2018 PV Reliability Workshop
Welcome!

Dirk Jordan
February 27 - March 1, 2018
Lakewood, Colorado

NREL/PR-5K00-72423
Special events

Tuesday:
Test beyond IEC 61215, e.g. Thresher Test etc.
IEC (No. 76), CSA (No. 75)
Group discussion over dinner, outside meeting room at 18:00

Friday:
Inverter roundtable, organized by EPRI
8:00 – 13:00
“The Panic Curve”

PV reliability workshop registrations

Days before workshop

Cumulative registration number

40  30  20  10  0

0  50  100  150  200
“The Panic Curve”

PV reliability workshop registrations

We’re going to be almost empty!!
“The Panic Curve”

PV reliability workshop registrations

We’re running out of space!!

We’re going to be almost empty!!
Thank you!

Committee:

Teresa Barnes
Markus Beck
Michael Bolen
Alessandra Colli
William Gambogi
Tassos Golnas
Sarah Kurtz
Olga Lavrova
Sumanth Lokanath
David Meakin
Andreas Meisel
Ingrid Repins
Mani G. TamizhMani
John Wohlgemuth

Special thanks to all the volunteers!!!
DOE PV Reliability Overview

Photovoltaics Reliability Workshop
February 27, 2018

- Dana Olson
The Historical Growth of the US PV Market

Gigawatt DC

EIA has released its Annual Energy Outlook (AEO) 2018, projecting that U.S. solar installed capacity will grow to 425 GW by 2050.

- Of the total, 251 GW is projected to be distributed PV, 172 GW utility-scale PV, and 2 GW of CSP.
- 425 GW of solar would represent approximately 24% of total U.S. installed capacity, supplying 16% of total U.S. electricity—all renewables are projected to supply 34%.

Distributed PV is projected to surpass utility-scale PV in installed capacity by 2026.

2050 capacity represents a growth of 17% above AEO 2017 capacity projections.

Source: EIA “Annual Energy Outlook 2018” (February 2018)
Half the Cost, More than Double the Solar

SunShot 2030 Goal + Low Cost Storage (3¢/kWh)
SunShot 2030 Goal (3¢/kWh)
SunShot 2020 Goal (6¢/kWh)
Progress Toward SETO Cost Goals

*Levelized cost of electricity (LCOE) progress and targets are calculated based on average U.S. climate and without the ITC or state/local incentives. The residential and commercial goals have been adjusted for inflation from 2010-17.
Role of Durability and Lifetime to Reach SETO Goals

Lowered risk with increased confidence depends on material science / quality?

100 MW\textsubscript{(DC)} One-Axis Tracking Systems With 1,860 kWh\textsubscript{(AC)}/kW\textsubscript{(DC)} First-Year Performance.
Includes 5 Year MACRS.
There are Many Technology Pathways to $0.03/kWh

- Cost and performance tradeoffs open up numerous pathways.
- All pathways require sustained, multifaceted innovation.

All curves represent 3¢/kWh LCOE in average U.S. climate

Scenarios assume: 7% WACC, 2.5% inflation, $4/kW-yr O&M, 21% capacity factor
Current SETO PV Research Funding Allocations

- National Lab: $143M
- University: $51M
- Industry (T2M program): $27M
- Industry (PV program): $26M
- Non-Profit: $20M
- Non-Profit (PV program): $14M
- National Lab (PV Systems): $9M
- National Lab (Supply Chain): $5M

Reliability / Bankability
- PVQAT, DuraMAT, Predicts...

- Cell: $68M
- Module: $20M
- Metrology: $14M
- Consortia: $9M
- Other: $5M

$86M (37%)
Reliability and Durability Challenges Remain

- Variability in performance based on manufacturer and bill of materials

- Same nameplate label, different BOM

- Can material quality differentiate products?

Source: DNV-GL, PV Reliability Scorecard 2017
Reliability and Durability Research Challenges

- Connect specific bills of materials and climates to degradation patterns?
- Do new materials introduce new (and old) degradation modes?
- Develop more accurate and shortened accelerated tests?
- Can physical models describe the degradation mechanisms induced by accelerated tests and field exposure?

Source: Kontges et al, IEA-PVPS, 2014
The Durable Module Materials Consortium (DuraMAT)

- 5-year Energy Materials Network consortium focused on precompetitive research into module packaging

- Who Is Involved
  - PV industry: R&D goals
  - National Labs: capability expertise
  - Universities: research infrastructure

- Goal: Accelerate PV module material design and improve durability

- Industrial Advisory Board (IAB)
  - 14 members, open to new members
  - Guides scope of projects and research focus

- Projects underway
  - 6 national laboratory capability development projects
  - 8 university research projects
  - 3 collaborative industry-lab projects, funded in 2017
  - 4 Spark projects (2 active, 2 selected)
# DuraMAT Lab Capabilities

<table>
<thead>
<tr>
<th>Area</th>
<th>Lead</th>
<th>Infrastructure</th>
<th>Demonstration Project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Data Mgmt. and Informatics</strong></td>
<td>Anubhav Jain, LBNL</td>
<td>Build data hub</td>
<td>PVDAQ</td>
</tr>
<tr>
<td><strong>Materials Forensics</strong></td>
<td>Mike Toney, SLAC</td>
<td>Multi-functional anti-soiling/AR coating, backsheet degradation, encapsulant adhesion</td>
<td>Multi-functional anti-soiling/AR coating, backsheet degradation, encapsulant adhesion</td>
</tr>
<tr>
<td><strong>Field Deployment</strong></td>
<td>Bruce King, Sandia</td>
<td>Upgrade data transfer</td>
<td>Development of non-destructive field test methods</td>
</tr>
<tr>
<td><strong>Predictive Simulation</strong></td>
<td>Kevin Leung, Sandia</td>
<td>Build full-size high aspect ratio module simulation toolset</td>
<td>Build full-size high aspect ratio module simulation toolset</td>
</tr>
<tr>
<td><strong>Module Prototype and Testing</strong></td>
<td>Peter Hacke, NREL</td>
<td>Combined Accelerated Stress Test of backsheets</td>
<td>Combined Accelerated Stress Test of backsheets</td>
</tr>
<tr>
<td><strong>Technology to Market</strong></td>
<td>Mike Woodhouse, NREL</td>
<td>Provide economic guidance impacts of capabilities and projects, critical industry issues</td>
<td>Provide economic guidance impacts of capabilities and projects, critical industry issues</td>
</tr>
</tbody>
</table>
DuraMat Capability Network and Project Areas

DuraMAT Projects

- Time-series data
- Multiscale model
- Interface Adhesion
- Interconnects
- Flexible Materials

Capability Network

- Data Analytics
- Predictive Simulation
- Materials Forensics
- Module Prototyping & Test
- Outdoor Testing
- TechnoEconomic
National Lab Capabilities to Understand Reliability

Predictive Simulation
Multi-stress models

Material Characterization
Anti-soiling coating characterization
Project: WattGlass

Automatically Detect Clear-Sky
Developed machine learning approaches based on NSRDB
Combined Accelerated Stress Test (C-AST)

**C-AST**

**Stresses:** Dynamic mechanical load, 1500V bias, rain, humidity freeze, thermal cycle, light

**Samples:** Four cell mini-modules, testing different backsheets

**Goal:** Identify and understand interactions between environmental stress factors on module degradation in order to develop better accelerated tests

**Capability Area & Teaming**

**Capability Area(s):** Forensics, Predictive Simulation, Field Deployment

**Team:** David Miller, Michael Kempe/NREL, Laura Schelhas/SLAC, Kevin Leung, Bruce King/ Sandia
How Can DuraMAT Help Address PV Reliability?

• The ‘big data’ challenge to understanding degradation
• Climate/stressor/material combinations and interactions

Source: EIA, 2017
Ways to Engage

- **Expanding DuraMAT Capabilities**
  -Are there capabilities from industry, universities, or national labs that you could contribute to the DuraMAT network?
  -What other capabilities would you like to see?
  -DuraMAT capability lab call for proposals out now

- **DuraMAT Research Funding**
  -Are there R&D projects that you could propose to DuraMAT funding opportunities to work with the capability network?
  -Next industry and academic funding opportunity coming in spring

- **Data Hub**
  -What dream dataset would you like to see in the Data Hub?
  -What types of analytic tools would be most helpful?
  -What dataset related to module durability would you be open to contributing to the Hub?
Thank you and welcome to the PV Reliability Workshop

Questions?

Dana Olson
dana.olson@hq.doe.gov
Key Results from All India Survey of PV Module Reliability: 2016

_Presenter: Narendra Shiradkar, PhD_
Assistant Professor & In-charge, PV Module Reliability Group, National Centre for Photovoltaic Research and Education (NCPRE), Department of Electrical Engineering, IIT Bombay, India
Email: naren@ee.iitb.ac.in
Contributors

NCPRE Students, Staff and Faculty:

National Institute of Solar Energy (NISE) Students, Staff and Scientists:
Birinchi Bora, Gopal Kumar, Yogesh Kumar Singh, Manander Bangar, Mithilesh Kumar, Avinash Kumar Haldkar, Ramayan Singh, Sahan Raghava, Manoj Morampudi, Gowri Ganesh, Rajesh Kumar and O. S. Sastry

Funding Courtesy:
• Ministry of New and Renewable Energy (MNRE), Govt. of India
• DST (SERIUS)
Outline

• Introduction to NCPRE, IIT Bombay
• Motivation and Overview of All India Surveys of PV Module Reliability: 2013, 2014 and 2018
• Overview of Module Degradation Rates in 2016 Survey (Focus on data from c-Si and mc-Si modules):
  ➢ Effect of Climatic Zone
  ➢ Effect of Age
  ➢ Effect of System Size
  ➢ Effect of Ground vs Roof Mounting
  ➢ Effect of Hot Cells
• Crack: Statistics, Correlation to Power Loss
• Wet Insulation Resistance Test Results
• Summary and Recommendations
• Upcoming All India Survey of PV Module Reliability: 2018
Introduction to NCPRE, IIT Bombay

• India’s Ambitious PV Deployment Goal: 100 GW by 2022
• National Centre for Photovoltaic Research and Education (NCPRE) established at IIT Bombay in 2010.
• NCPRE Phase-II Started in 2016.
• Funding: ~ $5 Million for 5 years, by Ministry of New and Renewable Energy (MNRE), Govt. of India
• Close collaboration with PV cell & module manufacturers and project developers in India.
• NCPRE Module Reliability Achievements:
  - All India Surveys of PV Module Reliability: 2013, 2014, 2016
  - Low Cost EL Camera, Outdoor Temperature Coefficient Measurement Device, Proof of Concept of Daytime Electroluminescence.
  - Industry Collaboration: CTM Loss Estimation, Correlating EVA durability and Vinyl Acetate Content, Effect of Transportation on Cracks.
  - Ongoing: PV Standards Development for Indian Conditions (Hot Climate, Transportation on Rough Terrain, Ensuring Manufacturing Quality)
All India Surveys of PV Module Reliability

• Joint activity of NCPRE and NISE\(^1\).

<table>
<thead>
<tr>
<th>Survey</th>
<th>Modules Inspected</th>
<th># Sites</th>
<th># Large Sites &gt; 100 KW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>63</td>
<td>26</td>
<td>--</td>
</tr>
<tr>
<td>2014</td>
<td>1148</td>
<td>51</td>
<td>6</td>
</tr>
<tr>
<td>2016</td>
<td>925</td>
<td>37</td>
<td>11</td>
</tr>
</tbody>
</table>

• Continuously increased the number and types of outdoor module characterization tests performed.
• Improvement in instrumentation in every survey.
• Continuous improvement in the methodology of sample selection. Sample size to remain close to 1000.
• In future surveys, we would like to further increase the number of ‘large’ sites as they are more representative of the PV deployments currently happening in India.

\(^1\)http://www.ncpre.iitb.ac.in/research/reports.html
All India Survey 2016

Work done jointly by NCPRE, SERIUS and NISE

Cold & Cloudy Zone
- No. of Sites: 1
- No. of Modules: 20

Cold & Sunny Zone
- No. of Sites: 4
- No. of Modules: 106

Hot & Dry Zone
- No. of Sites: 7
- No. of Modules: 201

Warm & Humid
- No. of Sites: 12
- No. of Modules: 267

Composite Zone
- No. of Sites: 9
- No. of Modules: 237

Moderate Zone
- No. of Sites: 4
- No. of Modules: 94

Characterization Techniques Used
- Illuminated I-V and Dark I-V tracing
- Illuminated IR and Dark IR imaging
- Daylight Electroluminescence imaging
- Interconnect failure test
- Insulation resistance test
- Visual degradation
- Inverter performance test
- Socio-economic checklist
- On-site temperature coefficient measurement

2016:
- Total No. of Sites: 37
- Total No. of Modules: 925
Overview of Degradation Rates: Screening Data with Abnormally High Degradation Rates

Group Y (‘Bad Sites’)  
Average Overall Degradation Rate for Sites > 2%/ year

Group X (‘Good Sites’)  
Average Overall Degradation Rate for Sites < 2%/ year

Classification based on ‘Good’ and ‘Bad’ sites

Analyze Effect of Climate, Age, System Size and Mounting on Degradation Rates
- Hot Zone results in higher degradation rate than Non-Hot Zone.
- Younger modules in hot zone are degrading faster than older modules.
Effect of Age

- Old modules mainly degrade by Isc and FF loss.
- Young modules predominantly show FF loss, which is significantly higher for group Y modules, likely due to higher cell cracks.
Effect of System Size

- In group X (‘good sites’), Larger systems are degrading slower than smaller systems.
- However, young modules at large sites in hot zones are degrading at a considerably high rate of 1.43%/year. These are the most common types of systems to be deployed in near future in India.
**Effect of Rack vs Roof Mounting**

- Note: ‘Roof Mounted’ modules in our study are actually rack mounted on flat roofs.
- For smaller systems, roof mounted modules are degrading at a faster rate than ground mounted modules.
- In 2014 survey, we conjectured that high temperature operation of rooftop modules may be a potential reason for higher degradation rate.
Module Temperature was translated to a reference condition of 1000 W/m² and 40 °C¹

\[ T_{\text{translated}} = 40 + \frac{(T_{\text{measured}} - T_{\text{ambient}}) \times 1000}{\text{Irradiance}} \]

- Note: ‘Roof Mounted’ modules in our study are actually rack mounted on flat roofs.
- No statistically significant difference is observed in module temperatures for ground vs roof mounted modules.
- Therefore, factors other than temperature are likely responsible for poor performance of roof mounted systems surveyed in this study.
- For example: Poor installation, cracks generated during transportation etc.

