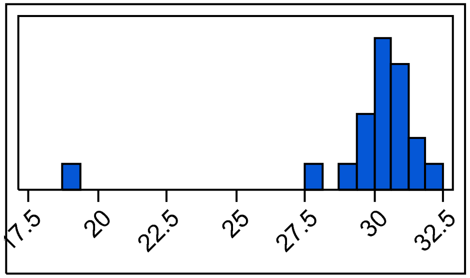
Israel – 1995 – 7 years



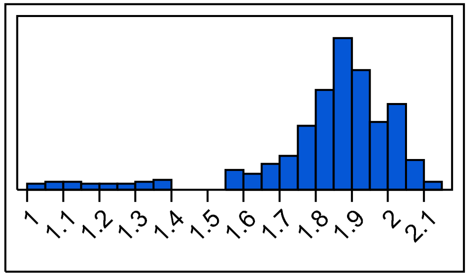
Japan – 2003 – 10 years



Sweden – 2006 – 25 years



Tunisia – 2008 – 25 years



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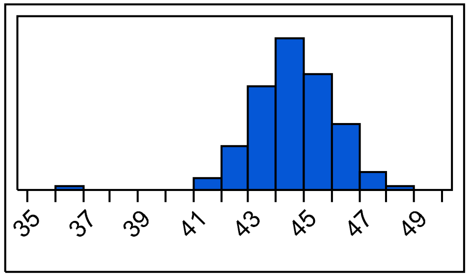

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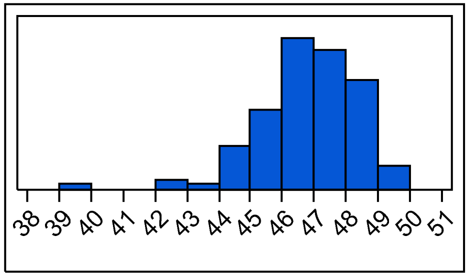

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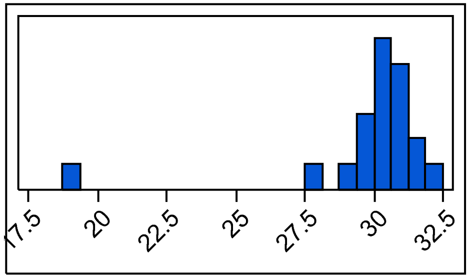
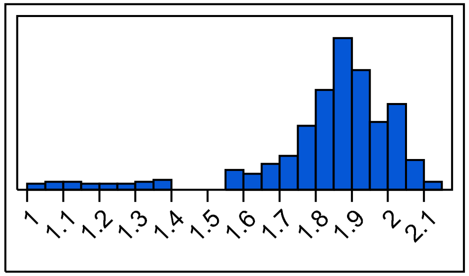
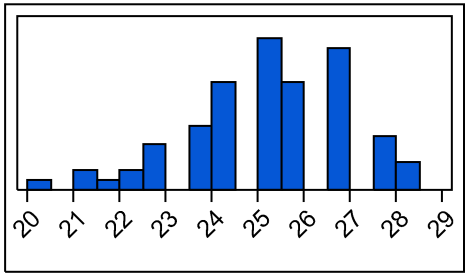


Tunisia – 2008 – 25 years



MA – 2010 – 30 years



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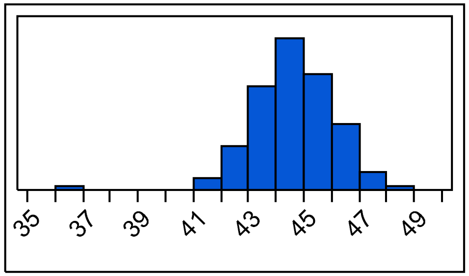

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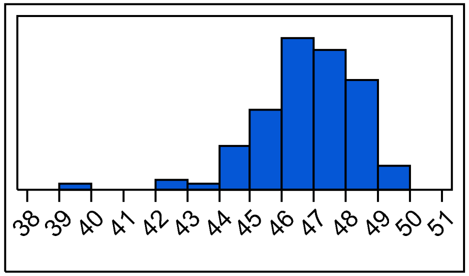

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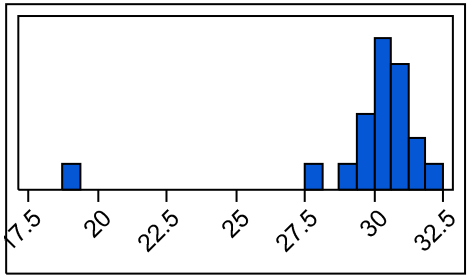

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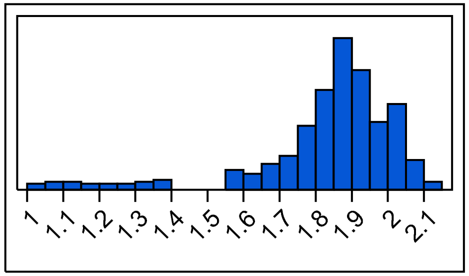

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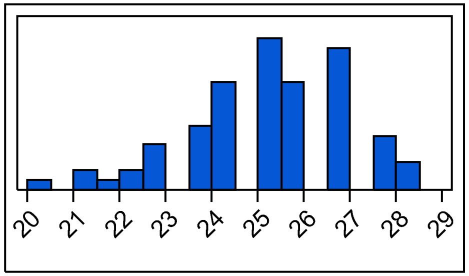
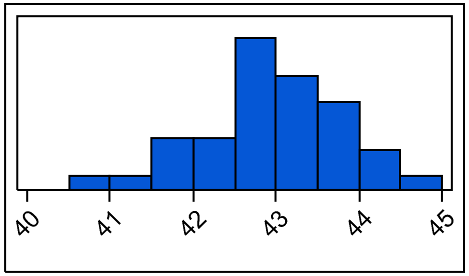


Spain – 2011 – 12 years



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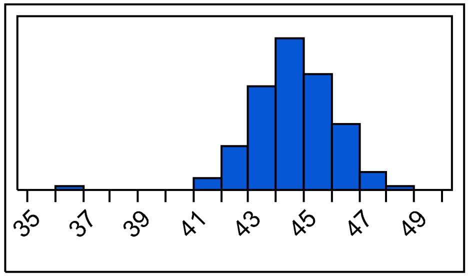

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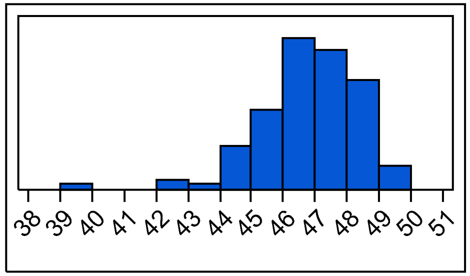
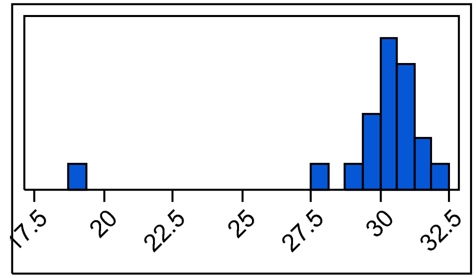
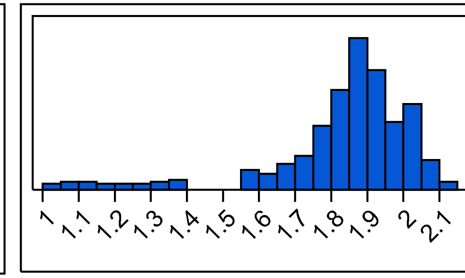


