Solar PV Module Durability Testing

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Presentation Outline

- Difference between durability and reliability
- Importance of durability
- Outdoor durability evaluation
- Indoor durability evaluation
- Summary
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• Difference between durability and reliability
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• Indoor durability evaluation
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Difference between durability and reliability
kWh is dictated by durability loss and reliability loss

Durability loss = Degradation rate below warranty rate

Reliability loss = Degradation rate above warranty rate

Note: Safety failed modules shall be replaced and these modules should be excluded from the degradation rate calculations
Possible degradation trends

A.W. Czanderna and G.J. Jorgensen; *Presented at Photovoltaics for the 21st Century Seattle, Washington, May 4, 1999*
Both durability & reliability issues: A hypothetical representation

Practical implication of these issues for stakeholders:

- Higher $/kWh
- Not bankable (high risk premium rate and O&M insurance backup!)

Source: ASU-PRL (Solar ABCs report)
Both durability & reliability issues: A hypothetical representation

- Solder bond fatigue
- EVA discoloring
- Delamination, cracked cell isolation
- PID
- Diode failure
- Cell interconnect breakage
- Corrosion of cell & interconnect
- LID 0.5-5%
- Glass AR deg.
- Contact failure j-box/string interconnect
- Glass breakage
- Loose frame

Source: IEA-PVPS-2014
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Importance of durability
Goal of project developers:
Securing low interest bank loan with no risk premium adders

Interest Rate = Interest Rate @ Zero Risk + Risk Premium Rate

Failures and Losses:
Three risk premium adders on the loan interest

Safety Failures:
Obsolete (irrespective of DR*)
100% risk premium adder

Reliability Failures:
Under-performance (>1%/year DR)
1%-100% risk premium adder

Durability Loss:
Better-performance (<1%/year DR)
0% risk premium adder

Note: The typical 20/20 warranty is assumed in the above example.

*DR = Degradation Rate
Reliability evaluation: Importance to stakeholders

To decrease levelized cost of energy (\$/kWh) by decreasing \"$/kW\" value and increasing \"h\" value.

Technical Levelized Cost of Energy (T-LCOE) of PV Module
\[ \$\text{/kWh} = \text{Bankability} \]

\text{Performance} \quad \text{Safety, Reliability and Durability}

\$\text{/kW} \quad h

\text{\textcolor{red}{\$/kW}} \text{dictated by:}
- \text{Material cost ($)}: \text{Materials and process cost per unit area}
- \text{Device Quality (kW)}: \text{Module efficiency per unit area}

\text{\textcolor{red}{h}} \text{dictated by:}
- \text{Packaging / Design Quality: Safety failures (SF) over time (obsolete)}
- \text{Manufacturing Quality: Reliability failures (RF) over time (under-performance; >1%/year degradation)}
- \text{Material Quality: Durability / Degradation loss (DL) over time (better-performance; <1%/year degradation)}

\text{SF = Safety Failure (Qualifies for safety returns); Identified by: Visual inspection, IR and Circuit/diode checker}
\text{RF = Reliability Failure (Qualifies for warranty claims); Identified by: I-V}
\text{DL = Durability Loss (Does not qualify for warranty claims); Identified by: I-V}

Source: ASU-PRL
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Outdoor durability evaluation
METRIC/NUMERIC Definition of Failures and Degradation

- Defects (D)
- Safety Issues
- Safety Failure (SF)
- Reliability Failure (RF)
- Durability Loss (DL)

DR = Degradation Rate

SF = Safety Failure (100% risk; Qualifies for safety returns;)
RF = Reliability Failure (1-100% risk proportional to DR; Qualifies for warranty claims)
DL = Durability Loss (0% risk; Does not qualify for warranty claims)
Field Evaluation of PV Modules:
Application of ASU-PRL’s Definitions on Field Failures and Degradation Determinations

Review:
Module Construction, Full I-V curves (STC and LowEs), Previous Reports, System Layout, Metered kWh and Weather Data

Visual Inspection:
All modules per NREL checklist

Inverter Ground Fault Events:
All safety failed strings

Thermal Imaging:
All modules

I-V & Megger Tests:
All hotspot modules

Diode/Circuit Test:
All modules

I-V Test and SunEye:
All strings (before cleaning)

I-V Test:
All modules in three best, worst and median strings (before cleaning)

I-V Test:
All diode-failed modules

I-V Test:
All strings (before cleaning)

I-V Test
(1000, 800 and 200 W/m²):
Three best modules from the best strings (after cleaning)

PID Check:
All modules in the best strings (after cleaning)

Cell-Crack Test:
All modules in the best strings (after cleaning)

Safety and Reliability Evaluation
Primary Goal: Identification of Safety Failures (SF) and Reliability Failures (RF)

Durability and Reliability Evaluation
Primary Goal: Identification of degradation rates (DR)
[Reliability Failure (RF) = if DR>1%/y; Durability Loss (DL)= if DR<1%/y)]
Defects (mono-Si; glass/polymer)