Effect of Hot Cells on Power Degradation

Example Criteria for Hot Cell (60 cell module, 17% efficiency):

\[ T_{\text{max cell, translated}} - T_{\text{module, translated}} > 5 \, ^\circ\text{C} \]

- Modules with hot cells show higher degradation than modules without hot cells in both climates.
- Modules with hot cells in hot climates degrade faster than modules with hot cells in non-hot climates.
- This indicates that modules having hot cells due to mismatch are even more susceptible for power degradation in hot climates.
### Crack Statistics

#### Percentage of Cells Affected by different types of cracks

<table>
<thead>
<tr>
<th></th>
<th>Mode A</th>
<th>Mode B</th>
<th>Mode C</th>
<th>Total No. of Cells Checked</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group X</strong></td>
<td>1.23</td>
<td>1.46</td>
<td>0.83</td>
<td>9464</td>
</tr>
<tr>
<td><strong>Group Y</strong></td>
<td>7.58</td>
<td>9.48</td>
<td>3.39</td>
<td>3300</td>
</tr>
<tr>
<td><strong>Young</strong></td>
<td>3.19</td>
<td>4.14</td>
<td>1.62</td>
<td>8952</td>
</tr>
<tr>
<td><strong>Old</strong></td>
<td>2.1</td>
<td>2.1</td>
<td>1.21</td>
<td>3812</td>
</tr>
<tr>
<td><strong>Rooftop</strong></td>
<td>3.07</td>
<td>3.97</td>
<td>2.22</td>
<td>4860</td>
</tr>
<tr>
<td><strong>Ground Mount</strong></td>
<td>2.75</td>
<td>3.26</td>
<td>1.05</td>
<td>7904</td>
</tr>
<tr>
<td><strong>Small System</strong></td>
<td>3.01</td>
<td>3.58</td>
<td>1.85</td>
<td>6920</td>
</tr>
<tr>
<td><strong>Large System</strong></td>
<td>2.7</td>
<td>3.47</td>
<td>1.08</td>
<td>5844</td>
</tr>
</tbody>
</table>
Wet Insulation Resistance Test Results

- Significant number of group Y modules (39%) and modules deployed in small systems (30%) fail wet insulation resistance test.
- This can be a safety hazard as most of these modules are mounted on rooftops.
- Older modules are more likely to fail the test.
14 out of 37 sites were deemed as ‘Group Y’ (Bad).

Common features of Group Y sites are that they are small size systems, made of young modules, deployed on rooftops in hot climates.

Module build quality and installation quality is likely to be poor. Significant cell cracking is seen.

Even degradation modes such as encapsulant browning that have a ‘known cure’ are predominantly seen in Group Y sites within first few years of operation.
Summary of Observations

• NCPRE has conducted 3 All India Surveys and two more surveys are planned in 2018 and 2020.
• Modules in hot climates are degrading faster than those in non-hot climates.
• Young modules in hot climates are degrading faster than old modules.
• Modules in rooftop systems are degrading faster than ground mounted modules and higher operating temperature is not the reason behind this trend.
• Hot cells and hot climates further exacerbate the degradation rates.
• Significantly higher extent of cracks is seen in Small Systems, deployed on roofs, made from Young modules.
• Modules in small systems and rooftops show significant number of failures under wet leakage test which can be a safety issue.
Recommendations

- There is urgent need to develop new qualification standards containing harsher yet relevant accelerated tests for modules deployed in hot climates.
- Due diligence needs to be exercised regarding quality of modules during procurement. On-site testing, third party audits and installation standards need to be followed.
- Module degradation rates in hot climates can be more than 1%/year, and this needs to be taken into account during project development stage.
- Module manufacturers and installers should place more emphasis on proper packaging and handling of the modules during transportation to mitigate cracking.
- It is felt that some of the quality issues seen especially in the young modules are the result of aggressive pricing and timelines and improper handling/installation.
Upcoming All India Survey 2018

• Set to begin on March 7, 2018.
• Even more ‘large’ (multi MW scale) plants are included.
• Sample selection is generally based on SCADA data obtained from plants before inspection.
• New inverter performance / power electronics related tests are included.
• This time we will try to bring degraded samples from field to lab for destructive root cause failure analysis to better understand failure mechanisms.
• Reference mini-module is to be used for irradiance measurements instead of a photodiode sensor.
• Any suggestions for upcoming All India Survey 2018 are most welcome!
Thank you!

Contact Information

Email: naren@ee.iitb.ac.in

All India Survey Reports Can be Downloaded for Free from Following Link:

http://www.ncpre.iitb.ac.in/research/reports.html
Observations and trends from 4 years of extended-duration testing of PV modules

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Henry.Hieslmair@DNVGL.com

Ryan Desharnais
Ryan.Desharnais@DNVGL.com
About DNV GL

- DNV GL is the world’s largest independent energy & renewable advisory firm.
- We have over 1000 experts focused on renewables.
- DNV GL has advised over 5500 solar projects.
- DNV GL has laboratory and field testing facilities.

**PV Module Reliability Scorecard Report 2017**

Report contributors:
- Jenye Ituabasi, VP Strategy & Business Development
- Frederic Dross, Head of Module Business

**ENERGY TRANSITION OUTLOOK 2017**

A global and regional forecast of the energy transition to 2050
70-75% of the BNEF Tier 1
50GW/year of module manufacturing
9 of the 10 global largest module manufacturers
### About the data analyzed in this presentation

- PQP performance data span 2013-2017; 33 PV Module Manufacturers; ≈2500 modules

<table>
<thead>
<tr>
<th>Tests</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC600</td>
<td>Thermal Cycling between -40°C and 85°C for 600 cycles</td>
</tr>
<tr>
<td>HF20</td>
<td>Humidity Freeze cycles from 85°C, 85% RH and -40°C for 20 cycles.</td>
</tr>
<tr>
<td>UV90</td>
<td>Ultra-Violet exposure to 90kW-hr/m2</td>
</tr>
<tr>
<td>DML+TC50+HF10</td>
<td>Dynamic Mechanical Load: 1000 cycles of ±1000Pa + TC50 + HF10</td>
</tr>
<tr>
<td>PID</td>
<td>DH96 with -1000V or -1500V bias</td>
</tr>
</tbody>
</table>

- **Outcomes: \( \Delta P_{\text{max}} \)**
- **Not discussing other failures; delamination, backsheet cracking, J-box issues, ...**
What can we learn about the tests themselves?
Correlation coefficient $r$

$$r = \frac{\text{covar}(x, y)}{S_x S_y}$$
### Correlations between the tests for $\Delta P_{\text{max}}$

<table>
<thead>
<tr>
<th></th>
<th>TC 600</th>
<th>DH 2000</th>
<th>HF 20</th>
<th>UV 90</th>
<th>DML+TC50+HF10</th>
<th>PID</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC 600</td>
<td></td>
<td>0.31</td>
<td>0.74</td>
<td>0.14</td>
<td>0.64</td>
<td></td>
</tr>
<tr>
<td>DH 2000</td>
<td></td>
<td></td>
<td>0.39</td>
<td>0.26</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>HF 20</td>
<td></td>
<td></td>
<td></td>
<td>0.10</td>
<td>0.63</td>
<td>0.03</td>
</tr>
<tr>
<td>UV 90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>DML+TC50+HF10</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>PID</td>
<td></td>
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</tbody>
</table>
Correlations of test duration for $\Delta P_{\text{max}}$

<table>
<thead>
<tr>
<th>Test Duration</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC 600</td>
<td>0.84</td>
</tr>
<tr>
<td>DH 3000</td>
<td>0.15*</td>
</tr>
<tr>
<td>HF 20</td>
<td>0.81</td>
</tr>
<tr>
<td>UV 90</td>
<td>0.64</td>
</tr>
<tr>
<td>DML+TC50+HF10</td>
<td></td>
</tr>
<tr>
<td>PID 192h</td>
<td>0.69</td>
</tr>
</tbody>
</table>

The diagram shows the correlation between TC 600 and TC 200 ($\Delta P_{\text{max}}$ %) with a correlation coefficient of 0.84.
### Correlations of test duration for $\Delta P_{\text{max}}$

<table>
<thead>
<tr>
<th></th>
<th>TC 600</th>
<th>DH 3000</th>
<th>HF 20</th>
<th>UV 90</th>
<th>DML+TC50 +HF10</th>
<th>PID 192h</th>
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<tbody>
<tr>
<td>TC 600</td>
<td>0.84</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>DH 3000</td>
<td></td>
<td>0.15*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HF 20</td>
<td></td>
<td></td>
<td>0.81</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>UV 90</td>
<td></td>
<td></td>
<td></td>
<td>0.64</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DML+TC50 +HF10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.86</td>
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</tr>
<tr>
<td>PID 192h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.69</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TC 200</th>
<th>DH 2000</th>
<th>HF 10</th>
<th>UV 45</th>
<th>DML+TC50</th>
<th>PID 96h</th>
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<tr>
<td></td>
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</tr>
</tbody>
</table>
Duration of the testing (various tests)

- Eliminate failures >8% and the correlation improves.
- Sign of catastrophic failures after 2000h
How are the modules changing over 4 years.
Modules efficiency over time

Module efficiency = (Nameplate P) / (glass area)

About $0.75\%_{\text{abs}}$/year
## Module changes over time

<table>
<thead>
<tr>
<th>Item</th>
<th>Change / year</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module Efficiency (%)</td>
<td>+0.75%(_{\text{abs}})</td>
<td>0.63</td>
</tr>
<tr>
<td>Number of bus bars*</td>
<td>+0.6 BB</td>
<td>0.68</td>
</tr>
<tr>
<td>Ribbon width</td>
<td>-0.20mm</td>
<td>0.67</td>
</tr>
<tr>
<td>Front Encapsulant Thickness</td>
<td>+0.025mm</td>
<td>0.50</td>
</tr>
<tr>
<td>Rear Encapsulant Thickness</td>
<td>+0.012mm</td>
<td>0.32</td>
</tr>
<tr>
<td>Frame thickness</td>
<td>No change</td>
<td></td>
</tr>
<tr>
<td>Glass thickness</td>
<td>No change</td>
<td></td>
</tr>
</tbody>
</table>

*excluding multi-wire
Change in BOM over time

- Number of Busbars (no multi-wire):
  - +0.6 BB/year

- Ribbon width (no multi-wire) (mm):
  - -0.2mm/year

Excluding multi-wire: 12 wires
Have the test results improved over 4 years?
### Test results over time for $\Delta P_{\text{max}}$

<table>
<thead>
<tr>
<th>Item</th>
<th>Change in $\Delta P_{\text{max}}$/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC600</td>
<td>+0.8%$_{\text{abs}}$</td>
</tr>
<tr>
<td>DH2000</td>
<td>-0.4%$_{\text{abs}}$</td>
</tr>
<tr>
<td>HF20</td>
<td>+0.5%$_{\text{abs}}$</td>
</tr>
<tr>
<td>UV90</td>
<td>+0.1%$_{\text{abs}}$</td>
</tr>
<tr>
<td>DML+TC50+HF10</td>
<td>+0.6%$_{\text{abs}}$</td>
</tr>
<tr>
<td>PID</td>
<td>+0.4%$_{\text{abs}}$</td>
</tr>
</tbody>
</table>

However, all correlations $< 0.28$
Changes in test results over time for $\Delta P_{\text{max}}$
Do higher module efficiencies have better reliability? PERC?
Test results vs module efficiency

The difference between mono and multi is statistically significant. $(p=0.005)$

Not enough PERC data

The difference between mono and multi is not statistically significant. $(p=0.26)$

Not enough PERC data
Test results vs module efficiency

![Diagram on left: HF20 vs Module Efficiency with correlation 0.32]

![Diagram on right: DML+TC50+HF10 vs Module Efficiency with correlation 0.32]
Test results vs module efficiency

- **UV 90kWh** vs **Module Efficiency (%)**
  - Correlation: -0.08

- **PID 85C/85%96h** vs **Module Efficiency (%)**
  - Correlation: -0.28
How do BOM properties impact test results?
Correlations of test duration $\Delta P_{\text{max}}$

Module property $\rightarrow$ Test Result

Number of busbars
Front Encapsulant Thickness
Rear Encapsulant Thickness
Total encapsulant thickness
Glass Thickness
Frame Thickness
Ribbon Width
Ribbon Thickness

Test Results:
- TC 600
- DH2000
- HF20
- UV 90 kWh
- DML+TC50+HF10
- PID 96 Hr
Correlations between BOM and Test $\Delta P_{\text{max}}$

Excluding multi-wire and PID > 10%
Encapsulant and Bus Bars vs TC 600

- Possible mechanism includes:
  - Mechanical stresses at solder pads and ribbons
  - Soldering stress incurred by soldering larger ribbons
How do test results vary by manufacturer?
Conclusions from $\Delta P_{\text{max}}$ analysis

- Observed correlations between:
  - the tests which involve thermal cycling
  - early test results and later test results, except DH

- Over the last 4 years, modules have:
  - become more efficient
  - more bus bars
  - thinner ribbons
  - not improved in test results

- We do not have enough PERC data to make reliability comparisons (yet)
- Mono did better than multi on TC600

- Module manufacturer is still a primary determinant of test results
PV Lifetime Project – Challenges of Measuring PV Module Degradation

Joshua S Stein, Bruce King, and Charles Robinson
Sandia National Laboratories

Chris Deline and Bill Sekulic
National Renewable Energy Laboratory

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy’s National Nuclear Security Administration under contract DE-NA0003525.
Project Goals

- Develop and standardize methods for measuring PV module and system degradation.
  - The path of degradation matters to LCOE.
- Apply methods to selected commercial PV modules
  - Three sites: New Mexico, Colorado, and Florida
  - Approximately 50 modules per climate (4 strings/system)
  - Modules obtained from at least two sources
  - Targeting top-selling module manufacturers (in US market) and a range of current cell technologies (focus on Si)
- Project is unique
  - Large number of modules will allow statistical characterization of variation in degradation within a module population – There is not a single rate!
  - Combination of indoor and outdoor methods applied to multiple sites as well as combining module-level with string-level monitoring.
  - Data and results will be shared
<table>
<thead>
<tr>
<th>Site</th>
<th>Manufacturer</th>
<th>Model</th>
<th>Technology</th>
<th># of modules</th>
<th>Installation Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>NM</td>
<td>Trina Solar</td>
<td>TSM-PD05.08 260W</td>
<td>poly-Si</td>
<td>56</td>
<td>June 2016</td>
</tr>
<tr>
<td>NM</td>
<td>Jinko Solar</td>
<td>JKM260P-60 260 W</td>
<td>poly-Si</td>
<td>56</td>
<td>June 2016</td>
</tr>
<tr>
<td>NM</td>
<td>SolarWorld</td>
<td>SW 245W Mono</td>
<td>mono-Si</td>
<td>21</td>
<td>2013</td>
</tr>
<tr>
<td>NM</td>
<td>Canadian Solar</td>
<td>CS6K-270P 270W</td>
<td>poly-Si</td>
<td>48</td>
<td>October 2017</td>
</tr>
<tr>
<td>NM</td>
<td>Canadian Solar</td>
<td>CS6K-275M 275W</td>
<td>mono-Si</td>
<td>48</td>
<td>October 2017</td>
</tr>
<tr>
<td>NN</td>
<td>Hanwha Q-Cells</td>
<td>Q.Plus BFR-G4.1 280W</td>
<td>poly-Si PERC</td>
<td>48</td>
<td>October 2017</td>
</tr>
<tr>
<td>NM</td>
<td>Hanwha Q-Cells</td>
<td>Q.Peak BLK G4.1 290W</td>
<td>mono-Si PERC</td>
<td>48</td>
<td>October 2017</td>
</tr>
<tr>
<td>NM</td>
<td>Panasonic</td>
<td>N325SA16 325W</td>
<td>HIT Mono</td>
<td>48</td>
<td>TBD</td>
</tr>
<tr>
<td>NM</td>
<td>LG</td>
<td>LG320N1K-A5 320W LG NeON2</td>
<td>N-type Si</td>
<td>48</td>
<td>TBD</td>
</tr>
<tr>
<td>CO</td>
<td>Trina Solar</td>
<td>TSM-PD05.08 260W</td>
<td>poly-Si</td>
<td>56</td>
<td>September 2016</td>
</tr>
<tr>
<td>CO</td>
<td>Jinko Solar</td>
<td>JKM260P-60 260W &amp; 265W</td>
<td>poly-Si</td>
<td>56</td>
<td>September 2016</td>
</tr>
<tr>
<td>CO</td>
<td>Hanwha Q-Cells</td>
<td>Q.Plus BFR-G4.1 280W</td>
<td>poly-Si PERC</td>
<td>28</td>
<td>October 2017</td>
</tr>
<tr>
<td>CO</td>
<td>Hanwha Q-Cells</td>
<td>Q.Peak BLK G4.1 290W</td>
<td>mono-Si PERC</td>
<td>28</td>
<td>October 2017</td>
</tr>
<tr>
<td>FL</td>
<td>Trina Solar</td>
<td>TSM-PD05.08 260W</td>
<td>poly-Si</td>
<td>56</td>
<td>September 2017</td>
</tr>
<tr>
<td>FL</td>
<td>Jinko Solar</td>
<td>JKM260P-60 260 W</td>
<td>poly-Si</td>
<td>56</td>
<td>September 2017</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>701 Modules</strong></td>
<td></td>
</tr>
</tbody>
</table>
PV Lifetime Systems (NM)

Trina (poly)  Jinko (poly)  SolarWorld/Enphase

Hanwha Q-Cells (mono and poly PERT)  Canadian Solar (mono and poly)
PV Lifetime Systems (NREL)

Trina (poly)  Jinko (poly)

Jinko (poly)  Trina (poly)  Hanwha Q-Cells (PERC)
PV Lifetime Systems (Florida)

Trina and Jinko (poly)
Monitoring Data

- **Indoor Flash Testing**
  - All modules flash tested after initial stabilization from light soaking.
  - Annual reflashing of ~12 modules per system.
  - Flasher stability tracked with use of control modules stored indoors.
    - Control modules include samples matching the systems under test.