Sweden – 2006 – 25 years



Tunisia – 2008 – 25 years



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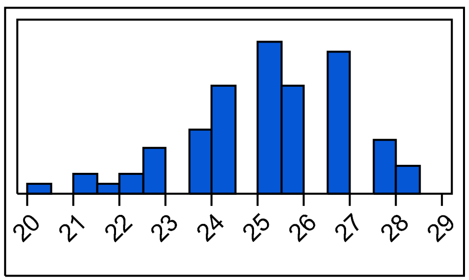
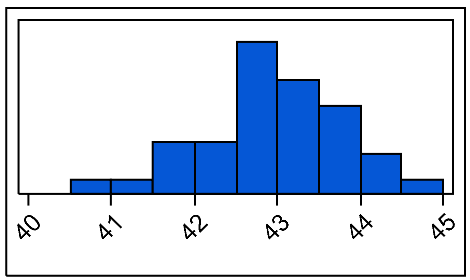
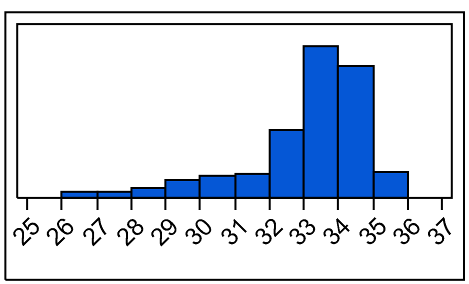


Spain – 2011 – 12 years



Switzerland – 2010 -20 years



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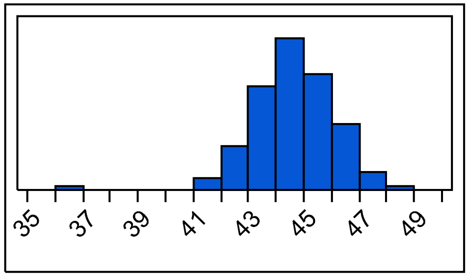
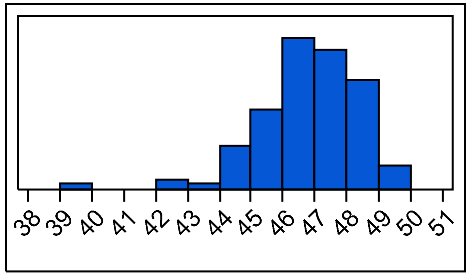
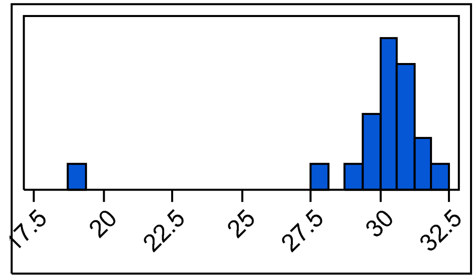


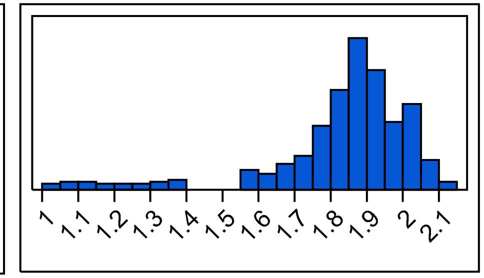
Japan – 2003 – 10 years



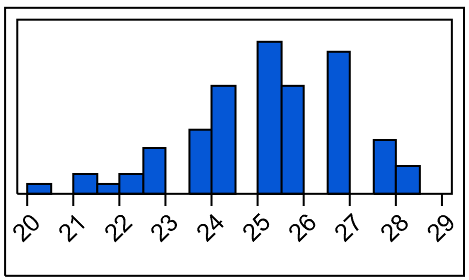
Sweden – 2006 – 25 years



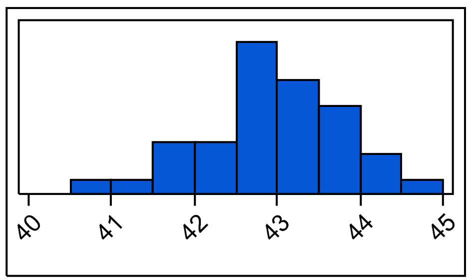
Tunisia – 2008 – 25 years



MA – 2010 – 30 years



Spain – 2011 – 12 years



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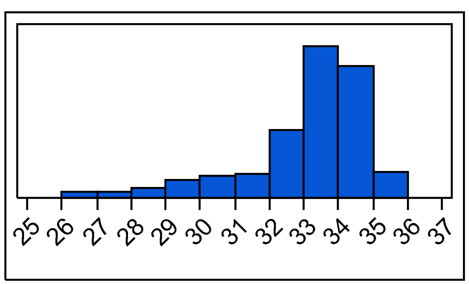
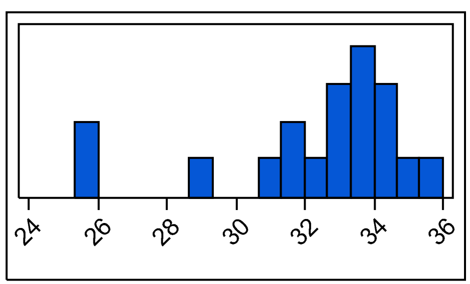


CO – 2012 – 15 years



I-V Distributions

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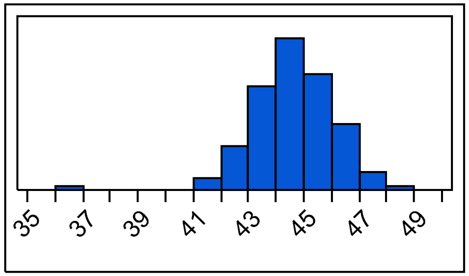
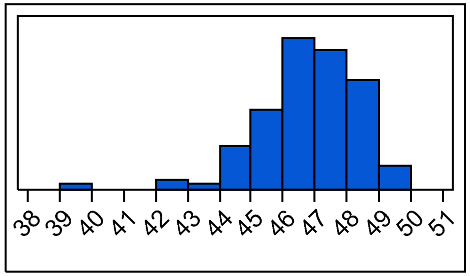


Japan – 2003 – 10 years



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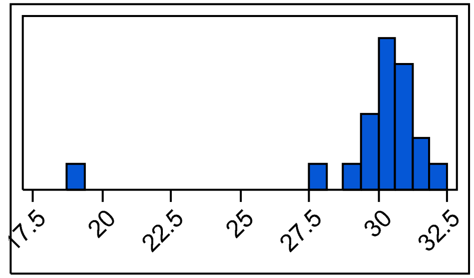
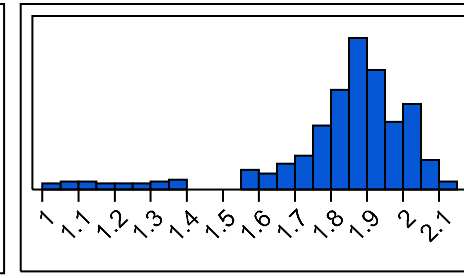