Defects with safety issues are identified on the plot. Other defects shown on the plot are classified as either RF or DL depending on degradation rates.
Examples of Safety Failures

12 Years – 1-axis Tracker

Hotspot leading to backsheet burning (along the busbars)

Ribbon-ribbon solder bond failure (with backsheet burning)

Failed Diodes (with no backsheet burning)

Backsheet Delamination (frameless modules)
Mapping of Safety Failures (Model G – Site 3)  

Framed - 12 Years – 1-axis Tracker

Safety failure rate at the plant level = 162/2352 = 7%

Primary failure mode: Ribbon-ribbon solder bond failure with backsheet burning

- Hotspot issues leading to backsheet burn (37/2352)
- Ribbon-ribbon solder bond failure with backsheet burn (86/2352)
- Failed diode with no backsheet burn (26/2352)
- Hotspot issues with backsheet burn + Ribbon-ribbon solder bond with backsheet burn (1/2352)
- Backsheet Delamination (10/2352)
- Backsheet Delamination + Ribbon-ribbon solder bond failure (2/2352)
Distribution of Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker

Histogram of Degradation of Power (%/year) of Model-G Modules

- **Normal**
- **Only Durability Issues** (only material issues)
- **Both Durability and Reliability Issues** (both materials and design/manufacturing issues)

**Statistics**
- Mean: 0.9476
- StDev: 0.3110
- N: 285
- Median: 0.964

**Primary degradation mode:** Solder bond degradation

No Potential Induced Degradation (PID) observed probably due to dry glass surface and/or positive bias strings

Total number of modules = 285 (safety failed modules excluded)

Average degradation = 0.95%/year
Distribution of Reliability Failures and Degradation Losses (Model G – Site 3)

12 Years – 1-axis Tracker

Reliability Failures and Durability Loss
(Based on I-V of 285 modules)
(Safety failed modules excluded)

- Durability Loss: 55% (<1% dr/yr)
- Reliability Failures: 45% (>1% dr/yr)
Distribution of Safety Failures, Reliability Failures and Degradation Losses (*Model G – Site 3*)

12 Years – 1-axis Tracker (combination of previous two slides)

Safety Failures, Reliability Failures and Durability Loss for the Power Plant

(SF based on entire power plant; RF and DL based on I-V of 285 modules)

- Safety Failures: 7%
- Durability Loss: 51% (<1% dr/yr)
- Reliability Failures: 42% (>1% dr/yr)

93 x 0.55 = 51%
93 x 0.45 = 42%
Linking Field Evaluation Data with Premium Risk Rate Calculation

A Conceptual Representation

Interest Rate

= Interest Rate @ Zero Risk
+ Risk Premium Rate

12 Years - 1-axis Tracker

Safety Failures, Reliability Failures and Durability Loss for the Power Plant
(SF based on entire power plant; RF and DL based on I-V of 285 modules)

Safety Failures 7%

Durability Loss 51%
(≤1% dr/yr)
93 x 0.55 = 51%

Reliability Failures 42%
(>1% dr/yr)
93 x 0.45 = 42%

Histogram of Degradation of Power (%/year) of Model-G Modules

Normal

0%
1%
100%

Risk Premium Rate Calculation
Hotspot modules degrade at higher rates (>3 times) \( (\text{Model G – Site 3}) \)

Model G:

Pmax degradation rate comparison between non-hotspot and hotspot modules

<table>
<thead>
<tr>
<th>Model-G non-hotspot modules</th>
<th>Model-G hotspot Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.94</td>
<td>2.83</td>
</tr>
</tbody>
</table>

No. of Modules

31#
Best Modules Experienced Only Durability Issues (*Model G – Site 3*)

1-axis Tracker

Field Age = 12 years
(Model-G)

Best, Median, Worst Strings - Best Modules (6 Strings; 18 Modules)

Primary degradation mode: Solder bond degradation

B = Best string; M = Median string; W = Worst string

Pmax loss ➔ FF loss ➔ Rs increase

BEST modules = 18 (safety failed modules excluded if any)

Mean degradation = 0.5%/year

Median degradation = 0.5%/year

Due to only intrinsic (materials) issues contributing to real wear out mechanisms
Worst Modules Experienced Both Reliability and Durability Issues *(Model G – Site 3)*

**1-axis Tracker**

Both ribbon-ribbon solder bonds failed.

Field Age = 12 years

Best, Median, Worst Strings - Worst Modules (6 Strings; 18 Modules)

Zero power

Blue Square (Mean)
Balck Square (Median)

Primary failure mode:
Ribbon-ribbon solder bond failure with backskin burning

WORST modules = 18 (safety failed modules included)

Mean degradation = 1.8-5.6%/year
Median degradation = 1.4-4%/year

Due to both intrinsic (materials) and extrinsic (design/manufacturing) issues
Not all defects are failures:
Cosmetic defects should not be considered;
Modes shall be risk prioritized for each climatic condition and each module construction type.