- **Outdoor Performance Monitoring**
  - Automatic string-level IV tracing (once every 30 min while irradiance is between 200-1400 W/m²)
  - POA irradiance, back of module temperatures
  - 1-min, string-level dc current and voltage monitoring

Pordis 140A Series II
8-32 Channel IV Tracer

http://www.pordis.com/products.html
Flash Simulator Stability and Uncertainty

- Most focus is on accuracy of flash tests – Power rating = $$$$$$
- Our project is focused on measuring the change in module performance over a long time period.
- How stable are flash testers over time (years)?
- Current and voltage calibrations are straightforward.
- Irradiance calibrations are more difficult.
  - Flash lamps degrade leading to changes in spatial uniformity and spectrum.
  - Ref cells/modules used to calibrate flash intensity may degrade.

**Our Proposed Solution:**
- Assume that a collection of stabilized PV modules stored indoors should remain stable for the project period.
- Collection is flashed periodically to track (and correct) changes that may occur.
- Collection helps to identify individual outliers to this assumption, which can be replaced.

- Will this work???
Sandia’s Performance Monitoring Module Library

- ~12 PV modules of different makes, models, and c-Si technologies.
- Flash tested regularly

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Alpha (%)</th>
<th>Beta (%)</th>
<th>Gamma (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP Solar</td>
<td>BP3220N</td>
<td>0.065</td>
<td>-0.36</td>
<td>-0.5</td>
</tr>
<tr>
<td>Jinko Solar</td>
<td>JKM260P</td>
<td>0.06</td>
<td>-0.31</td>
<td>-0.41</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>PV-UE125MF5N</td>
<td>0.054</td>
<td>-0.343</td>
<td>-0.45</td>
</tr>
<tr>
<td>Moser Baer</td>
<td>MBPV CAAP</td>
<td>0.11</td>
<td>-0.344</td>
<td>-0.43</td>
</tr>
<tr>
<td>SolarWorld</td>
<td>SW 260 POLY</td>
<td>0.051</td>
<td>-0.31</td>
<td>-0.41</td>
</tr>
<tr>
<td>SolarWorld</td>
<td>SW 270 MONO</td>
<td>0.07</td>
<td>-0.29</td>
<td>-0.41</td>
</tr>
<tr>
<td>SolarWorld</td>
<td>SW 290 MONO</td>
<td>0.04</td>
<td>-0.31</td>
<td>-0.41</td>
</tr>
<tr>
<td>SunPower</td>
<td>SPR-318E-WHT-D</td>
<td>0.0565</td>
<td>-0.27</td>
<td>-0.38</td>
</tr>
<tr>
<td>Tenesol</td>
<td>TE235-60P+</td>
<td>0.0565</td>
<td>-0.3486</td>
<td>-0.43</td>
</tr>
<tr>
<td>Trina Solar</td>
<td>TSM260PD05.08</td>
<td>0.05</td>
<td>-0.32</td>
<td>-0.41</td>
</tr>
<tr>
<td>Universal Solar</td>
<td>WX230P-US</td>
<td>0.046</td>
<td>-0.3</td>
<td>-0.47</td>
</tr>
<tr>
<td>Yingli</td>
<td>YL220(156)</td>
<td>0.1</td>
<td>-0.37</td>
<td>-0.45</td>
</tr>
</tbody>
</table>
Temperature correct $P_{\text{max}}$ using gamma values from spec sheets as:
\[ P_{\text{max}}T = \frac{P_{\text{max}}}{1 + \left(\frac{\text{gamma}_i}{100}\right) \times (\text{temp} - 25)} \]

Calculate normalized power residuals for each module as:
\[ \frac{(P_{\text{max}}T_t - P_{\text{max}}T_1)}{P_{\text{max}}T_1} \times 100 \]

Temperatures vary by 1-2 °C during testing days.

- Doors to lab were opened frequently during busy period in Sep.
- We believe that the TC was changed during this period. (We will record such changes in the future)
VocT, IscT, and FF

- ~0.4% increase in Voc between Sep and Nov, then return in mid Dec.
  - Could be a thermocouple being switched (~reading high by ~1+ degC)
- Isc values increase for SolarWorld 270M and 290M in this same interval. These modules are changing relative to the others in the library.
- Power changes tend to follow changes in FF
Temperature correction reduces variability
Example data from NREL
Example data from NREL
What Have We Learned?

- A collection of control modules appears to be justified since individual modules in our study started to deviate.
  - 2 deviated in Isc, one in FF – these will be replaced.

- Module temperature measurement
  - Taped-on thermocouple is not sufficient.
  - 4-wire RTD spring-loaded probe will increase our accuracy.
  - We will make several measurements across module to ensure uniformity.

- Errors of up to ±1% appear to be the best we can currently expect.
  - This means that degradation rates of 1%/year or lower will take several years to measure with confidence. We are waiting to release results until confidence levels are better understood.
  - New temperature probe may reduce this uncertainty in the future.
The search for root cause: status of LeTID in PERC modules

Mallory A. Jensen and Tonio Buonassissi
Massachusetts Institute of Technology (USA)

2018 Photovoltaic Reliability Workshop

February 27, 2018
An organized search for root-cause

**Light and Elevated Temperature Induced Degradation (LeTID)**
- Multicrystalline LID
- PERC LID
- Carrier-Induced Degradation (CID)

**WHAT**

**WHERE**

**WHEN**

**WHY**

**WHO**

*today’s focus*
WHAT is LeTID?

modules [1]

Degradation followed by regeneration under the same conditions

Accelerate timescale with higher temperature and illumination intensity

wafers [3]

WHEN and WHERE does LeTID occur?

**degradation conditions [1]-[7]**

- Temperature: 50°C up to 140°C
- Illumination intensity: 0.15 up to 44.8 kW/m²

**cell architecture [1]-[4]**

- Enhanced in PERC vs. Al-BSF
- High temperature firing step required

**substrates**

- First observed in multicrystalline silicon
- Recent observations of similar behavior in Czochralski [8] and Float-Zone [9]
- Enhanced as-grown compared to after gettering [3], [10]-[11]

---

WHY does LeTID occur?

**carrier-induced degradation (CID)**

- Dependence on operating condition – faster degradation at $V_{oc}$ [1]
- Degradation rate directly proportional to excess carrier density [2]-[3]

**PERC vs. Al-BSF**

- Is PERC just more sensitive to bulk lifetime changes?
- Slower or no degradation in Al-BSF likely due to lower operating injection level

---

WHO – what defect is causing LeTID?

**recombination activity**

possible defect parameters [1], [2]

![Graph showing recombination activity and possible defect parameters](image)

Significant difference between undegraded and degraded recombination

High $k$ value [1]-[4] – positively-charged, donor-type defect

Recombination-active defect forms early in degradation and increases in concentration

Temperature-dependent $k$ **consistent** with reported values for Mo, but **not** Ti or W

*true defect may not yet be characterized

---

WHO – what defect is causing LeTID?

**solubility and diffusivity [1]**

**Hypotheses:** metal impurity causes LeTID, metal impurity distributions change during firing, metal precipitates may be related to LeTID

- Metal-rich particles **decrease in size** but **increase in density** after firing

- **Solubility and diffusivity** required for sufficient interstitial increase consistent with fast diffusers like Cu and Ni, Co [2]-[3]

---

**Hypothesis:** Hydrogen is at the root cause of LeTID, either forming a recombination-active complex or associating/dissociating from the background bulk defect during degradation and subsequent regeneration.

FIG. 5. Illustration of the first two hydrogenation cycles. Top left: Hydrogen passivation of boron atoms in the first few microns (170°C). Bottom left: Indiffusion of hydrogen into the sample bulk (250°C). The boron atoms in the first few microns can trap hydrogen again. Bottom right: Re-passivation of boron atoms in the first few microns (170°C). Top right: Further indiffusion of hydrogen into the bulk. Cyclic application of these steps yields an augmented hydrogen concentration in the bulk.

WHO – what defect is causing LeTID?

*Bulk hydrogen* (rather than firing time-temperature) is necessary for degradation to occur.

*Bulk hydrogen* is not the only prerequisite: firing without hydrogen renders the defect inactive.

*Excess hydrogen* (longer MIRHP times) leads to lower LeTID defect concentrations.

HOW does the LeTID defect cause degradation?

inspiration for a physics-based model [1]

<table>
<thead>
<tr>
<th>state 1</th>
<th>after firing, before degradation</th>
<th>( M_i)-( H_x ) complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>state 2</td>
<td>maximum degradation</td>
<td>( M_i ) and ( H )</td>
</tr>
<tr>
<td>state 3</td>
<td>complete regeneration</td>
<td>( M_i)-( H_x ) complex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...or ( M_i ) to surface</td>
</tr>
</tbody>
</table>

for example...

**HOW** does the LeTID defect cause degradation?

**Inspiration for a Physics-Based Model [1]**

<table>
<thead>
<tr>
<th>State 1</th>
<th>After firing, before degradation</th>
<th>$M_i$-$H_x$ complex</th>
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<tbody>
<tr>
<td>State 2</td>
<td>Maximum degradation</td>
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</tr>
<tr>
<td>State 3</td>
<td>Complete regeneration</td>
<td>$M_i$-$H_x$ complex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>...or $M_i$ to surface</td>
</tr>
</tbody>
</table>

**Possible Physics-Based Model**

- $\Delta n$ change leads to changes in [2]-[3]:
  - Occupation probability
  - Charge state fractions
  - Defect complexes

- Possible spectroscopic value in assessing occupation probability in different states [4]-[5]

---

Summary and recommended next steps

**WHAT**
well-defined by experiment

**WHEN**
carrier-induced degradation, especially in higher efficiency devices requiring metallization firing

**WHERE**
side-by-side investigation of multi and monocrystalline LeTID

**WHY**
- define solubility and diffusivity of mobile LeTID defect
- confirm observations of suppressed LeTID with increasing [H]
- define stability of defect/defect complexes in each state through experiment
- compare stability to DLTS studies (Ex. Co-H [1], Pt-H [2])

**WHO**
- mobile component: bulk hydrogen
- metal impurity moves: Cu, Ni, or Co
- metal impurity stationary: Mo or other slow diffuser

**HOW**
- possible modulation of occupation probability through carrier injection
- spectroscopic investigations of occupation probability – experiment and simulation

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- University of New South Wales: Ziv Hameiri, Mattias K. Juhl, Yan Zhu, Carlos Vargas
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  - National Research Foundation Singapore through the Singapore MIT Alliance for Research and Technology’s “Low energy electronic systems (LEES) IRG” research
  - Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center
- Harvard Center for Nanoscale Systems (NSF No. ECS-0335765)
- Advanced Photon Source at Argonne National Laboratory (U.S. DOE No. DE-AC02-06CH11357)
ADDITIONAL SLIDES
Existing solutions for PERC mc-Si LETID

Change firing profile [1]-[4]

Change PDG time-temperature profile [5]-[6]

Change bulk material quality [7]

Apply accelerated degradation to finished modules [3], [8]

Require solutions robust to:
- Architecture changes (higher $\Delta n$)
- Cell and module process changes
- Upstream polysilicon and growth modifications

Root cause analysis: Focus on WHY, WHO, and HOW

---

WHEN and WHERE does LeTID occur?

Illumination at 75°C (adapted from [1])

**cell architecture** [1]-[4]
- Enhanced in PERC vs. Al-BSF
- High temperature firing step required

Figure adapted from [4]

**degradation conditions** [1]-[7]
- Temperature: 50°C up to 140°C
- Illumination intensity: 0.15 up to 44.8 kW/m²
- Activation energy [6]:
  - fast $E_A = 0.89 \pm 0.04$ eV
  - slow $E_A = 0.94 \pm 0.06$ eV
- Pre-annealing in dark changes behavior [7]

Figure from [7]

---

WHEN and WHERE does LeTID occur?

Illumination at 75°C (adapted from [1])

substrates

- First observed in multicrystalline silicon (mc-Si)
- High effective defect concentrations as-grown compared to after gettering [3], [10]-[11]
- Recent observations of similar behavior in Czochralski [8] and Float-Zone [9]

WHY does LeTID occur?

carrier-induced degradation (CID)

- Dependence on operating condition – faster degradation at $V_{oc}$ [1]
  \[ \Delta n(I_{sc}) < \Delta n(V_{oc}) \]
- Degradation rate directly proportional to excess carrier density [2]-[3]

WHY is LeTID more pronounced in PERC than Al-BSF?

- High efficiency PERC more sensitive to bulk lifetime changes
- Defect not activated during Al-BSF cell processing
- Slower or no degradation in Al-BSF due to lower operating injection level

WHO – what defect is causing LeTID?

**recombination activity**

*injection-dependent lifetime spectroscopy*

---

**Figure from [2]**

- Estimate defect-related lifetime ($\tau_{SRH}$)
- Calculate possible defect parameters:
  
  \[
  k = \frac{\sigma_n}{\sigma_p} \quad E_t - E_v
  \]

---

- Significant difference between undegraded and degraded
- Midgap parameters:
  
  \[
  26 < k < 36 \ [1]-[2] \quad k = 20 \pm 7 \ [3] \quad 29 < k < 33 \ [4]
  \]
- High $k$ value – positively-charged, donor-type defect [1]

**Candidate defects**: Ti, Mo, W

---

WHO – what defect is causing LeTID?

recombination activity

temperature- and injection-dependent lifetime spectroscopy

Figure from [4]

Molybdenum [5]

\[ 0.3 \text{ eV} < E_t - E_v < 0.7 \text{ eV} \] [2]

\[ E_t - E_i = -0.32 \text{ eV} \text{ or } E_t - E_i = 0.21 \text{ eV} \] [4]

\[ E_t - E_i = -0.21 \text{ eV} \text{ or } E_t - E_i = 0.10 \text{ eV} \] [5]

- Temperature-dependent \( k \) and \( \sigma_n \) consistent with reported values for Mo, but not Ti

*true defect may not yet be characterized

WHO – what defect is causing LeTID?