Tunisia – 2008 – 25 years



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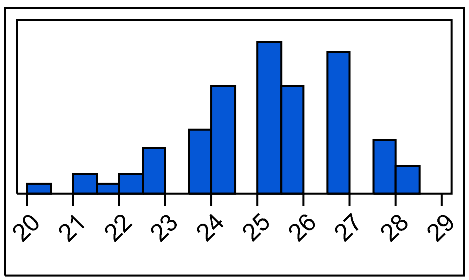
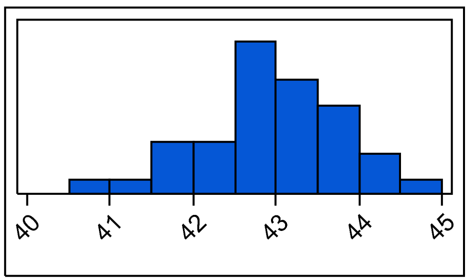
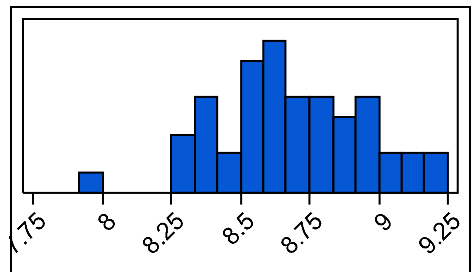
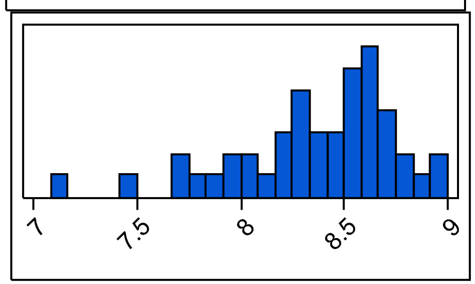


Spain – 2011 – 12 years

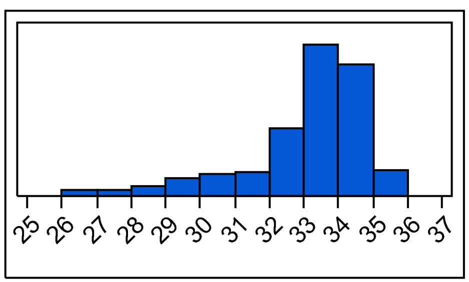


Italy – 2010 –
23 & 30 years

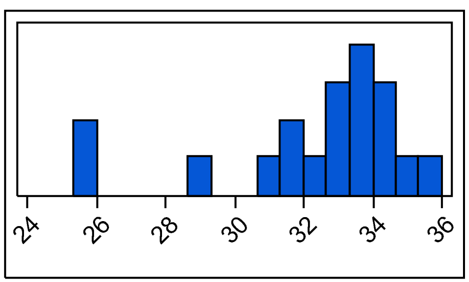




Switzerland – 2010 -20 years

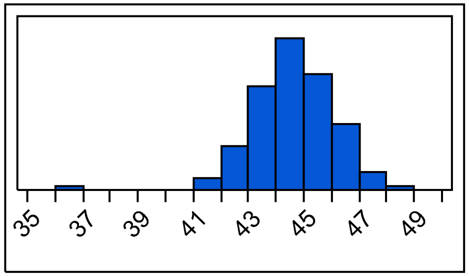


CO – 2012 – 15 years



I-V Distributions

Israel – 1995 – 7 years



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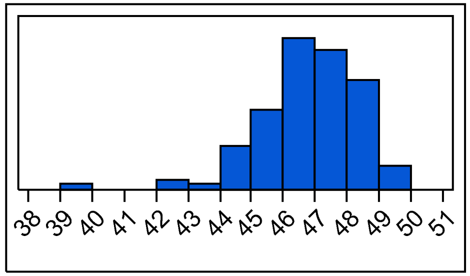

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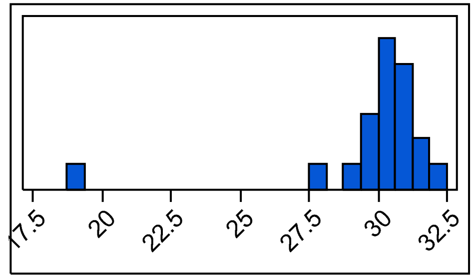
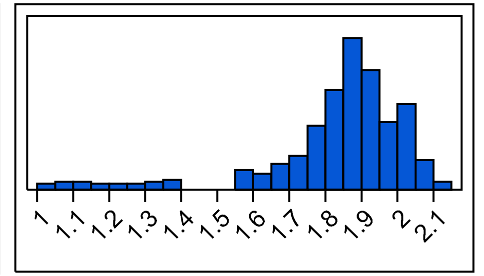


Tunisia – 2008 – 25 years



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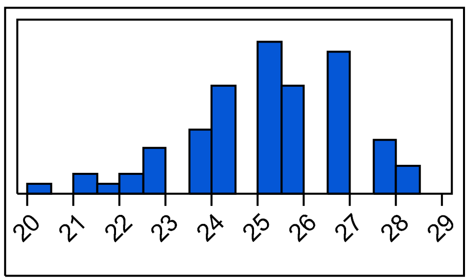
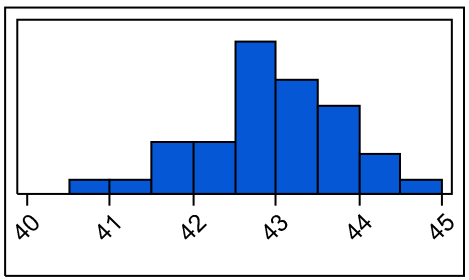
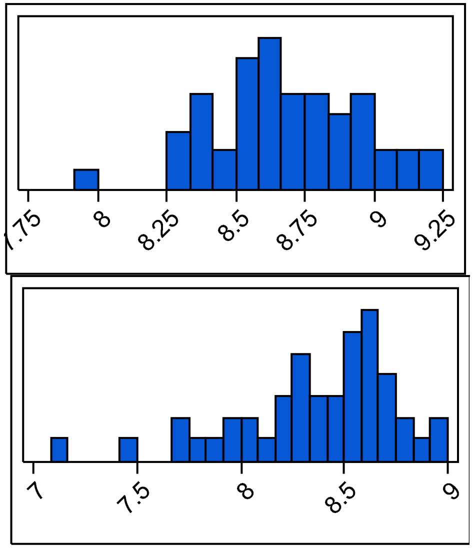


