Outline

- Introduction
  - I-V parameter degradation analysis
  - I-V parameter distribution
  - Climatic trends
- Conclusion
Introduction - Degradation Rates ($R_d$)

$R_d$ (Module 1) = 0.8 %/year
$R_d$ (Module 2) = 0.8 %/year
Introduction- Degradation Rates ($R_d$)

2 modules: Different observation lengths, seasonality etc.

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

NREL – Outdoor Test Facility

Photo by Warren Gretz, NREL/PIX 03877
Introduction- Degradation Rates ($R_d$)

NREL – Outdoor Test Facility

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\textsubscript{D} Uncertainty Impact on Warranty

Maximum module warranty - 2010

Monte Carlo Simulation for year 25

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

Source: Photon International, Feb 2010

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

Need to determine R\textsubscript{d} \textit{accurately}
Degradation Rates – Literature Survey

Number of Degradation rates ($R_d$) from literature: 2128

Median: 0.5 %/year
Average: 0.8 %/year
# reported rates = 2128

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

Most modules degrade by ca. 0.5 %/year

Literature Degradation Rates

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

> 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 Rd
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

Degradation Rate (%/year)

Pmax 639 632 591 584
Isc
Voc
FF
IV Parameter

Degradation Rate (%/year)

Pmax 476 475 473 397
Isc
Voc
FF
IV Parameter
I-V Parameters by Technology

**Mono-Si**

- Pmax: 639
- Isc: 632
- Voc: 591
- FF: 584

**Multi-Si**

- Pmax: 476
- Isc: 475
- Voc: 473
- FF: 397

NREL study – May 2012 – World Renewable Energy Forum

- Pmax correlated to Isc loss
- 9/12 modules

- Pmax correlated to FF loss
- 3/12 modules

Smith et al., World Renewable Energy Forum, May 2012
I-V Parameters by Technology

Mono-Si

Pmax correlated to Isc loss
9/12 modules

Multi-Si

Pmax correlated to FF loss
3/12 modules

Thin-film

NREL study – May 2012 – World Renewable Energy Forum

Smith et al., World Renewable Energy Forum, May 2012
I-V Parameters by Technology

**Mono-Si**

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<tr>
<th>Parameter</th>
<th>Degradation Rate (%/year)</th>
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**Multi-Si**

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**Thin-film**

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<td>Voc</td>
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<td>FF</td>
<td>33</td>
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</table>

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

Degradation for c-Si Isc; Thin-film FF
Climate Analysis

Based on Köppen-Geiger Classification

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<tr>
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</table>

Label within Climate Code1
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

- \( P_{\text{max}} \) most strongly correlated with \( I_{\text{sc}} \) losses
- \( I_{\text{sc}} \) losses: discoloration, soiling, delamination, light-induced degradation
- Majority of studies report discolor. & delam.
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\( P_{\text{max}} \) correlated with \( I_{\text{sc}} \) 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

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

Tail from study that showed high corrosion

Hot & Humid shows mixture of degradation
Hot & Humid by Decade

Decade 1

Decade 2

Decade 3

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

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

Different long-term performance recommendation based on climate


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

Color: I-V parameter
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Distribution width

Coefficient of Variation (CoV): Standard deviation/ Mean

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

Number of Modules: 500, 100, 10
Module I-V Distribution

Distribution width

Distribution symmetry

Coefficient of Variation (CoV): Standard deviation/ Mean

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

Number of Modules

500 100 10
Module I-V Distribution

Distribution width

Coefficient of Variation (%)

Years

Pmax
Isc
Voc
FF

Number of Modules
500 100 10

Distribution symmetry

Distribution Skewness

Years

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

Coefficient of Variation (CoV): Standard deviation/ Mean
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

Number of Modules

500 100 10
Module I-V Distribution

Distribution width

Distribution symmetry

Coefficient of Variation (CoV): Standard deviation/ Mean

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

Number of Modules

500 100 10
Module I-V Distribution

Distributions widen and skew with field exposure
I-V Distributions

Israel – 1995 – 7 years
I-V Distributions

Israel – 1995 – 7 years

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

Module Parameter Distributions similar to $R_d$ Distribution
Module Failure Mechanisms

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

Wohlgemuth et al., IEEE International Reliability Physics Symposium, Monterey, CA, USA, 2011.
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
10 normal distributions, take the smallest value
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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

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
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
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.
Thank you for your attention

Vielen Dank für Ihre Aufmerksamkeit

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