**solubility and diffusivity [1]**

Hypotheses: metal impurity causes LeTID, metal impurity distributions change during firing, metal precipitates may be related to LeTID

After firing...
- particles decrease in size but increase in density
- interstitials may remain in bulk and participate in LeTID

Solubility and diffusivity required for sufficient interstitial increase consistent with fast diffusers like Cu and Ni
- Co likely also consistent [2]-[3]

Primary mechanism: segregation from emitter

---

HOW does the LeTID defect cause degradation?

possible physics-based model

- $\Delta n$ change leads to changes in:
  - Occupation probability
  - Charge state fractions
  - Defect complexes

- Possible spectroscopic value in assessing occupation probability in different states [3]-[4]

Recommended next research steps

**WHEN** and **WHERE:**
- Side-by-side comparison of multi and monocrystalline LeTID

**WHO:**
- Define solubility and diffusivity of mobile LeTID defect
- Confirm observations of suppressed LeTID with increasing [H]

**HOW:**
- Spectroscopic investigations of occupation probability – experiment and simulation

**WHO** and **HOW:**
- Define stability of defect/defect complexes in each state through experiment
- Compare complex stability to DLTS studies (Ex. Co-H [1], Pt-H [2])

---

Multi-scale defect characterization of degraded Si, CdTe, and CIGS modules

Steve Johnston

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PV Reliability Workshop
Feb. 27 – Mar. 1, 2018
Lakewood, CO
Outline

• Cameras and imaging techniques
• Module imaging, coring, and characterization
• Examples:
  • Si potential-induced degradation (PID-shunting)
  • CdTe degradation by heat and light
  • CIGS reverse-bias breakdown
Imaging for Photovoltaics

**Princeton Instruments**
- PIXIS 1024BR
  - Si CCD camera
  - Photoluminescence (PL) imaging
  - Electroluminescence (EL) imaging
  - Reverse-Bias EL imaging (ReBEL)

**FLIR**
- SC2500N
  - InGaAs camera
  - PL and EL imaging
    - Band-to-band
    - Defect band

**Cedip Silver 660M**
- FLIR SC5600-M
  - InSb camera
  - Lock-In Thermography
    - Dark (DLIT)
    - Illuminated (ILIT)

- Silicon charge-coupled device (CCD) 16-bit camera with 1024 x 1024 pixels (13 µm pixel pitch), cooled to ~ -60°C
- InGaAs 14-bit lock-in camera with 320 x 256 pixels (30 µm pixel pitch), uncooled
- InSb 14-bit lock-in camera with 640 x 512 pixels (15 µm pixel pitch), cooled to ~80K
- Various lenses for each camera for fields of view from ~1 mm up to full module size.
Module imaging:

• Enclosure for dark background.

• Laser-rated curtains.

• Motion control stages and various camera lenses for full module and zoomed-in fields of view.
Returned from field with PID-s failure

Roof installation, about 3 years; system voltage about 390V.

15% power drop
Mostly due to fill factor of 69% instead of typical 76%+ and MPP current of 7.4A instead of typical 8.2A+.

Most degraded cells with PID signature of shunts near frame.
Example of higher resolution images of PID-s defect areas on the module

areas marked for coring
Core Selected Areas from Degraded Modules

- Accurately locate defects on the backsheet using thermal imaging.
- Use paper template to record defect locations.

Frame partially removed for defects near the edge.
Through-the-backsheet Coring of a Si Module

Dremel tool to remove backsheet.

Cores from ~12 to 25 mm diameter

Dissolve glue in acetone.

Wrench for shear stress.

Glue on post

Diamond-based coring drill bit

Cored area

8
Si coring and zoom imaging

EL before coring

(≈2 to 3 mm between grid lines)

PL after coring

Area within red outline is unchanged after coring.

DLIT showing shunt locations

2.5 mm

○ Laser marks
Use laser marks and EBIC to further zoom into shunt defect.

DLIT

FIB marks → SEM

EBIC

EBIC

Shunt

25µm

1 mm
Use laser marks and EBIC to further zoom into shunt defect

DLIT

FIB marks SEM

EBIC

Ga\(^{+}\), Na\(^{+}\) TOF-SIMS Image
Sodium at a concentration of 0.1-1 atomic % decorating a structural defect consistently observed.
Dwelling SEM beam anneals shunt

- Sodium segregates to the surface upon PID recovery of a single shunt.

3-D rendering of sodium signal 300x300x0.3µm
Electron-beam annealed shunt – different Na profile

- Sodium segregates to the surface upon PID recovery of a single shunt.

![Image of Electron-beam annealed shunt – different Na profile](image)

- Annealed shunt
- Non-annealed shunt

- Sodium Concentration (cm$^{-3}$) vs. Sputter Time (s)

- ~70nm
- ~300nm

- Graph showing Sodium Concentration (cm$^{-3}$) over Sputter Time (s) for Annealed Shunt and Non-Annealed Shunt.
PL imaging of CdTe solar cells and modules

- Photoluminescence (PL) imaging
- Electroluminescence (EL) imaging
Stress mini-module with ~1-Sun light and 100° C

Module performance degradation over ~400 hours

Before stress

After stress

~1-Sun excitation intensity

PL

Before stress

After stress

12 cm
Core selected areas from degraded modules

Use diamond-based coring bit to cut through glass and thin film, and then glue posts to cored glass.

After the glue is set, use a wrench to shear the sample from the module.

Soak in acetone to dissolve Super Glue and remove post. Or, use a short post that fits in measurement tools and does not need to be removed.

Cored samples: ~12 to 25 mm diameter
### PL imaging on cored regions from degraded CdTe mini-module

<table>
<thead>
<tr>
<th>Degradation Level</th>
<th>PL Imaging</th>
<th>Average PL Counts per Minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Least degraded</td>
<td><img src="image1.png" alt="Image" /></td>
<td>8000</td>
</tr>
<tr>
<td>Mid-degraded</td>
<td><img src="image2.png" alt="Image" /></td>
<td>6700</td>
</tr>
<tr>
<td>Most degraded</td>
<td><img src="image3.png" alt="Image" /></td>
<td>3000</td>
</tr>
</tbody>
</table>

**25 mm**

---

*National Renewable Energy Laboratory*
Cu profiles of stressed CdTe cores using Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)

More Cu detected at the front interface correlates to reduced PL intensity and more degradation.
Kelvin Probe Force Microscopy (KPFM) potential imaging on cross-sections of stressed CdTe cored samples

Ion transport (Cu-ions) to front junction leads to [1]:
• deep defect generation – increased carrier recombination (reduced PL intensity), and
• shallow centers for increased doping.

Increased shallow acceptors due to degradation leads to narrower space charge region.

Partial Shading and Field-degraded CIGS Modules

- ~10 years, $P_{\text{max}}$ change: $-0.70 +/- 0.08$ %/year;
- Degradation is primarily in fill factor (FF).

EL dark spots correspond to shunts seen by thermal imaging (DLIT)

5% immediate power loss from partial shading

\[ V_{\text{fwd}} \]
\[ V_{\text{rev}} \]

Damage in Monolithic Thin-Film Photovoltaic Modules Due to Partial Shade
Timothy J. Silverman, Lorelle Mansfield, Ingrid Repins, and Sarah Kurtz,

(cells are ~5 mm wide)
Cross-sectional SEM views of wormlike defects

- Voids create raised bumps within the material.
- Voids appear in the CIGS layer, often near the top ZnO interface.
- Defects appear to grow when voids propagate along the CIGS/ZnO interface.

Cross-section across defect.

Cross-section along direction of propagation.
Observe breakdown using a thermal (InSb) camera – detect heat signature from defects

Gradually increase applied reverse bias until breakdown initiates. Wormlike defects form and propagate.

But, if significant reverse bias is applied and current is limited, breakdown sites may become apparent without wormlike defects or any significant damage.
### Predicting the origins of worm-like defects

- We stressed pairs of cells by applying $20 \, V_{\text{rev}}$ but limited current to $< 0.2 \, \text{mA/cm}^2$.
- For each test, we count localized hot spots.
- Then, we allow more current to flow and watch where wormlike defects originate.
- We compare how many sites were accurately predicted.

<table>
<thead>
<tr>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 1</th>
<th>Sample 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted</td>
<td>4</td>
<td>9</td>
<td>10</td>
<td>12</td>
</tr>
</tbody>
</table>

- Some different breakdown sites appear.
- Some wormlike defects begin near a scribe line,
- While others originate within the cells.

45/46, or $\sim 98\%$ of current-limited hot spots became breakdown sites.

Overall, 45/53 $\sim 85\%$ predicted breakdown sites.
Suspected breakdown defect sites – tested with low current

**Overhead SEM view**

**FIB cross-sectional SEM view**

**Pinhole/pit/crater type**

**Nodule/bump/inclusion type**
Summary and Acknowledgements

• PL, EL, and thermal imaging used to identify non-uniform degradation.
• Coring of different sample areas from modules for microscopic analysis.
• Si, CdTe, and CIGS modules;
• Degradation mechanisms such as PID-s, heat, light, and partial shading.
• Marco Nardone at Bowling Green State University uses experimental results to build Comsol models for various degradation mechanisms.
• Future topics: scribe-line related breakdown sites, other PID (corrosion, thin-films), high-efficiency module types; LID/LeTID.

Acknowledgements: This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.
Materials forensics for understanding PV module material durability

Laura T. Schelhas
SLAC National Accelerator Laboratory

Collaborators:
Stephanie Moffitt, Mike Toney (SLAC)
Robert (Drew) Fleming, Corey Thompson (WattGlass)
Outline

• What is materials forensics?
  – And how can it help PV reliability

• Where are the problem areas?
  – And what are we doing to address them...

• Deeper dive: Anti-soiling coatings (ASC)
  – Motivation – dirty modules are bad...
  – Morphology/Surface chemistry

• Conclusions/Summary
What is materials forensics?

And how can it help PV reliability?

1. Decide on PV interface/materials
2. Source samples
3. Characterize
4. What is not understood?
5. Tool Development
6. How has it failed?
7. New interface
   Or repeat

What is not understood?

• Field-test
• Acc. age

Improve
What is materials forensics?

And how can it help PV reliability?

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What is not understood?

Tool Development

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Source samples
What is materials forensics?

*And how can it help PV reliability?*

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What is not understood?

**DuraMAT**

Durable Module Materials Consortium

Source samples

Tool Development

Improve
3. Backsheets: 
**Numerous interfaces of interest:**
- Backsheet --- Cell
- Backsheet --- Environment
- Intralayer interfaces within backsheets

**Important problem areas:**
- Embrittlement
- Adhesion
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TPE – aged backsheets show measurable structural changes via XRD

Collaboration w/ Peter Hacke (C-AST)
Interfaces & surfaces common failure points

2. Encapsulant --- Cell
Initial focus area: Metal/encapsulant
Metals: Solder, busbar, interconnects, contacts
Important problem areas:
• Delamination
• Corrosion
Characterize: Microstructure + chemical environment
Interfaces & surfaces common failure points

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• Delamination
• Corrosion
Characterize: Microstructure + chemical environment

Collaboration: Nick Bosco
Cell aged: 400 hr, 85%RH/85°C, 1kV
Ripped apart
Chemical analysis of heterogeneous degradation ongoing
Interfaces & surfaces common failure points

1. Glass/Coating --- Environment
   - Durability – adhesion to top glass (PVQAT)
     - Abrasion + wear over time
   - Chemical interfaces – dirt to coating interface (DuraMAT)
     - Morphology and surface chemistry functionality
Interfaces & surfaces common failure points

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See DuraMAT capability 3 poster (Moffitt/Toney) for more details...
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   • Adhesion

See DuraMAT capability 3 poster (Moffitt/Toney) for more details...
Motivation for anti-soiling coatings (ASC)

- 60% loss after sandstorm or 0.4-0.8% loss by average daily dust
- Must deploy a large workforce to clean the modules
- Water can be a scarce resource
- Cleaning can damage the panels

Potential solution is to create a coating resistant to soiling.

Many research efforts have focused on micro-structuring of coatings, but not the chemistry of the surface.

Goal: Develop a better understanding of chemistry and morphology behind the anti-soiling coatings.
Forensic approach to understanding ASC durability

Pristine anti-soiling coatings:
- Porous morphology which reduces flat area available for Van Der Waals binding of soil particles (SAXS/SEM)
- Hydrophobic/hydrophilic surface chemistry (XPS/XAS):
  - discourages chemical bonding of soil molecules
  - Promotes self-cleaning
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At SLAC we are exploring the durability of the coatings against:

Changes in surface energy

Infill of pores

Permanent binding of dirt molecules
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Poster: “Advanced Multifunctional Coatings for PV Glass to Reduce Soiling and PID Losses”
Tues/Wed 1:00 pm
Forensic approach to understanding ASC functionality

Part 1: Morphology
• Porous structure discourages soiling
  – Understanding how microstructure of the films evolves with soiling
• SAXS to measure film morphology
• SEM microscopy to image surfaces

Part 2: Surface chemistry
• Chemical environment dictates how soil can bond
• Can evolve after exposure to soil, humidity, temp, etc
  – XAS, XPS to measure evolution
Electrons travel in a ring

X-ray energy is tuned

As they lose momentum high-energy X-rays are created

12 keV

X-rays scatter off the sample

A detector is placed far from the sample to collect the X-rays that scatter at a small angle

3 meters

Small angle X-ray scattering (SAXS) at SSRL
Grazing incidence SAXS geometry

- Industry-relevant samples
- i.e. thick glass vs silicon (transmission)

Detector direction

X-ray path

X-ray energy is tuned 12 keV

Q: scattering vector

0.2°

3 meters
2D images are integrated to 1D $Q$ vs Intensity plots

Intensity is related to the number of X-rays which scatter

$Q$ vector (Å$^{-1}$) $Q$ is related to the scattering angle
WattGlass pristine samples show good uniformity

- Good uniformity between samples
WattGlass pristine samples show good uniformity

- Good uniformity between samples
WattGlass pristine samples show good uniformity

In-plane GI-SAXS

Primary Feature

- 20 nm spheres

Secondary Feature

Bigger features

Smaller features

- slightly larger than 20nm spheres \((2\pi)/Q\)
Soiling Protocol:

1 cycle AZ dust (sample SLM35)
- 5 seconds of creating a dust cloud
- 1 minute of letting the dust settle
- Gently tap excess dust off

Water Bubbler

28% humidity
20.5° C

Dirt

Sample

Air Line
Soiling Protocol:

1 cycle AZ dust (sample SLM35)
- 5 seconds of creating a dust cloud
- 1 minute of letting the dust settle
- Gently tap excess dust off

5 cycle AZ dust w/ final wipe (sample SLM39)
- After soiling, rinse w/ filtered water
- Repeat soiling 4 more times
- Gently tap excess dust off
- Wipe w/ a kimwipe

*Extreme testing protocol, have not yet confirmed against real world conditions*
Soiling Protocol:

1 cycle AZ dust (sample SLM35)

5 cycle AZ dust w/ final wipe (sample SLM39)
1 soiling cycle shows little change to morphology

In-plane GI-SAXS

Watt on glass (SLM35)
Watt on glass (SLM39)
1 cycle AZ dust (SLM35)

Intensity (counts)

Q vector (Å⁻¹)
1 soiling cycle shows little change to morphology

- In-plane GI-SAXS
- Watt on glass (SLM35)
- Watt on glass (SLM39)
- 1 cycle AZ dust (SLM35)

- Micron-sized dust
- 20 nm spheres
- Bigger features
- Smaller features

Intensity (counts) vs. Q vector (Å⁻¹)
5 soiling cycles shows loss of contrast

In-plane GI-SAXS

- Watt on glass (SLM35)
- Watt on glass (SLM39)
- 1 cycle AZ dust (SLM35)
- 5 cycle AZ w/ final wipe (SLM39)

Intensity (counts)

Q vector (Å⁻¹)
5 soiling cycles shows loss of contrast

- In-plane GI-SAXS
  - Pores filling with dirt? = Loss of contrast
  - Watt on glass (SLM35)
  - Watt on glass (SLM39)
  - 1 cycle AZ dust (SLM35)
  - 5 cycle AZ w/ final wipe (SLM39)