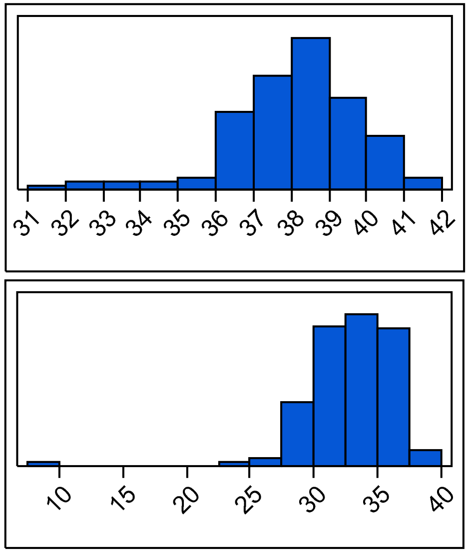
Spain – 2011 – 12 years



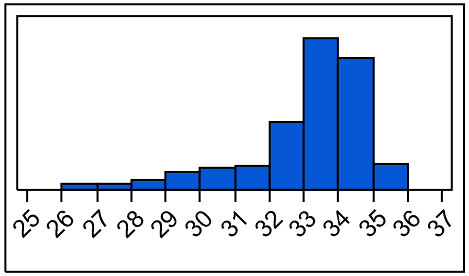
Italy – 2010 –
23 & 30 years



CA – 2011 –
11 & 20 years



Switzerland – 2010 -20 years



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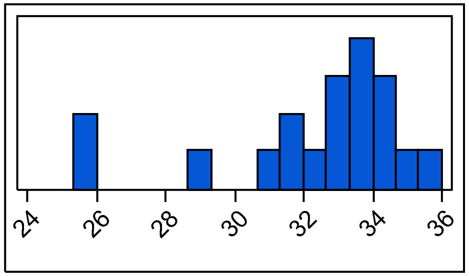

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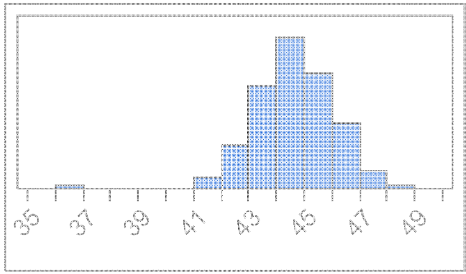

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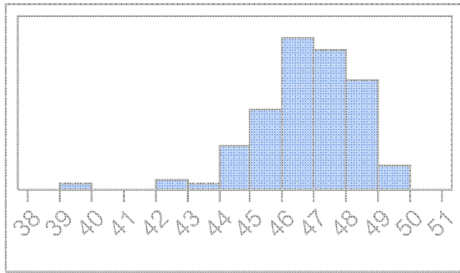

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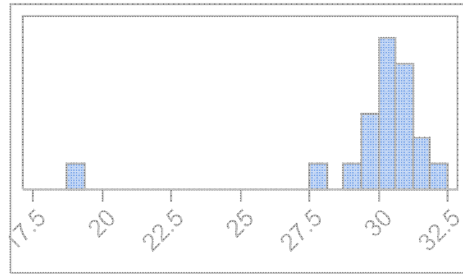

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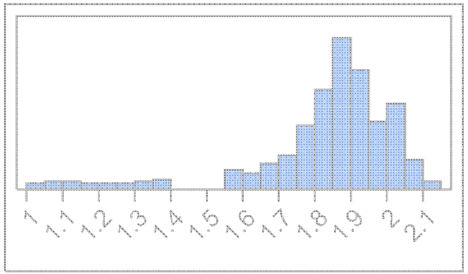

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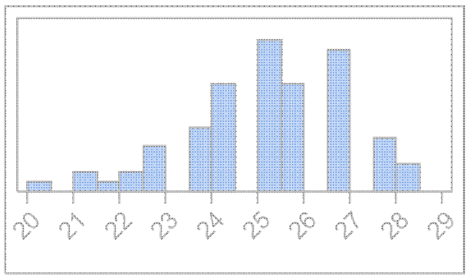

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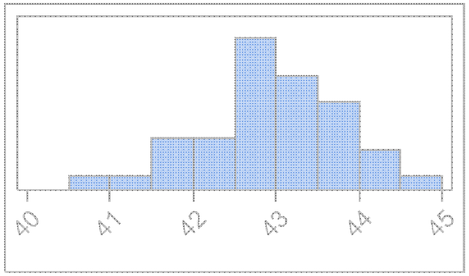

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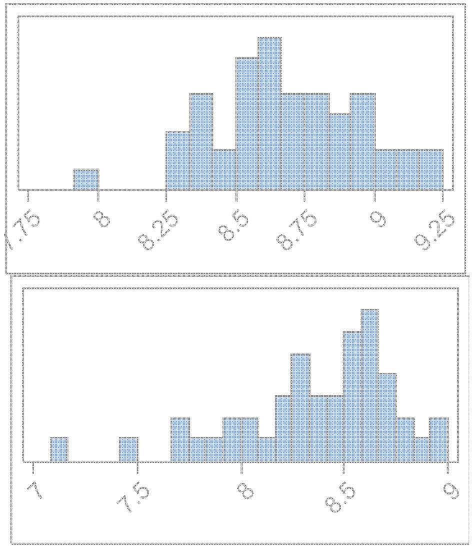

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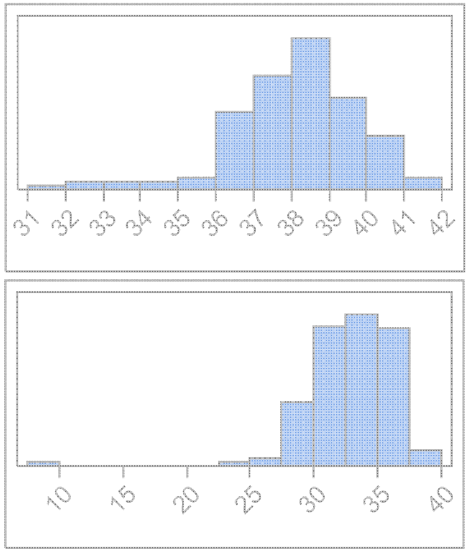

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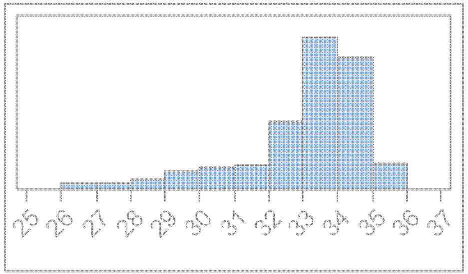

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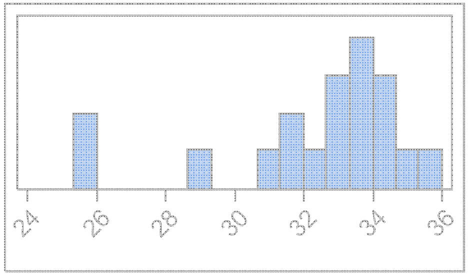