Source: IEA-PVPS-2014
Not all defects are failures:
Cosmetic defects should not be considered;
Modes shall be risk prioritized for each climatic condition and each module construction type

Source: ASU-PRL
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Indoor durability evaluation
Degradation rate calculation may be influenced by nameplate rating practice which in turn is influenced by demand & supply of the market.

Under-rated modules will show POSITIVE degradation rate
Over-rated modules will show OVERLY NEGATIVE degradation rate

- Cross check the degradation rate with kWh based degradation rate using Performance Index (PI) method

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>389</td>
<td>278</td>
<td>304</td>
<td>478</td>
<td>825</td>
<td></td>
</tr>
</tbody>
</table>
Degradation rate may depend on the country of production.

Stark design quality variation between the regions has been observed.

- **HF10 test**: Region/country 3 (RL-3) has the highest and abnormal failure rate
  - Potential reasons: Polymeric material and/or interface issue
- **Hotspot test**: Region/country 2 (RL-2) has the highest and abnormal failure rate
  - Potential reasons: Cell quality and/or tabbing issue
- **TC200 test**: Almost all the regions/countries suffer
  - Potential reasons: Metallic material and/or interface issue
Degradation rate can be decreased through beyond-Qualification tests such as Qualification Plus, Comparative and Lifetime tests.

### Three Types of Accelerated Tests

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Qualification</th>
<th>Comparative</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate or Application (Mounting)</td>
<td>Minimum design requirement</td>
<td>Comparison of products</td>
<td>Substantiation of warranty</td>
</tr>
<tr>
<td>Quantification</td>
<td>Pass/fail</td>
<td>Relative</td>
<td>Absolute</td>
</tr>
<tr>
<td></td>
<td>Not differentiated</td>
<td>Differentiated</td>
<td>Differentiated</td>
</tr>
</tbody>
</table>

**Existing**

**New test**

Qualification PLUS

Source:
Degradation rate can be decreased through beyond-Qualification tests such as Qualification Plus, Comparative and Lifetime tests.
Degradation rate can be decreased through beyond-Qualification tests such as Qualification PLUS

Photovoltaic Module Qualification Plus Testing

Sarah Kurtz, John Wohlgemuth, Michael Kempe, Nick Bosco, Peter Hacke, Dirk Jordan, David C. Miller, and Timothy J. Silverman
National Renewable Energy Laboratory

Nancy Phillips
3M

Thomas Earnest
DuPont

Ralph Romero
Black & Veatch

December 2013

http://www.nrel.gov/docs/fy14osti/60950.pdf (available for free downloading)
# Qualification PLUS Testing Comparison with Qualification Testing

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Qualification</th>
<th>Qualification PLUS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Module Testing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>&lt; 3 months</td>
<td>&lt; 3 months</td>
</tr>
<tr>
<td>Sample size for each sequence</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Thermal cycling test</td>
<td>200 cycles</td>
<td>500 cycles</td>
</tr>
<tr>
<td>Dynamic load test before the humidity freeze sequence tests</td>
<td>None</td>
<td>1000 cycles of 1000Pa</td>
</tr>
<tr>
<td>Potential induced degradation (PID)*</td>
<td>Not required</td>
<td>60°C/85%RH for 96 hours</td>
</tr>
<tr>
<td>Hot spot</td>
<td>Test method not adequate</td>
<td>Use ASTM E2481-06 method</td>
</tr>
<tr>
<td><strong>Component Testing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Duration</td>
<td>Not required</td>
<td>&lt; 6 months</td>
</tr>
<tr>
<td>Sample size for each sequence</td>
<td>None</td>
<td>3-12</td>
</tr>
<tr>
<td>UV exposure test for encapsulants, backsheets, connectors, and junction boxes</td>
<td>15 kWh/m² @ 60°C and humidity not controlled</td>
<td>224-320 kWh/m² @ 50-70°C and humidity controlled</td>
</tr>
<tr>
<td>Bypass diode test</td>
<td>1 hour</td>
<td>96 hours</td>
</tr>
<tr>
<td><strong>Manufacturing Quality</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quality Management System (QMS)</td>
<td>Not required</td>
<td>Addition of PV-specific requirements to ISO9001</td>
</tr>
</tbody>
</table>

* Discussed further

Potential induced degradation (PID) is a major degradation issue in humid/rainy locations.

PID

No PID

Transformerless Inverter

Potential induced degradation (PID) is a major degradation issue in humid/rainy locations.
PID: Not fully recovered

PID (aluminum method): 60°C, -600V, 88h

• Only about 96% recovered
• Responses from blue photons are not recovered

Source: J. Oh et al (ASU-PRL), IEEE PVSC 2014 (submitted)
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Summary
• Differences between durability and reliability losses are defined and the definitions have been applied in the outdoor evaluations
• Importance of durability for bankability is explained
• A systematic outdoor durability evaluation approach to determine climate specific degradation rate is presented
• A few key indoor durability evaluations are presented
Theses of ASU-PRL students can be freely downloaded at:

repository.asu.edu

(search under “TamizhMani”)

Thanks for your attention!