Intensity (counts) vs. Q vector (Å⁻¹)
SEM shows loss of microstructure

- Pristine
- 5x dirt + wash/wipe
XPS shows evidence of residual dirt in 5x sample
Forensic approach to understanding ASC functionality

Part 1: Morphology
• Porous structure discourages soiling
  – Understanding how microstructure of the films evolves with soiling
• SAXS to measure film morphology
• SEM microscopy to image surfaces

Part 2: Surface chemistry
• Chemical environment dictates how soil can bond
• Can evolve after exposure to soil, humidity, temp, etc
  – XAS, XPS to measure evolution
XPS results show shifts in Oxygen environment

- Small changes in oxygen 1s:
  - Change in the coating chemistry (1x - brown)
  - Chemisorption of dirt particles (5x - black)
Summary + next steps

Forensic analysis of interfaces on going:
- Cell/Encapsulant
- Backsheets
- Air/glass (coatings)

ASC coatings demonstration:
- Observed microstructural changes to the coatings after soiling
  - Hypothesis back filling of the pores with soluble dirt components
- Chemical environment of the coating evolving with soiling
  - XAS analysis on-going
- Preliminary results acquired
  - Systematic soiling study planned March 2018

New areas for materials forensics approach?
Acknowledgements

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Michael F. Toney (right)
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DuraMAT
Durable Module Materials Consortium

Energy Materials Network
U.S. Department of Energy

Corey Thompson (left)
corey@wattglass.com
Robert (Drew) Fleming (right)
drew@wattglass.com
## XPS chemical analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>C 1s (atomic %)</th>
<th>O 1s</th>
<th>Si 2s</th>
<th>Na 1s</th>
<th>Ca 2p</th>
<th>Mg 2s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean</td>
<td>4.8 ± 0.4</td>
<td>60.3 ± 0.3</td>
<td>34.8 ± 0.9</td>
<td>&lt;1, &gt;0.1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1 cycle Az</td>
<td>5.9 ± 0.5</td>
<td>59.1 ± 1.5</td>
<td>34.4 ± 1.7</td>
<td>0.6 ± 0.1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5 cycle + wash + wipe</td>
<td>23.1 ± 1.2</td>
<td>47.7 ± 1.5</td>
<td>24.8 ± 1.0</td>
<td>2.1 ± 0.2</td>
<td>1.7 ± 0.3</td>
<td>&lt;2, &gt;0.2</td>
</tr>
</tbody>
</table>
Loss of SAXS contrast hypotheses

Reason contrast may disappear:

1) Morphology has filled w/ AZ dust
   • Primary component is silica
   
   - Cuddihy 1980 - “sub-surface deposition of particles may be caused by solubility of salt solutions”
   
   - Isle 2016 - in evidence of cementation process fibrous structures left behind after water cycling included Si, Mg, Al, Fe, Na, Ca. Needles look about 16nm. Condensation but not rain, 28 days.

2) Coating is no longer on the glass
   • Soiling method may be too vigorous
Water content imaging in photovoltaic module packaging materials

Mihail Bora
Who cares about water?

Thin film

Flexible barriers

Double glass design

Silver alternatives

Floating solar
It is easier to solve a problem that is measurable.
Hydroscanner: water content imaging

Water content: when, where and how much
- 10 um spatial resolution
- $10^{-5}$ by weight concentration resolution
- Water Vapor Transmission Rate comparable to calcium test

Tested on various samples
- Components: back sheet, encapsulant, front sheet
- Laminates
- Modules: breathable and double glas
Fundamental principle of operation

Transmission spectra of wet (85 °C, 85% relative humidity) and dry ethylene vinyl acetate (EVA)
Water absorption band at 4000 to 3000 cm\(^{-1}\)
Spot testing of laminate samples

Spectroscopic testing can determine both concentration and diffusion coefficient.
Back sheet imaging

The effective concentration in the wet spot is \( \sim 0.24\% \)
Concentration resolution \( 10^{-5} \) by weight
Time evolution and steady state

Concentration profile is linear in steady state (~2 hours)
Average saturation normalized concentration 0.5
Laminate encapsulant testing

Ethylene vinyl acetate under damp heat testing conditions followed by moisture release at room temperature. Fick’s diffusion model does not fit the experiment.
Module testing

Imaging of the space in between cells
Breathable module room temperature partial immersion in water
Double glass module testing in damp heat conditions
Defect detection in moisture barriers

Sample scribed to damage the oxide and allow water diffusion inside the substrate
Exposure to water for 2 hours
Visual inspection of the damage

Side illumination and black background for better scattering contrast
Imaging for defect detection

Sample tested after exposure to water

Sample tested 24 hours later
Moisture diffused out

Detection of water diffusion in the substrate through the scratch
Scattering is reduced in infrared vs visible because of longer wavelength
Laminate barrier testing

Water that passes through the defect diffuses on the underside of the barrier and into EVA.

Defect size increases with exposure time.
Summary

Developed a method to map water content in photovoltaic packaging materials
Acknowledgement

SETO provided funding for this work

Collaborators and organizations that send us samples for testing:
Vitriflex, 3M, Canadian Solar, DNV-GL, D2Solar, MiaSolé, Prism Solar Technologies, Tomark-Worthen
The instrument can be loaned for evaluation

Cooperative Research and Development Agreements, ‘No cost’

Future applications through DuraMAT.org

bora1@llnl.gov
Thermal-mechanical modeling of PV modules and components

James Y. Hartley† (SNL), Scott A. Roberts (SNL), Nick Bosco (NREL), Laura Schelhas (SLAC)

†Thermal Sciences and Engineering Department
Sandia National Laboratories, Albuquerque, NM

February 26, 2018
NREL Photovoltaic Reliability Workshop, Lakewood, CO
Outline

- Predictive simulation: Motivation and vision
- Modeling capability development and applications
  - Module level modeling
  - Cell level model
  - Coupled electrical modeling
- Complementary experimental efforts
- Discussion and next steps
Motivation and vision

- Predictive simulation is a tool that enriches characterization, testing, design, and data analytics in the PV durability space.

What is the driving force for delamination between layers?

What about a fielded design could have led to mass failures?

What encapsulant properties are most associated with cell cracking?

Are we really capturing a lifetime of exposure in accelerated tests?

DuraMAT Capability Area 2: Predictive Simulation

“This capability will be a suite of modeling and simulation tools, model workflows, and a community of experts who work in concert with experiments and data analytics… to help interpret and enrich existing test/experimental data, design durability-testing experiments, and help create design rules for Materials Discovery”
Outline

- Predictive simulation: Motivation and vision

- **Modeling capability development and applications**
  - Module level modeling
  - Cell level model
  - Coupled electrical modeling

- Complementary experimental efforts

- Discussion and next steps
Modeling Capabilities

- All analysis steps performed in-house:
  - SIERRA engineering mechanics code suite
    - Transient thermal, solid mechanics, thermal-mechanical coupling
    - Many material models, contact interactions, etc.
    - ...anything that defines or could happen to a PV module
  - Meshing (CUBIT) and parametric analyses (DAKOTA) platform
  - High performance computing
- Enables efficient coupling, troubleshooting, and new feature development

Simulation codes and capabilities at Sandia National Labs
Module level models

- Module-scale thermal-mechanical models have been developed
  - Generic thin film and c-Si examples
  - Key areas investigated: Behavior of large laminate sheets, adhesives, frame members including connections and fixturing

Representative finite element models of thin film and c-Si modules
Module level model capabilities and applications

- Able to accept thermal and mechanical inputs, transient or steady state
- Applications: Boundary condition determination for cell level models and experiments, areas of interest under environmental loads

Is testing a 2x2 cell mini-module representative?

**Thermal load:**

25°C -> 85°C

What cell positions see the most stress, under what loads?

Are cell stresses symmetric?

Modeled c-Si module state at 85°C with boundary conditions
Cell level model

- Cell-scale thermal-mechanical model
  - Adds resolution of interconnects and solder not included in module-scale models
  - Uses domain of two quarter cells and interconnects between them
    - Mostly symmetric stress distribution observed from module scale studies
  - Key areas investigated: Stress generation at solder and material interfaces

Representative cell-level models (Glass and EVA hidden for clarity)
Cell level model capabilities and applications

- Able to accept thermal and mechanical inputs, standalone or mapped from module scale models
- Applications: Understand component level stresses and directions, design sensitivity studies (with semi-automated meshing and parameter sampling)

Variable geometric parameters of interest to stress generation

- Are there detectable trends between geometry and stress magnitudes?
- Can we develop some design rules for reliability?
- What $G_c$ measurement is most applicable to delamination?
Coupled electrical modeling

- Coupled electrical characteristics may be modeled as equivalent circuits
  - Accepts environmental illumination as input, solves for voltage, current to find heat generated, coupled to thermal model
    - Applies best to thin film technologies (can assume heat generation from one surface)
  - Applications: Prediction of steady state operating temperatures under variable lighting, input to study shunting or hotspot thermal mechanical effects

\[ I = I_L - I_0 \left[ \exp \left( \frac{V + IR_s}{nVT} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \]

Schematic of equivalent circuit models and spatial mapping to a thermal model
Outline

- Predictive simulation: Motivation and vision
- Modeling capability development and applications
  - Module level modeling
  - Cell level model
  - Coupled electrical modeling
- Complementary experimental efforts
- Discussion and next steps
Some complementary experimental efforts

- Experimental efforts are directed at materials characterization and model validation (and sometimes both):

  - Materials Characterization:
    - **Encapsulant mechanical properties**
      - Viscoelasticity, temperature, processing, aging
    - Commercial EVA to start, compare with alternatives
  
  - Model Validation
    - Module scale deflection vs. load tests (thermal and mechanical loads)
    - Cell scale deflection vs. load tests (thermal and mechanical loads)
    - Predicted stress vs. interface adhesion strengths + observed failures
    - Novel in-situ techniques

*Win Win Precision Technology Co., Ltd.*

*Sinovoltaics.com*
Outline

- Predictive simulation: Motivation and vision
- Modeling capability development and applications
  - Module level modeling
  - Cell level model
  - Coupled electrical modeling
- Complementary experimental efforts
- Discussion and next steps
Discussion and next steps

- Modeling capability build-out mostly complete
  - Model validation and materials characterization ongoing
  - Many features to be added in parallel with experiments: Viscoelasticity, viscoplasticity/fatigue models, cohesive zones, contacts and interactions as indicated by validation testing

- Some areas for collaboration- we could improve capability with your:
  - Material samples
  - Material processing history information
  - New and aged modules, cell assemblies, components
  - Lab collected module or component test data
  - Feedback on specific failures and issues
  - Feedback on open knowledge gaps
Discussion and next steps

Capability 2

Simulation Build-Out
- Module-level model build-out begins
- Exercise sub-models to determine property needs
- Design sub-model validation requirements
- Sub-model Parametric studies

Application and Validation
- Sub-model validation
- Module scale parametric studies and application

DuraMAT Begins
- Q1-2017
- Q3-2017
- Q1-2018
- Q2-2018
- Q2-2019
- Q1-2020

Scoping Studies
- Scope required sub-models
- Scope module-scale model requirements

Materials Characterization and Validation Experiments
- Capability build-out
- Material properties measurements
- Sub-model validation experiments

Documented and Packaged Capability
Automatic detection of clear sky periods using ground and satellite based solar resource data

Benjamin Ellis, Michael Deceglie, and Anubhav Jain

2/27/2018
Motivation

NREL and kWh Analytics are developing RdTools for calculating degradation rate of PV systems.

Recent study illustrated the importance of considering clear sky conditions in degradation rate calculations.

RdTools is seeking a robust, out-of-the-box method for clear sky detection.

Filtering clear sky periods significantly changes calculated degradation rate!

D. C. Jordan, C. Deline, S. R. Kurtz, G. M. Kimball, and M. Anderson, “Robust PV Degradation Methodology and Application,” Accepted JPV.
Clear sky detection

Identifying clear sky periods is relatively easy to do by eye
Clear sky detection

Identifying clear sky periods is relatively easy to do by eye

- Persistent clouds
- Scattered clouds
- Generally clear
Previous work

Reno and Hansen (PVLib) method determines clear sky periods by comparing measured irradiance (GHI) to modeled, clear sky irradiance (GHI\textsubscript{CS})

This method calculates five features along a moving window between the two irradiance curves

Clear periods occur in windows where the difference of features are all below user-defined thresholds (clear skies are defined as periods where GHI and GHI\textsubscript{CS} are indistinguishable)

PVLib features

1. Difference of mean GHI and GHI\textsubscript{CS}
2. Difference of maximum GHI and GHI\textsubscript{CS}
3. Difference of line length of GHI vs. time curve and GHI\textsubscript{CS}
4. Difference of standard deviation of slopes in GHI and GHI\textsubscript{CS}
5. Maximum difference in slopes between GHI and GHI\textsubscript{CS}

If the all five features are below corresponding thresholds, the periods are labeled as clear sky

Generalizing PVLib detection

PVLib classifications compare well to previous detection schemes at multiple locations.

Reno and Hansen method has a few drawbacks:

• What are the right thresholds to use (default values assume 1-minute data)?
• Do thresholds change based on location?
• Does data frequency affect the thresholds?

We are developing methods that automatically learn these thresholds.

Our work will enable PV researchers to consistently filter and identify clear sky periods at multiple locations and frequencies by providing optimal thresholds.
Automatic threshold determination

We automatically determine the thresholds by minimizing the error in PVLib determinations versus known sky conditions.

Measured GHI comes from ground-based collectors at sites in the NREL MIDC network.