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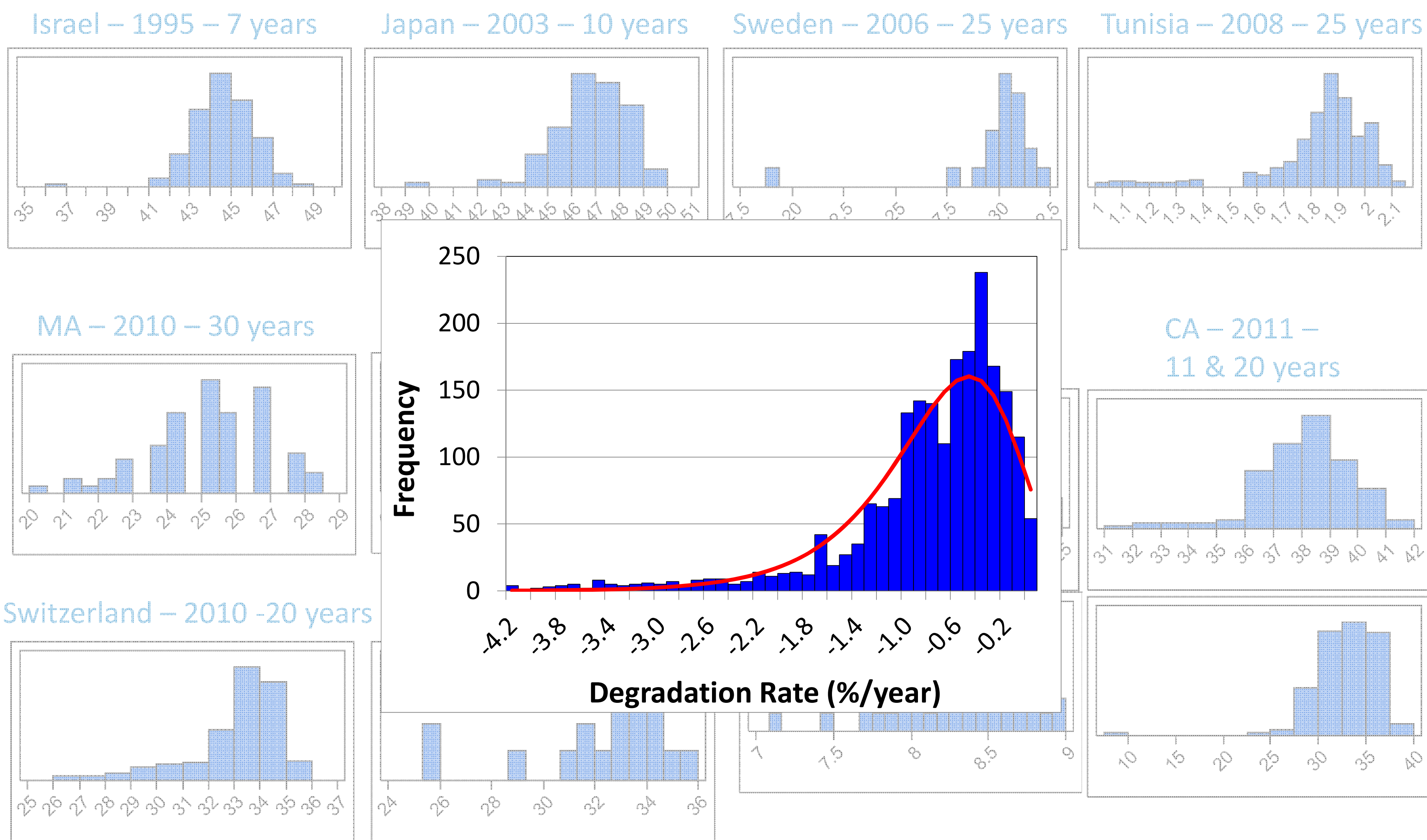

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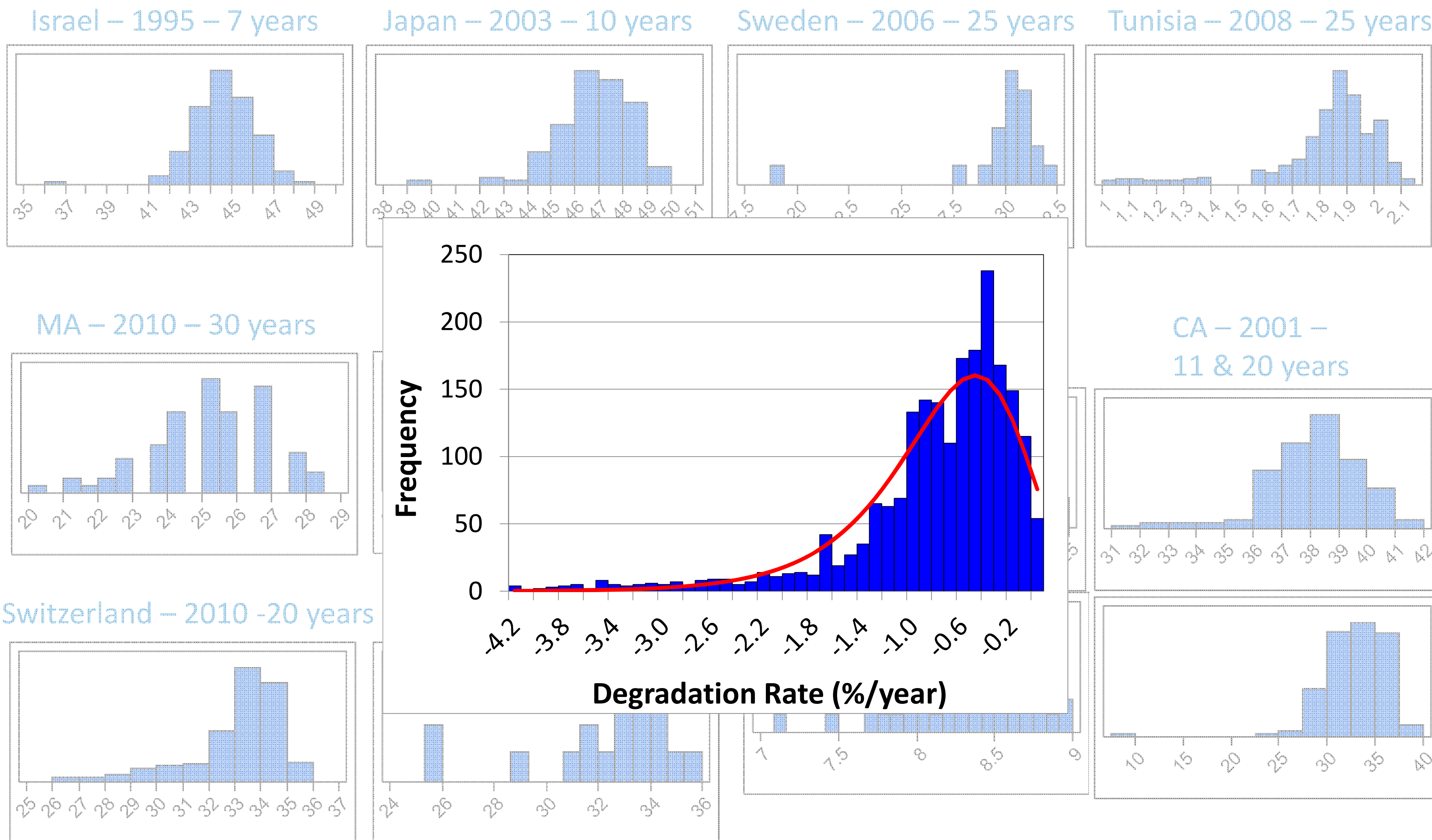


Module Parameter Distributions similar to R_d Distribution

Module Failure Mechanisms

TABLE 1
Common Failure Modes for Crystalline Silicon Modules

Failure Modes
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"

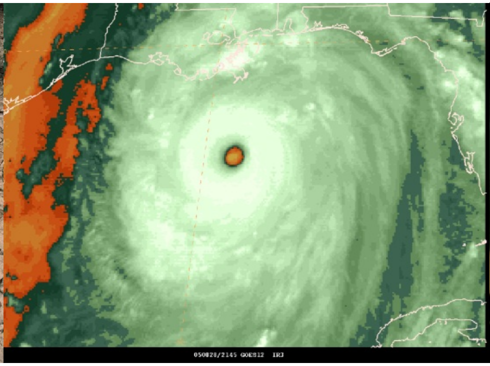
Module may be modeled by Extreme Value Distribution

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

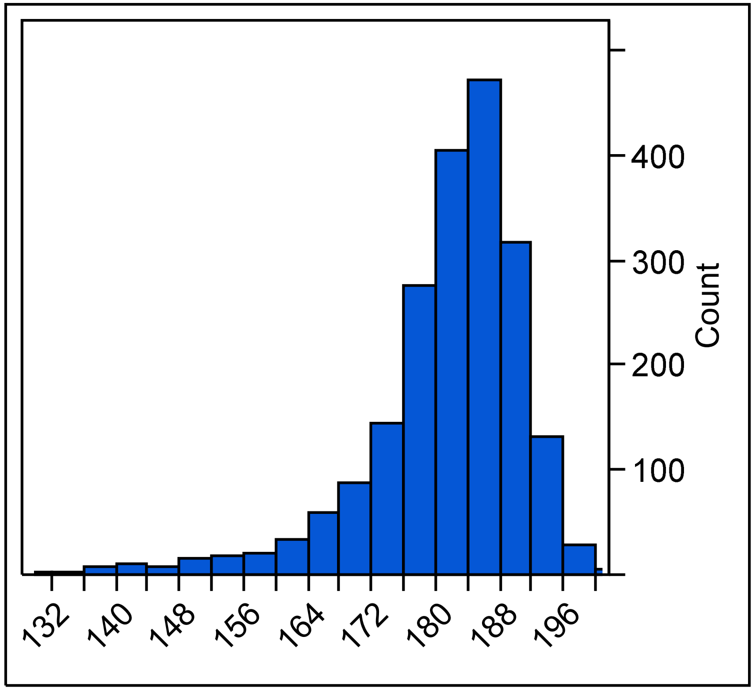
Photos from University Corporation for Atmospheric Research

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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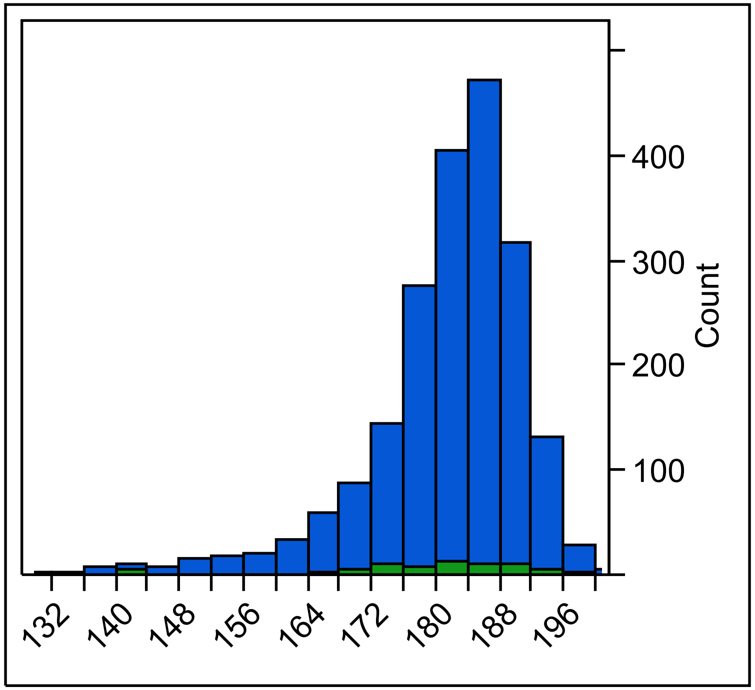