Known sky conditions are taken from satellite determination via the NSRDB.
MIDC and NSRDB data

NSRDB:
- 30 minute frequency
- 4kmX4km spatial resolution (entire USA)

MIDC:
- 1 minute frequency (at selected sites)
- Availability varies based on site
- Needs overlap with NSRDB

SRRL BMS
- Ground (blue) vs. NSRDB (orange)
- RMSE = 97
- RMSE (cloudy) = 159
- RMSE (clear) = 64
- Sep 2007 – June 2012
Scoring PVLib versus NSRDB

Only score at every 30\textsuperscript{th} minute due to NSRDB frequency restriction

Scoring using $F_{0.5}$ score which stresses precision - important in RdTools application

\[ F_\beta = \frac{(1 + \beta^2) \cdot \text{true positive}}{(1 + \beta^2) \cdot \text{true positive} + \beta^2 \cdot \text{false negative} + \text{false positive}} \]

\[ = (1 + \beta^2) \cdot \frac{\text{precision} \cdot \text{recall}}{(\beta^2 \cdot \text{precision}) + \text{recall}} \]
Data cleaning

Filter out any periods missing cloud data from NSRDB

Ignore periods that violate working definition of clear sky (GHI and GHI\textsubscript{CS} be indistinguishable)

There are many cases where periods are labeled as cloudy despite close agreement between GHI and GHI\textsubscript{CS}

Likewise there are periods that are labeled as clear that have large differences between GHI and GHI\textsubscript{CS}

All measured values are within 60 W/m\textsuperscript{2} from clear sky curve

These points are considered to be mislabeled and are removed
Input irradiance and set of PVLib parameters

Use optimization algorithm to predict next set of parameters using previous parameter sets and errors

Score PVLib classifications versus NSRDB labels

If error is low enough, return PVLib parameters

Optimization procedure
Optimization algorithms

Genetic algorithm

• ‘Survival of the fittest’ eventually converges on a set of optimal thresholds

• Evaluate error between NSRDB and a population of PVLib thresholds

• Generate next generation based on a subset of the best performers (lowest error)

Gaussian process

• Learn the relationship between PVLib and NSRDB error over set of potential thresholds

• Predict new sets of PVLib thresholds based on previous sets and errors

• Explore regions of threshold space where minima may exist
Genetic algorithm results
Results for 6 MIDC sites at frequencies of 5, 10, 15, and 30 minutes

No optimized results for 1-minute data because genetic algorithm is too slow

<table>
<thead>
<tr>
<th>Freq</th>
<th>BMS</th>
<th>HSU</th>
<th>LMU</th>
<th>ORNL</th>
<th>LRSS</th>
<th>UNLV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.911</td>
<td>0.915</td>
<td>0.938</td>
<td>0.862</td>
<td>0.913</td>
<td>0.955</td>
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<tr>
<td>10</td>
<td>0.911</td>
<td>0.914</td>
<td>0.946</td>
<td>0.864</td>
<td>0.915</td>
<td>0.959</td>
</tr>
<tr>
<td>15</td>
<td>0.905</td>
<td>0.910</td>
<td>0.944</td>
<td>0.869</td>
<td>0.917</td>
<td>0.958</td>
</tr>
<tr>
<td>30</td>
<td>0.892</td>
<td>0.907</td>
<td>0.944</td>
<td>0.857</td>
<td>0.907</td>
<td>0.958</td>
</tr>
</tbody>
</table>

F-scores calculated using genetic algorithm
Visualized results (BMS, 30 minute frequency)
Visualized results (BMS, 15 minute frequency)
Visualized results (BMS, 10 minute frequency)
Visualized results (BMS, 5 minute frequency)
Default thresholds versus optimized thresholds (BMS, 30 minute data)

Optimized PVLib thresholds

Visual inspection shows good performance

Default PVLib thresholds

Some obvious misses on both days
Default thresholds versus optimized thresholds
(BMS, 5 minute data)

Optimized PVLib thresholds

Default PVLib thresholds
Poor performance on first day, better performance on second
Gaussian process results

Results for BMS site

Optimized parameters for 30, 15, 10, 5, and 1-minute frequency data

Scores are slightly lower than genetic algorithm

F-scores for optimized PVLib thresholds at BMS

<table>
<thead>
<tr>
<th>Freq</th>
<th>30</th>
<th>15</th>
<th>10</th>
<th>5</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian process</td>
<td>0.877</td>
<td>0.888</td>
<td>0.893</td>
<td>0.885</td>
<td>0.832</td>
</tr>
<tr>
<td>Genetic algorithm</td>
<td>0.892</td>
<td>0.905</td>
<td>0.911</td>
<td>0.911</td>
<td>N/A</td>
</tr>
<tr>
<td>Default</td>
<td>0.496</td>
<td>0.609</td>
<td>0.744</td>
<td>0.838</td>
<td>0.901</td>
</tr>
</tbody>
</table>
Visualized results (30 minute frequency)
Visualized results (15 minute frequency)
Visualized results (10 minute frequency)
Visualized results (5 minute frequency)
Visualized results (1 minute frequency)
Conclusions

We have displayed a method for automatically determining PVLib thresholds by combining ground and satellite solar resource data.

Both genetic algorithms and Gaussian processes showed promising results; F-scores generally above 0.85.

Future work

Find optimal parameters for PVLib for more sites.

Search of a set of ‘universal’ parameters that provide consistent performance at all locations and data frequencies.

Use optimized clear sky detection in downstream analysis.
Thank you!

Anubhav Jain
Mike Deceglie (NREL and kWh Analytics)
Manajit Sengupta and Aron Habte (NSRDB)

Thank you for your attention!

Stop by the DuraMat Data Management & Analytics poster!
\[ x_1 = \bar{G} - \bar{G}_{CS} \]
\[ x_2 = \max(\{G_i, \ldots, G_n\}) - \max(\{G_{CS,i}, \ldots, G_{CS,n}\}) \]
\[ x_3 = G^{LL} - G^{LL}_{CS} \]
\[ G^{LL} = \sum_{i=1}^{n-1} \sqrt{(G_{i+1} - G_i)^2 + (t_{i+1} - t_i)^2} \]
\[ x_4 = \sigma_G - \sigma_{G_{CS}} \]
\[ \sigma_G = \frac{1}{\bar{G}} \left( \frac{1}{n-1} \sum_{i=1}^{n-1} (s_i - \bar{s})^2 \right) \]
\[ x_5 = \max(|\alpha_{G,i} - \alpha_{G_{CS},i}|) \]

\[ \alpha_G = G_{i+1} - G_i, \forall i \in \{1, \ldots, n-1\} \]
MIDC and NSRDB data

NSRDB:
- 30 minute frequency
- 4kmX4km spatial resolution (entire USA)
- Provides comprehensive set of meteorological data
- Provides several cloud classifications; this work only bins all classifications to ‘clear’ and ‘not clear’

MIDC:
- 1 minute frequency (at selected sites)
- Availability varies based on site
- Needs overlap with NSRDB
Outline

• What do we mean by Harmonization
• IEC PV Standards that have been harmonized already
• What kind of documents should we prioritize for future harmonization
• Documents for harmonization from USTAG meeting on February 26, 2018
What do we mean by Harmonization

• Harmonization of IEC and UL documents
  – UL has much smaller number of PV standards than IEC.
  – First priority should be to accept as much as possible from IEC documents and specify US National Differences where it is necessary.

• Establishment of US National Standards through ANSI
  – In some cases it is important to have a US National Standard.
  – In those cases we must work through a Standards Development Organization (SDO) to get an IEC document accepted as a US National Standard

• We had choice of SDO’s for the second category, but USTAG picked UL as SDO because they could handle both categories.
Safety versus other aspects of Harmonization

- Acceptance of most IEC documents should not require National Difference
- This however does not hold for safety related documents as each developed country has its own methods of insuring electrical safety.
- For example in Europe they use reinforced insulation while in the US we use grounding as main safety approach.
- Therefore most safety related documents will have National Differences.
IEC Standards that have been Harmonized with UL Standards

• UL 1741 on Inverter safety has been harmonized with IEC 62109-1

• UL 1703 on PV Module Safety has been harmonized with IEC 61730-1 and IEC 61730-2
IEC 61730 US National Differences

- Added references to a number of UL documents and National Electric code (NEC).
- Rewrote earthing/grounding to agree with US practice and NEC.
- Reduced voltage for inherent safety from 35 to 30 volts.
- Added some requirements to traceability of manufacturing codes.
- Added UL fire testing requirements and markings.
- Added some clarification on installation instructions.
- Indicated that non-locking connectors are only allowed in low voltage (less than 30 v) systems.
- Increased the pass/fail level for wire and junction box adhesion.
- Deleted the requirement for distance through insulation.
- Clarified how cemented joints can be used.
- Added RTI/RTE requirements that were inadvertently left out of 61730.
Schedule for Implementation of Harmonization of UL 1703 & IEC 61730

• UL 61730-1 and -2 were published in December, 2017

• PV modules may now be safety certified to UL 61730.

• PV module may still be safety certified or recertified to UL 1703.

• After December, 2019 all safety certifications must be to UL 61730.
IEC Standards that are US National Standards

• IEC 61215 Series on Module Qualification has been accepted as a US National Standard
  – Edition 2
  – IEC 61215-1, IEC 61215-1-1 and IEC 61215-2
  – In process IEC 61215-1-2, IEC 61215-1-3, IEC 61215-1-4

• IEC 62108 on CPV Design Qualification

• IEC 62093 on Design Qualification of BOS Components
What kind of documents should we be making US National Standards

- Those that have parallel UL safety documents should be the priority to harmonized.

- Other IEC documents should only be made into US National Standards if they:
  - Can be used for certification
  - Are likely to involve follow up audits
  - Are to be used in a Conformity Assessment System like IECRE.
UL Documents that Should be Harmonized

- UL 6703 for PV Connectors to be harmonized with IEC 62852.
- UL 3730 for PV Junction Boxes to be harmonized with IEC 62790.
- Both of these are necessary and in process as they impact IEC/UL 61730.
IEC Documents that we should make into US National Standards – From USTAG

- IEC TS 62915: Retest Guidelines for Module Qualification and Safety Certification
- IEC TS 62491: Terrestrial photovoltaic (PV) modules – Guidelines for increased confidence in PV module design qualification and type approval
- IEC TS 63049: Terrestrial photovoltaic (PV) systems - Guidelines for effective quality assurance in PV systems installation, operation and maintenance
- IEC 62446-1: Grid connected photovoltaic systems - Minimum requirements for system documentation, commissioning tests and inspection
- IEC 61724-1: Photovoltaic system performance - Part 1: Monitoring
- IEC 61724-2: Photovoltaic system performance - Part 2: Capacity evaluation method
- IEC 62738: Design guidelines and recommendations for ground-mounted photovoltaic power plants
Summary

• There is a lot of Harmonization work ahead for the UL PV STPs.
• Many will be handled by existing STPs, but at least one new STP may be required.
• If you are interested in working on this harmonization effort please see Kent Whitfield or myself.
• The list I have given is only a snap shot as new standards are developed by both IEC and UL. Think arc detection and rapid shut-off.
This presentation was made possible by NREL Subcontract CHQ-7-70067-07 for consulting services and ADC-8-82033-01 to PowerMark Corporation to manage the USTAG to IEC TC82.

Thank You for Attention

The End
Overview of 61215 Edition 2 Development

Presented by Ingrid Repins, NREL, project leader


PV Reliability Workshop; Wednesday, February 28, 2018

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
Overview of 61215 Edition 2 Development

1. Introduction and history of the IEC 61215 series of standards.
2. Document schedule
Additions or changes:
3. Procedures for bifacial modules
4. Addition of dynamic mechanical load test
5. Addition of potential induced degradation test
6. Simulator requirements
7. Use of representative samples
8. Other changes
History of PV Module Design Qualification Standard 61215

• Answer the question: Is it likely that the module will perform as expected over the years?
• Based in empirical observations of field failures, and development of associated accelerated tests.

Jet Propulsion Laboratory executed a series of “block buys” in 1975-1986

Design modules to pass tests
Deploy modules
Identify failures
Define associated accelerated tests

Figure 2. Test apparatus for wet insulation-resistance test.

The proposed test procedure is currently under consideration by research laboratories such as JPL and SERI, module manufacturers, and industry users; it consists of using a simple trough apparatus, shown in Figure 2, containing a tap water/surfactant solution, and of using a spray bottle to “wet” thoroughly both surfaces of the module. Each module edge is immersed in turn in a tap water/surfactant solution and the resistance is measured between the shorted module terminations and the solution with an applied 500 V d.c. test voltage. The edge with the lowest resistance is thus determined; this edge is re-immersed in the solution and the test voltage of 500 V d.c. is applied between the shorted module terminations and the solution. The module is then sprayed with the same tap water/surfactant solution and the resistance is recorded after 2 min. The pass/fail criterion now under consideration is between 100 and 1000 MΩ. Factors behind the selection of this level are described next.

3.2. Wet insulation-resistance pass/fail criterion

The basis of the proposed qualification test is the characterization of the module’s insulation-resistance, which can be described by two different values: a dry insulation-resistance, R_D, for low-humidity environments, and a wet insulation-resistance, R_w, for high-humidity environments.

For considerations of personal safety and ground-fault arcing, it is the worst-case lowest value of R_w which is likely to be the critical level. However, for long-term electrochemical corrosion, the integrated effects of leakage currents during dry periods must also be considered.

3.4. Moisture effects

Moisture entering a PV module diffuses along interfaces and accumulates in the insulation. The quantity of moisture sorbed by the insulation is a function of the temperature and atmospheric vapor pressure; the amount of moisture sorbed by PV module encapsulants PVB and EVA has been measured and is presented in Figure 4. The retained moisture provides an electrolytic medium for the dissolution of ionizing species, thereby increasing the electrical conductance of the insulation and its interfaces. Increases in the bulk conductivity of PVB and EVA as functions of increasing relative humidity and temperature are shown in Figure 5. Interface conductivities of PVB-glass and EVA-glass combinations are presented in Figure 6 and 7, respectively. Surface conductivity data for the two encapsulants were also measured, but are not presented here.

Increased material and interface conductivities accelerate galvanic corrosion potentials within PV modules.
## History of PV Module Design Qualification Standard 61215

<table>
<thead>
<tr>
<th>Test</th>
<th>Block I</th>
<th>Block II</th>
<th>Block III</th>
<th>Block IV</th>
<th>Block V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Cycles</td>
<td>100 cycles -40 to +90°C</td>
<td>50 cycles -40 to +90°C</td>
<td>50 cycles -40 to +90°C</td>
<td>50 cycles -40 to +90°C</td>
<td>200 cycles -40 to +90°C</td>
</tr>
<tr>
<td>Humidity (humidity / freeze)</td>
<td>70°C, 90% RH, 68 hrs</td>
<td>5 cycles -40°C, 90%RH to -23°C</td>
<td>5 cycles -40°C, 90%RH to -23°C</td>
<td>5 cycles -40°C, 90%RH to -23°C</td>
<td>10 cycles: 20 h at 85°C / 85% RH, 4 h excursion to -40°C</td>
</tr>
<tr>
<td>Hot Spot (intrusive)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mechanical Load</td>
<td>100 cycles ± 2400 Pa</td>
<td>100 cycles ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td>10000 ± 2400 Pa</td>
<td></td>
</tr>
<tr>
<td>Hail</td>
<td></td>
<td></td>
<td>9 impacts ¾” – 45 mph</td>
<td>10 impacts 1” – 52 mph</td>
<td></td>
</tr>
<tr>
<td>High Pot</td>
<td>&lt;15 μA 1500 V</td>
<td>&lt; 50 μA 1500 V</td>
<td>&lt; 50 μA 1500 V</td>
<td>&lt; 50 μA 2*Vs+1000</td>
<td></td>
</tr>
</tbody>
</table>

Aspects of these tests and conditions are the same as what’s in today’s IEC 61215 series.
Incorporation of these accelerated tests and related work into IEC 61215 (design qualification) and IEC 61730 (safety) standards has resulted in typical performance warranties around 25 years (and climbing).

The tests developed in the block buy program increased deployed module lifetime dramatically.

Typical module lifetimes were less than 1 year but are now estimated to be greater than 10 years. (Ten-year warranties are now available.)
IEC 61215: 1993 edition 1
Design qualification for x-Si modules

IEC 61215: 1996 edition 1
Design qualification for thin film modules
• Written with a-Si in mind
• Added wet leakage current test
• Thermal annealing and light soak to characterize power retention

IEC 61215 series edition 2
Design qualification for PV modules
• In progress, the subject of this talk.
• New edition, not an amendment
• CD ready for distribution to WG2
• Expect publication 2018 / 2019

IEC 61215: 2005 edition 2
Design qualification for x-Si modules
• Add wet leakage current, bypass diode thermal tests
• Remove twist test (no module failed)
• Improvements to levels, wording

IEC 61215: 2008 edition 2
Design qualification for thin film modules
• Same tests as 61215
• Some procedural differences

IEC 61215:2016 series edition 1
Design qualification for PV modules
• 61215-1 for requirements, -2 for methods, -1- x for technology-specific instruction
• Test all cell technologies to same standard
• Several requirements made more stringent
• No new tests

Corrigendum to IEC 61215: 2016 edition 1
• Correct some minor mistakes
• Publication expected any day

History of PV Module Design Qualification Standard 61215
Changes in 61215 series, edition 2 (in progress)

1. Introduction and history of the IEC 61215 series of standards.
2. Document schedule

Additions or changes:

3. Procedures for bifacial modules
4. Addition of dynamic mechanical load test
5. Addition of potential induced degradation test
6. Simulator requirements
7. Use of representative samples
8. Other changes
Procedures for Bifacial Modules

- Bifacial modules are qualified under 61215:2016 as if back side produces no power.
- Procedures for bifacial measurement were developed in 60904-1-2. That document is now approved to advance to DTS stage.
- One-sided equivalent irradiance method from 60904-1-2 is used for IV measurement
- Gates 1 and 2 (nameplate verification and performance retention) will be performed at STC, and at highest claimed rear irradiance, or 200 W/m², whichever is larger.
- Tests utilizing current based on $I_{mp}$ or $I_{sc}$ will utilize the higher of the two irradiances.