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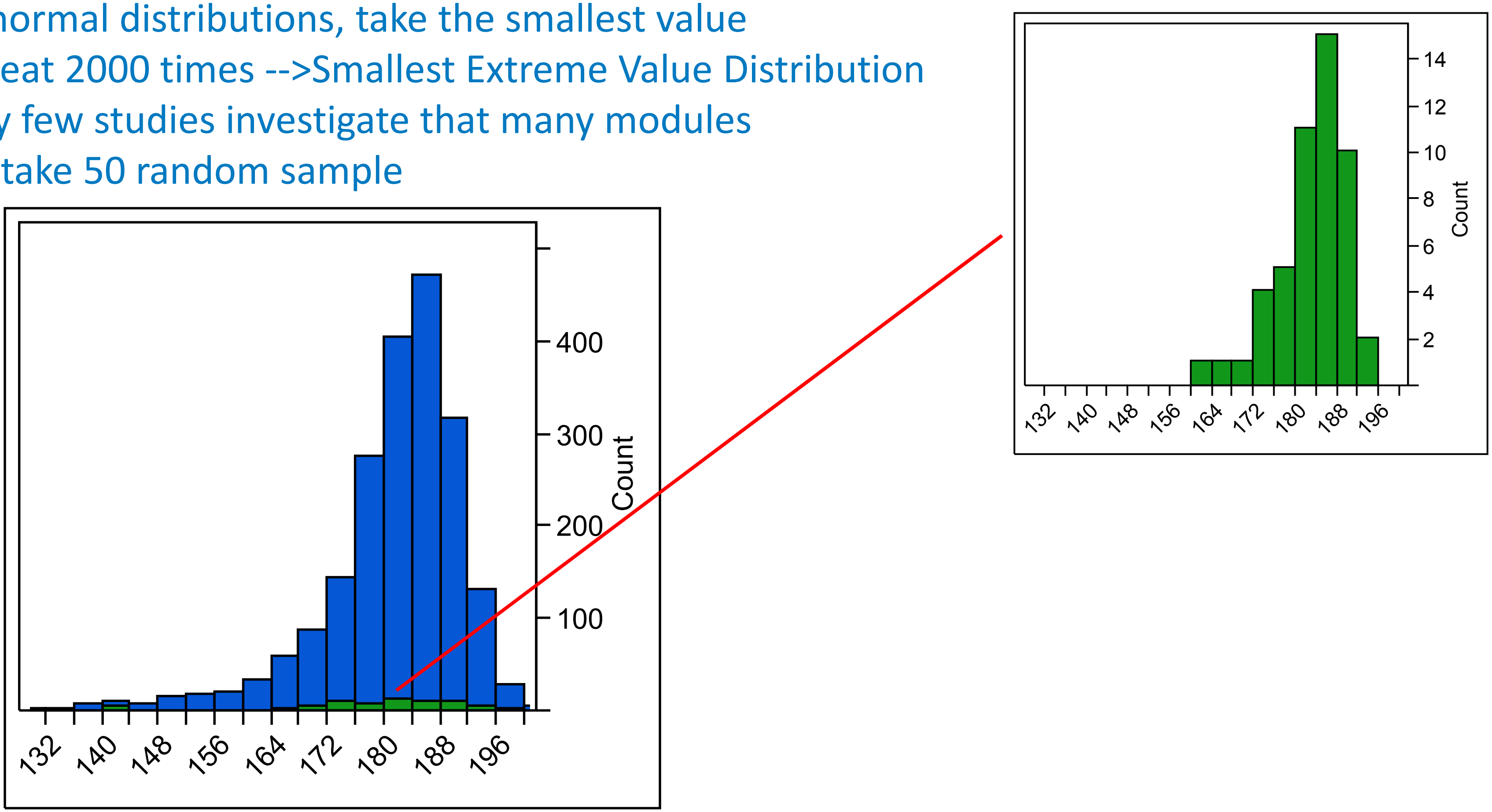
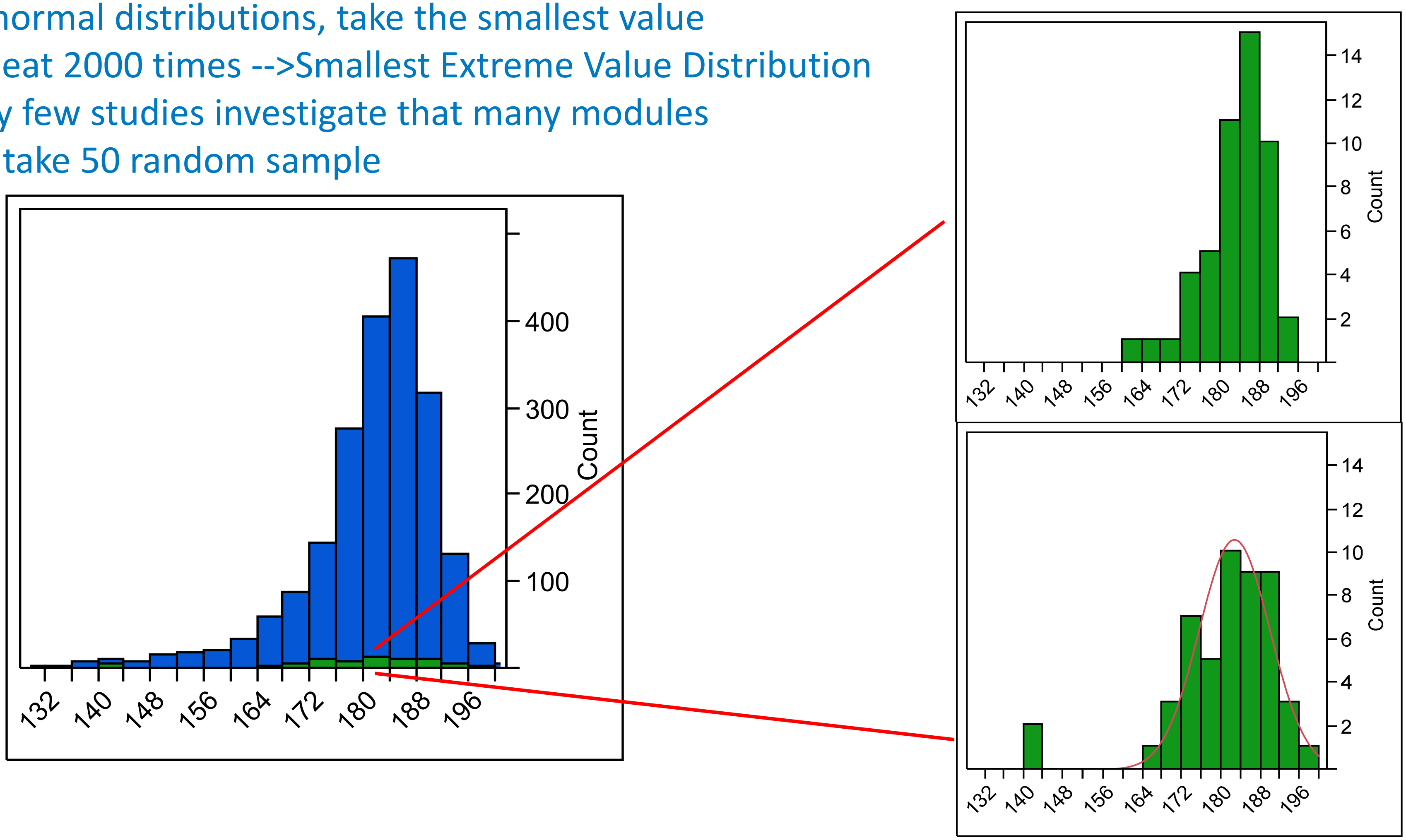


System Performance

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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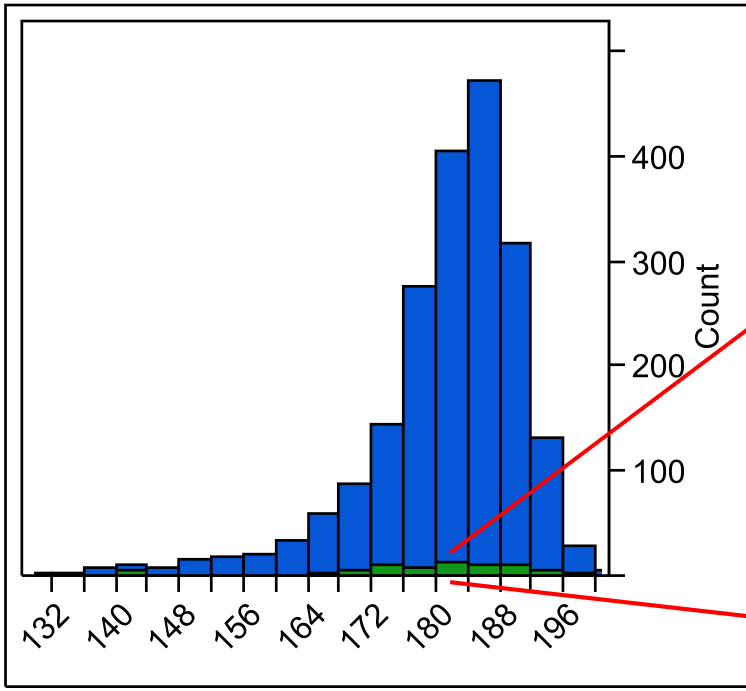
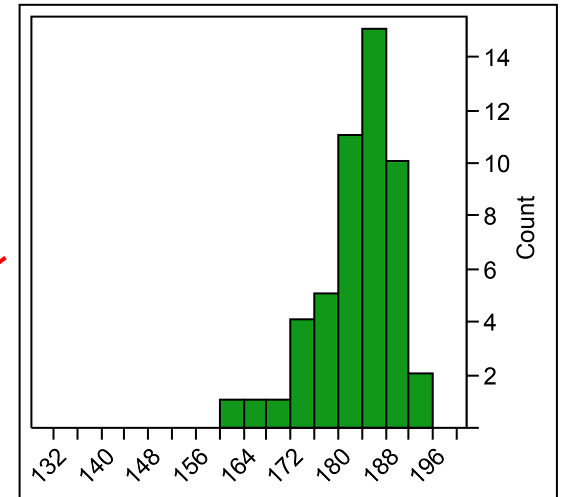
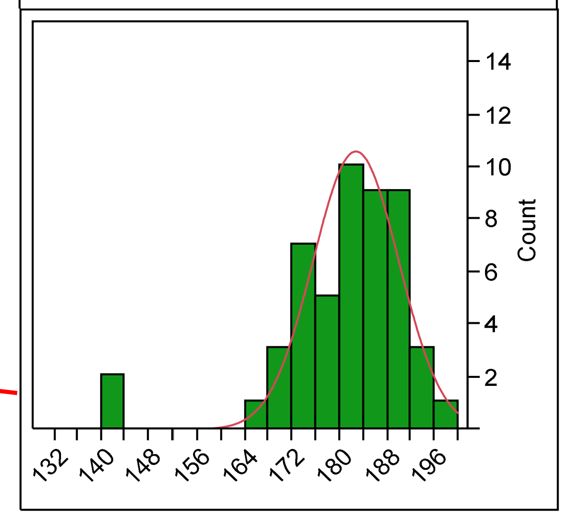


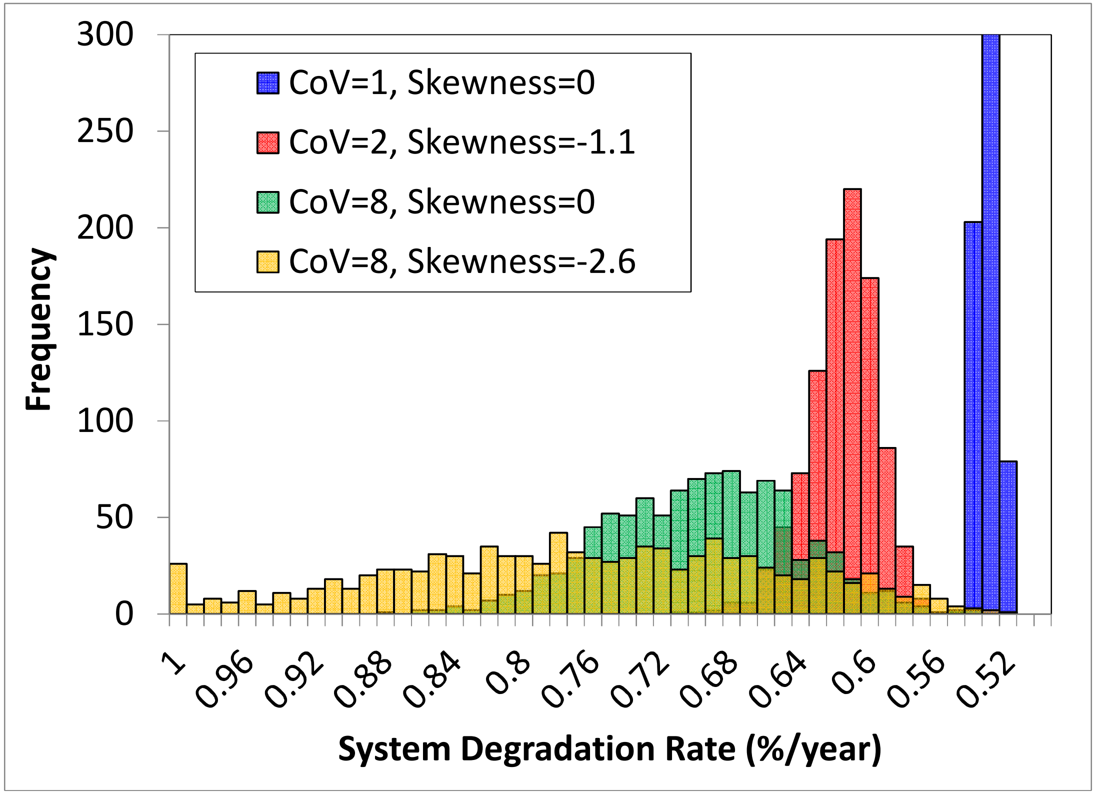




Outlier may be indicative of skewed distribution
Takes sufficient field exposure & sample size to see it

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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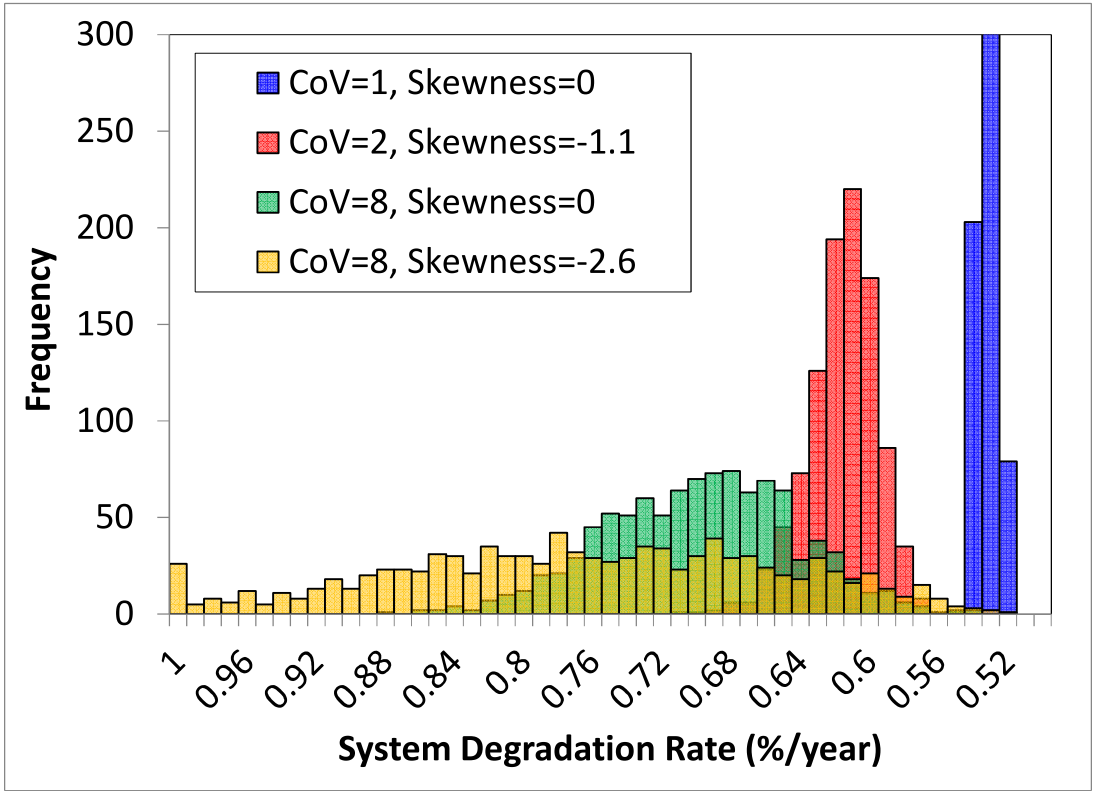

Distribution of module degradation affects system degradation

Summary

1. **Individual trends**
   - c-Si Pmax decline is most strongly correlated with Isc , 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

Vielen Dank für Ihre Aufmerksamkeit

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