New edition will check this and apply this higher current during stress tests

IEC 61215-2:2016 tests only this

---

**Electrical Specifications**

<table>
<thead>
<tr>
<th>Specifications</th>
<th>STC</th>
<th>5%</th>
<th>10%</th>
<th>15%</th>
<th>20%</th>
<th>25%</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power ($P_{max}$)</td>
<td>190 W</td>
<td>199 W</td>
<td>208 W</td>
<td>216 W</td>
<td>225 W</td>
<td>234 W</td>
<td>243 W</td>
</tr>
<tr>
<td>Maximum Power Voltage ($V_{pm}$)</td>
<td>55.3 V</td>
<td>55.3 V</td>
<td>55.3 V</td>
<td>55.4 V</td>
<td>55.5 V</td>
<td>55.5 V</td>
<td>55.6 V</td>
</tr>
<tr>
<td>Maximum Power Current ($I_{pm}$)</td>
<td>3.44 A</td>
<td>3.60 A</td>
<td>3.75 A</td>
<td>3.91 A</td>
<td>4.06 A</td>
<td>4.22 A</td>
<td>4.37 A</td>
</tr>
<tr>
<td>Open Circuit Voltage ($V_{oc}$)</td>
<td>68.1 V</td>
<td>68.3 V</td>
<td>68.4 V</td>
<td>68.5 V</td>
<td>68.6 V</td>
<td>68.6 V</td>
<td>68.8 V</td>
</tr>
<tr>
<td>Short Circuit Current ($I_{sc}$)</td>
<td>3.7 A</td>
<td>3.89 A</td>
<td>4.07 A</td>
<td>4.26 A</td>
<td>4.44 A</td>
<td>4.63 A</td>
<td>4.81 A</td>
</tr>
</tbody>
</table>

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*NATIONAL RENEWABLE ENERGY LABORATORY*
Addition of Dynamic Mechanical Load (DML) Test

- Tests for extreme susceptibility to mechanical stress. (E.g. cells that are already cracked at right.)
- 1000 Pa for 1000 cycles, based largely on BP data.
- Enough force and repetition to detect pre-existing problems.
- It is not a module abuse test (1000 Pa = 0.15 psi)
- Test is added in sequence C, between UV and thermal cycling
- Test is taken from IEC TS 62782

Figure 2 NIR Image of selected cells from module produced with too much force on tabber/stringer.

Addition of Potential Induced Degradation (PID) Test

- Some modules degrade after extended system voltage stress (PID).
- Previous edition of 61215 series contained no PID test. This degradation mode is now well-known.
- Use test procedure from IEC TS 62804-1, with harshest of 3 stress levels. (85 °C/ 85% RH/ 96 hrs/ $V_{sys}$)
- Mounting affects PID. Use manufacturer-recommended mounting during test.
- Wet leakage current tested < 8 hours after end of stress.
- Stabilization: Short light soak (0.8 kWh/m²) to reverse charge polarization in Si. Typical light soak for setting metastable state in thin films.
Addition of Potential Induced Degradation (PID) Test

- Data indicate that acceleration factors for current Si products are likely several times larger than those for current thin film products.
- The PID test for Si may be around 20 years equivalent exposure in a climate like Florida, USA.
- Choice was made to subject all modules of all types to the same conditions (harshest in 62804-1) because:
  - Several major module manufacturers had already selected the 85°C/85% RH/96 hr stress level for internal qualification programs.
  - Use of a light soak may lead to some power recovery, justifying increased stress level.
  - Use of modules in PID-prone environments (e.g. very rainy) may warrant a harsh test.
  - Acceleration factors may vary with module design and mounting within a given device technology.
  - The most susceptible designs from each device technology fail.
  - Application of the same conditions to all module designs where possible is consistent with the rest of the standard (now stated explicitly in scope.)

![PID Test Graph](image)

- 61215 test duration
- 61215 pass threshold
Use of “Representative Samples”

• A small fraction of new products anticipated for qualification are much larger than typical test equipment.
• Requiring a test lab to obtain custom test equipment for one product is expensive and would create an unfair barrier to certification.
• Thus, representative samples may be used for applying stress and evaluating gate 2 on very large modules.
• Must include all the components of the module, except some repeated parts.
• A full-sized sample is still required for nameplate verification (gate 1).
• A “very large” module is one that will not fit on the largest commercially-available AAA simulator. (2.6 m x 2.1 m)
• Reduced dimension(s) shall be no less than one half those that define a very large module.
• As per above requirements, one-cell mini-modules, for example, are NOT acceptable for qualification testing.
Change in Simulator Requirements - Wavelength

Simulator options for power measurement in 61215:2016

Class AAA simulator

(A Really Good Simulator)

BBA simulator + reference module of same size and cell technology

(A Really Good Reference Module)

Spectral responsivity of module + BBA simulator spectral data

(Really Good Data)

• **Problem**: Published data show that use of AAA simulator without spectral mismatch correction can result in systematic offset.

• **Lab must specify measurement uncertainty, but cannot do so without knowledge of spectral mismatch to AAA simulator.**

• Furthermore, **with** spectral mismatch correction, CBA simulator provides accurate current measurement.

*Cheat Sheet*: **CBA = class C wavelength distribution, class B uniformity, class A stability**
Change in Simulator Requirements - Wavelength

Simulator options for power measurement in 61215:2016

- **Class AAA simulator**
- **Only for Gate 2**
  (A Really Good Simulator)
- **BBA simulator + reference module of same and cell technology**
  (A Really Good Reference Module)
- **Spectral responsivity of module + BBA simulator spectral data**
  (Really Good Data)

**Improvement:**
- For gate 1 (compare absolute module power with label), remove AAA simulator option, and allow CBA simulators with reference module or spectral data.
- For gate 2 (performance change before and after stress) also allow AAA simulator without spectral mismatch correction.

*Cheat Sheet:* CBA = class C wavelength distribution, class B uniformity, class A stability
Change in Simulator Requirements – Uniformity

- Even with best calibration procedure, uncertainty in power measurement with class B uniformity can exceed 3% for typical Si modules. (Below left graph.)
- For newer, higher fill factor cells, the impact of nonuniformity is even greater. (Below right graph.)
- Require class A uniformity
- Exception: Very large modules may still use class B for nameplate verification

Cheat Sheet: CBA = class C wavelength distribution, class B uniformity, class A stability
Other Changes

- Use of IEC TS 62915 to determine re-test requirements is mandated via use of “shall.”
- Hot spot test fixed. Some instructions for singulated vs. monolithically integrated (MLI) cells were mixed in previous edition. (General method for MLI cells has not changed since IEC 61646.) Edits made so that test procedure is clear and possible (larger current range).
- 5 N weight on junction box during thermal cycling
- Fewer modules in sequence A (performance at NMOT, low irradiance, and T coefficients). However, due to addition of PID test, to complete the entire test flow increases by 1.
- Revisions to NMOT are occurring entirely within 61853-2 (amendment approved for CD as of January 2018). No redundant text or exclusions in 61215.
- Limit bypass diode testing to three diodes.
- Revert insulation test to 2005 version. Do not need to cover all polymeric surfaces with foil. Thus surface tracking can once again be observed.
- Bending test for flexible modules. Bend around mandrill matching manufacturers specified bend radius, 25 times.
- Numerous clarifications and improvements to wording (without changing content).
- Informative annex added to 61215-1 to help users and committees understand why changes were made.
Climate Specific Thermal Cycling, Motivation for IEC 62892

Nick Bosco NREL
2018 PV Reliability Workshop
thermomechanical fatigue in solder


\[ N_f = \frac{1}{2} \left( \frac{K_c}{\Delta T} \right)^{-1/c} \]

Engelmaier model

\[ N_f = K_{CM} \Delta T^{-2} f^{1/3} \exp \left( \frac{E_a}{\delta kT} \right) \]

Norris and Landzberg model

unified viscoplastic constitutive model

\[ \frac{d\varepsilon_p}{dt} = A \exp \left( \frac{Q}{\delta kT} \right) \frac{1}{s^*} \sinh \frac{\sigma^*}{s^*} \]

\[ \sigma^* = \frac{s_h}{\xi} \left( \frac{\dot{\varepsilon}_{pl,eq}}{Ad} \right)^n \left( \frac{\dot{\varepsilon}_{pl,eq}}{Ad} \right)^m \]

\[ s^* = \frac{1}{A} \exp \left( \frac{Q}{\delta kT} \right) \left( \frac{\dot{\varepsilon}_{pl,eq}}{Ad} \right)^n \left( \frac{\dot{\varepsilon}_{pl,eq}}{Ad} \right)^m \]

\[ D \approx W_{pl} = \int |\sigma| d\varepsilon_{pl} \]
simulations and analysis

Damage accumulated during large changes in temperature

Sunny days are less damaging

Short period clouding contributes little to damage

Period and duration of clouding are very important

experimental validation

1cm² III-V cell on carrier
Pb-Sn solder
15 samples per rate
Imaged every ~500 cycles

1cm² III-V cell on carrier
Pb-Sn solder
1 sample per rate
Imaged every 250 cycles

*while cycles are referred to by temperature ramp rate, relative dwell times are also changing

Overall, the trend in overall test time with increasing ramp rate follows the expected trend.

Experimental measurements of crack growth are in good agreement with simulated damage.

finite element modeling

Seven cities examined

<table>
<thead>
<tr>
<th>city</th>
<th>climate</th>
<th>mean monthly max temp (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix</td>
<td>Hot and Dry</td>
<td>38</td>
</tr>
<tr>
<td>Chennai</td>
<td>Hot and Humid</td>
<td>37</td>
</tr>
<tr>
<td>Tucson</td>
<td>Hot and Dry</td>
<td>36</td>
</tr>
<tr>
<td>Bhogat</td>
<td>Hot and Humid</td>
<td>35</td>
</tr>
<tr>
<td>Kalaeloa</td>
<td>Hot and Humid</td>
<td>31</td>
</tr>
<tr>
<td>Golden</td>
<td>Temperate</td>
<td>27</td>
</tr>
<tr>
<td>Sioux Falls</td>
<td>Cold</td>
<td>23</td>
</tr>
</tbody>
</table>

Definition of climates

<table>
<thead>
<tr>
<th>climate</th>
<th>mean monthly max temp (°C)</th>
<th>mean relative humidity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot and Dry</td>
<td>&gt;30</td>
<td>&lt;55</td>
</tr>
<tr>
<td>hot and humid</td>
<td>&gt;30</td>
<td>&gt;55</td>
</tr>
<tr>
<td>temperate</td>
<td>25-30</td>
<td>&lt;75</td>
</tr>
<tr>
<td>cold</td>
<td>&lt;25</td>
<td>All values</td>
</tr>
<tr>
<td>composite</td>
<td>when 6 months or more do not fall within any of the above categories</td>
<td></td>
</tr>
</tbody>
</table>
results and analysis

FEM simulation of solder damage accumulation over one year’s exposure

Comparison of solder damage with mean monthly max temp

We wanted to create a simple equation that could predict the FEM calculated damage.

This equation also gives us an insight about which weather characteristics contribute to solder fatigue damage.

\[ D = K \cdot \text{rev}(T_m)^a \cdot DT^n \cdot \exp\left(\frac{E_a}{kT_{\text{max}}}ight) \]

### Results and Analysis

<table>
<thead>
<tr>
<th>city</th>
<th>( T_{\text{max}} ), mean daily max cell temp (C)</th>
<th>( \Delta T ), mean daily max cell temp change (C)</th>
<th>( r(57) ), number of temp reversals across 57 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chennai</td>
<td>59</td>
<td>35.5</td>
<td>2228</td>
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<tr>
<td>Phoenix</td>
<td>53.4</td>
<td>34.7</td>
<td>1264</td>
</tr>
<tr>
<td>Tucson</td>
<td>53.2</td>
<td>37</td>
<td>1474</td>
</tr>
<tr>
<td>Kalaeloa</td>
<td>51.2</td>
<td>30.7</td>
<td>142</td>
</tr>
<tr>
<td>Bhogat</td>
<td>49.7</td>
<td>27.9</td>
<td>174</td>
</tr>
<tr>
<td>Golden</td>
<td>37.6</td>
<td>33.4</td>
<td>466</td>
</tr>
<tr>
<td>Sioux Falls</td>
<td>25.8</td>
<td>23.5</td>
<td>0</td>
</tr>
</tbody>
</table>

results and analysis

Equivalency of accelerated testing

The same accelerated test will have very different interpretations depending on intended deployment location.
results and analysis

We wanted to create a simple equation that could predict the FEM calculated damage.

This equation also gives us an insight about which weather characteristics contribute to solder fatigue damage.

\[ D = K \cdot \text{rev}(T_m)^a \cdot DT^n \cdot \exp\left(\frac{E_a}{kT_{\text{max}}}\right) \]

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<tr>
<td>Sioux Falls</td>
<td>25.8</td>
<td>23.5</td>
<td>0</td>
</tr>
</tbody>
</table>

If the damage accumulated over 25 years, according to:

\[
D = K \cdot \text{rev}(T_m)^a \cdot DT^n \cdot \exp \left( \frac{E_a}{kT_{\text{max}}} \right)
\]

Is greater than the damage accumulated in 200-250 thermal cycles...

IEC 62892 is suggested to evaluate long-term durability.

<table>
<thead>
<tr>
<th>City%</th>
<th>$\bar{T}<em>{c</em>{\text{max}}}$ °C</th>
<th>$\Delta T$ °C%</th>
<th>$r(55)$%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix, %AZ%</td>
<td>52.1%</td>
<td>33.2%</td>
<td>396%</td>
</tr>
<tr>
<td>Freiburg, %DE%</td>
<td>30.2%</td>
<td>21.5%</td>
<td>38%</td>
</tr>
</tbody>
</table>

IEC 62892: Test procedure for extended thermal cycling of PV modules
Find the maximum module operating temperature according to MST 21 $T_{CON}$

If reducing test time is desired, choose a higher maximum cycling temperature $T_{MAX}$

Calculate the number of equivalent cycles according to:

$$N_e = 150470 \cdot (T_{MAX} - T_{CON} + 125)^2 \exp\left(\frac{1414}{T_{MAX} - T_{CON} + 358}\right)$$

climate specific/ HT acceleration

Test for hot environments, and leverage acceleration at higher cycling temperatures.
95% of the modules represented by the samples submitted for this test should pass an equivalency of 500 thermal cycles.

The number of required cycles therefore scales with the number of modules submitted for test.

Weibull distribution shape parameter of 6.

$$N_R = -N_c^6 \cdot \frac{0.95}{\ln(N)}$$

<table>
<thead>
<tr>
<th>$T_{\text{MAX}}$ $T_{\text{CON}}$ °C</th>
<th>2&amp;</th>
<th>3&amp;</th>
<th>4&amp;</th>
<th>5&amp;</th>
<th>6&amp;</th>
<th>7&amp;</th>
<th>8&amp;</th>
<th>9&amp;</th>
<th>10&amp;</th>
</tr>
</thead>
<tbody>
<tr>
<td>0&amp;</td>
<td>731!</td>
<td>683!</td>
<td>651!</td>
<td>627!</td>
<td>609!</td>
<td>593!</td>
<td>580!</td>
<td>569!</td>
<td>559!</td>
</tr>
<tr>
<td>1&amp;</td>
<td>711!</td>
<td>665!</td>
<td>634!</td>
<td>611!</td>
<td>592!</td>
<td>577!</td>
<td>565!</td>
<td>554!</td>
<td>544!</td>
</tr>
<tr>
<td>2&amp;</td>
<td>693!</td>
<td>647!</td>
<td>617!</td>
<td>594!</td>
<td>577!</td>
<td>562!</td>
<td>550!</td>
<td>539!</td>
<td>530!</td>
</tr>
<tr>
<td>3&amp;</td>
<td>674!</td>
<td>630!</td>
<td>601!</td>
<td>579!</td>
<td>562!</td>
<td>547!</td>
<td>535!</td>
<td>525!</td>
<td>516!</td>
</tr>
<tr>
<td>4&amp;</td>
<td>657!</td>
<td>614!</td>
<td>585!</td>
<td>564!</td>
<td>547!</td>
<td>533!</td>
<td>521!</td>
<td>511!</td>
<td>502!</td>
</tr>
<tr>
<td>5&amp;</td>
<td>640!</td>
<td>598!</td>
<td>570!</td>
<td>549!</td>
<td>533!</td>
<td>519!</td>
<td>508!</td>
<td>498!</td>
<td>489!</td>
</tr>
<tr>
<td>6&amp;</td>
<td>623!</td>
<td>583!</td>
<td>555!</td>
<td>535!</td>
<td>519!</td>
<td>506!</td>
<td>495!</td>
<td>485!</td>
<td>477!</td>
</tr>
<tr>
<td>7&amp;</td>
<td>608!</td>
<td>568!</td>
<td>541!</td>
<td>521!</td>
<td>506!</td>
<td>493!</td>
<td>482!</td>
<td>473!</td>
<td>465!</td>
</tr>
<tr>
<td>8&amp;</td>
<td>592!</td>
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<td>528!</td>
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<td>493!</td>
<td>481!</td>
<td>470!</td>
<td>461!</td>
<td>453!</td>
</tr>
</tbody>
</table>
Goal and Activities for PVQAT TG3 (T, RH, V)

CORE ACTIVITIES - MISSION STATEMENT 2012 (J. Wohlgemuth presentation):

• The ingress of moisture with or without electrical bias has been shown to cause corrosion and charge movement in PV modules.

• The Existing Damp Heat Test of 85°C and 85% RH for 1000 hours, appears to result in relative humidity levels far above that which will ever be seen outdoors for breathable package designs and may overstress the module.

• For semi-hermetic designs, 1000 hours may not be long enough to simulate 20 years of moisture ingress through the moisture barriers.

• There are multiple humidity and humidity/electrical bias degradation modes with widely varying acceleration factors.

• The group’s development of true accelerated lifetime tests must take variation of environmental conditions into account.

Some NEW or AMPLIFIED points since 2017
→ Suggested to move to module degradation in general
→ Multiple stress factors of the natural environment
→ Consideration of variations in environmental conditions
→ Differing mechanism-specific acceleration factors
PVQAT TG 3 brainstorm over teleconference:

• “Mode-interactive stress factor spreadsheet”
  - Interaction of stress factors of the lead to occurrence of degradation modes
  - Can be used when considering how to better select factors for inclusion into an accelerated stress test for the listed mechanisms

<table>
<thead>
<tr>
<th>Mode</th>
<th>Relevant Stress Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>PID</td>
<td>System voltage</td>
</tr>
<tr>
<td></td>
<td>High temperature</td>
</tr>
<tr>
<td></td>
<td>Humidity</td>
</tr>
<tr>
<td></td>
<td>Light</td>
</tr>
<tr>
<td></td>
<td>Stress history</td>
</tr>
<tr>
<td></td>
<td>Bias (Voc vs. Vmp)</td>
</tr>
<tr>
<td></td>
<td>Injected carriers</td>
</tr>
<tr>
<td>LID (various types)</td>
<td>Light</td>
</tr>
<tr>
<td></td>
<td>Temperature</td>
</tr>
<tr>
<td></td>
<td>Injected carriers</td>
</tr>
<tr>
<td>Solder fatigue failure</td>
<td>High temperature</td>
</tr>
<tr>
<td></td>
<td>Temperature cycling</td>
</tr>
<tr>
<td></td>
<td>Mechanical stress</td>
</tr>
<tr>
<td></td>
<td>Humidity (w/EVA and solder flux acidity)</td>
</tr>
<tr>
<td>Ag grid finger delamination</td>
<td>High temperature</td>
</tr>
<tr>
<td></td>
<td>Humidity (w/EVA acidity)</td>
</tr>
<tr>
<td></td>
<td>? temperature cycling</td>
</tr>
<tr>
<td></td>
<td>? mechanical stress</td>
</tr>
</tbody>
</table>
Snail trails - corrosion

Presented by: Paul Gebhardt (Fraunhofer ISE) PVQAT TG3

- Cracks → moisture ingress → gridfinger corrosion → (expanded reaction products, mechanical stress) → delamination

- Four different kinds of “snail tracks”
- Formation dependent on stress factors (indoor/outdoor) & ...
- Depends on material properties / processing:
  - Quality and additives of EVA material (Ag$_2$Ac$_2$ and Ag$_3$PO$_4$)
  - Additives of back sheet material (Ag$_2$S)
  - Gas permeability back sheet material (Ag$_2$CO$_3$, Ag$_2$S, Ag$_2$Ac$_2$, Ag$_3$PO$_4$)
  - Cell metallization firing process (Ag$_2$CO$_3$)
TRINA: Solder bond failure found to be higher in hot-humid environment over hot-dry environment
- Failure involving \( \text{Ag}_3\text{Sn} \) intermetallic

At least two things going on at the same time

**Fatigue**
Coffin Manson/Norris Lanzberg

\[
\text{Damage} = C \Delta T^a r(T)^b e^{E/kT}
\]

**Corrosion**
Moisture, Temperature, halogens
Developed for Al metallization

Exponential
\[
\text{TTF} = A e^{a\text{RH}} e^{E/kT}
\]

Hallberg-Peck
\[
\text{TTF} = A \text{RH}^n e^{E/kT}
\]

**Implication:**
- Glass/glass modules
- Low/no-acid encapsulants
Corrosion in thin-films/bar graphing
\((Na \rightarrow TCO + moisture ingress)\)

Polarization (IBC, PERC)
\((charging \ in \ passivation)\)

PID-shunting
\((Na \rightarrow \text{junctions})\)
c-Si, TF

PID-delamination (c-Si)
\((Na \rightarrow \text{interface, humidity})\)
PID-centric standards

**Crystalline silicon**

- **IEC 62804-1:2015** Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1: Crystalline silicon
  - *published*

**Power loss**

**IEC 62804-1-1**: Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 1-1: Crystalline silicon delamination
  - *to CD stage*

**Thin film, moisture sensitive films using moisture barriers**

- **IEC 62804-2**: Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 2: Thin Film
  - *(not for moisture ingress case)*
  - *to CD stage*

- **IEC 62804-2-1**: Photovoltaic (PV) modules – Test methods for the detection of potential-induced degradation – Part 2-1: Thin Film delamination
  - *to CD stage*
PVQAT TG3 Stress factors combined: PID case

• Now: mechanism-specific tests
  – Known failure mechanisms
  – Minimal examination of interdependencies
  – Numerous modules and multiple parallel tests
PVQAT TG3 Stress factors combined: PID case

1) System voltage: Electric field drives ions

Observed migration of positive ions toward (−) high voltage surface

Hacke and coworkers, 2011

Naumann and coworkers, 2013
1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
PVQAT TG3 Stress factors combined: PID case

1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
3) Humidity: Promotes conductivity on the module
   (humidity internally also promotes conductivity and corrosion)

\[ \frac{P_{\text{max}}}{P_{\text{max}_0}} = 1 - 2 \times 10^{-8} e^{\frac{-0.88}{kT}} \cdot RH\%^{14.24} \cdot t^2 \]

Hacke and coworkers, 2014
1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
3) Humidity: Promotes conductivity on the module
   (humidity internally also promotes conductivity and corrosion)
4) Light: Promotes photoconductivity in SiNₓ, neutralizing advancing ions
PVQAT TG3 Stress factors combined: PID case

1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
3) Humidity: Promotes conductivity on the module surface and in the module
   (humidity internally also promotes conductivity and corrosion)
4) Light: Promotes photoconductivity in SiN, neutralizing advancing ions
5) Soiling: Promotes conductivity on the module surface

Unsoiled -3.5%  Soiled -17.2%

Hacke and coworkers, 2015
PVQAT TG3 Stress factors combined: PID case

1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
3) Humidity: Promotes conductivity on the module
   (humidity internally also promotes conductivity and corrosion)
4) Light: Promotes photoconductivity in SiNₓ, neutralizing advancing ions
5) Soiling: Makes the surface more conductive, especially in elevated humidity
6) History: Na drifting and diffusing with diurnal and seasonal cycles

Hacke and coworkers, 2013

Harvey and coworkers, 2018
PVQAT TG3 Stress factors combined: PID case

1) System voltage: Electric field drives ions
2) Temperature: Makes ions mobile
3) Humidity: Promotes conductivity on the module
   (humidity internally also promotes conductivity and corrosion)
4) Light: Promotes photoconductivity in SiNx, neutralizing advancing ions
5) Soiling: Makes the surface more conductive, especially in elevated humidity
6) History: Na drifting and diffusing with diurnal and seasonal cycles
7) Mechanical stress: Failure of moisture barrier

Kempe and coworkers, 2012
PVQAT TG3 Combined accelerated stress testing

• Now: mechanism-specific tests
  – Known failure mechanisms
  – Minimal examination of interdependencies
  – Numerous modules and multiple parallel tests

• Combined-accelerated stress testing
  – Combine the stress factors & levels of the natural environment
  – Fewer modules, fewer parallel tests
  – Discover mechanisms not a-priori known in new module designs
  – Reduce residual risk, accelerate time to market and bankability
  – Product differentiation
  – Reduce costly overdesign
  – Application of weathering models
PVQAT TG3 Combined accelerated stress testing

Atlas XR 260
- full spectrum light
  (top and bottom with reflectors)
- T
- RH
- water spray
- system voltage
- mechanical loading
- in-situ monitoring (LIV and/or DIV)
PVQAT TG3 Combined accelerated stress testing

<table>
<thead>
<tr>
<th>Step Number</th>
<th>Step Minutes</th>
<th>Function</th>
<th>Irradiance Set Point(^1) @340nm (W/m(^2)/nm)</th>
<th>Black Panel Temperature Set Point(^1)</th>
<th>Chamber Air Temperature Set Point(^1)</th>
<th>Relative Humidity Set Point(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>240</td>
<td>dark + spray</td>
<td>-</td>
<td>-</td>
<td>40°C</td>
<td>95%</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>light</td>
<td>0.40</td>
<td>50°C</td>
<td>42°C</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>270</td>
<td>light</td>
<td>0.80</td>
<td>70°C</td>
<td>50°C</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>light</td>
<td>0.40</td>
<td>50°C</td>
<td>42°C</td>
<td>50%</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>dark + spray</td>
<td>-</td>
<td>-</td>
<td>40°C</td>
<td>95%</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>dark + spray</td>
<td>-</td>
<td>-</td>
<td>40°C</td>
<td>95%</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>light</td>
<td>0.40</td>
<td>50°C</td>
<td>42°C</td>
<td>50%</td>
</tr>
<tr>
<td>8</td>
<td>120</td>
<td>light</td>
<td>0.80</td>
<td>70°C</td>
<td>50°C</td>
<td>50%</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>dark</td>
<td>-</td>
<td>-</td>
<td>40°C</td>
<td>50%</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Repeat steps 6-9 an additional 3 times (for a total of 24 hours = 1 cycle)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- Include effects of dew: rain, 95% RH
- Include a freeze here: -20°C

ASTM 7869- based (origin: paint/coating industry)
PVQAT TG 3 upcoming items

PVQAT TG3 Telecon. **Tuesday, 6 March** T. Tanahashi /K. Sakurai-san AIST project: Backsheet Degradation Caused by UV irradiation + Temperature: Focus on safety/integrity

**Backsheet experiment:** AIST – NREL – DuPont – Mitsui Chemical: *Shared Module Build*

<table>
<thead>
<tr>
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<th>PVF-Polyester-PVF</th>
<th>Polyamide</th>
<th>PVDF</th>
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<tr>
<td>UV absorbing EVA</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>Non-UV absorbing EVA</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
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</table>

**DuPont MAST**

Super Xenon Combined Weather Chamber

**AIST**

**NREL**

Atlas XR 260 - based

PVQAT TG3 Telecon **27 March** Prof. Marko Jankovec, U. Ljubljani: Moisture ingress measurements
Please give me your business card to join PVQAT TG 3

Thank you

www.nrel.gov

Publication Number
TG4 Update: Diodes, Shading

Climate and mounting specific accelerated test development

Vivek Gade — Jabil, representing the Americas
Narendra Shiradkar — IIT Bombay, representing India
Paul Robusto — Miasole, representing the Americas
Jos Van Loo—Diotec, Germany
Xian Dong — Zhongshan University, representing China
Chandler Zhang — Trina Solar, representing China
Overview

• History
• Discussions on standards and developments.
• Update from China team.
• Update from India Field survey data.
• Scope for investigating new tests.
• Next generation diode designs.
• Conclusion
History

• 2011:
  - Task Group 4 reviewed testing standards and identified potential gaps
  - Accuracy of diode technical data sheet. Qualification tests that ensure reliability.
  - Electrostatic Discharge (ESD) susceptibility.

• 2012:
  - ESD testing HBM, MBD, IEC Model
  - Extended bypass diode tests. HTRB and thermal cycling testing
  - Statistical and Weibull

• 2013:
  - IEC 62916, NWIP Bypass diode electrostatic discharge
  - Thermal runaway tests and runaway models.

• 2014:
  - IEC 62916 TS ESD Technical Specification CD was under review.
  - IEC 62979 Ed1.0, NWIP on Thermal Runaway was approved.

• 2015:
  - IEC 62916 TS ESD Technical Specification CDV
  - IEC 62979 Ed1.0, Thermal Runaway CD was out for vote.

• 2016:
  - IEC 62916 TS ESD Technical Specification DTS approved in April awaiting publication.
  - IEC 62979 Ed1.0, Thermal Runaway FDIS stage.

• 2017:

• Until recently, ESD was a major cause for diode failures in a PV module manufacturing line. The diodes may fail during module assembly due to high voltage spikes generated through contact by humans / machines or equipment such as flash tester.

• Gaps Addressed: Initiatives from PVQAT diode group members has led to the development of IEC TS 62916:2017, (drafted by Kent Whitfield) to assess the susceptibility of bypass diodes against failure by ESD. The test specification provides opportunity to perform the tests and measure the efficacy of this test. This also helps address any need to make further changes and if no changes are needed based on the data collected this can be potentially be a test standard in the future and potentially be made a mandatory standard test.
c) Thermal Runaway in Reverse Bias / Forward to reverse transition

• Diode operates at high temperature if the partial shading is held on the module for significant amount of time. If shading is suddenly removed, diode immediately turns to reverse bias. If the power dissipation in reverse bias is more than the power taken out by the junction box cooling system, the temperature of diode begins to increase further. Since reverse current (and power dissipation) exponentially increases with temperature, this leads to further rise in temperature until this cyclic process results in diode failure.

• Gaps: Until recently, there was no standard available that would test the junction boxes for susceptibility against failure by thermal runaway. Initiatives from PVQAT diode group members has led to the development of IEC 62979 (drafted by Uchida-san, Japan) to assess the susceptibility of junction boxes towards thermal runaway. However, qualification under this standard is not yet mandatory.
Thermal runaway procedure question

- To ensure stability the forward power dissipation is higher than the reverse power dissipation.
- Normally one writes the equation as $P_f > P_r$. The real formula is more like $V_f \cdot I_f \cdot R_{thj-a} > I_r \cdot V_r \cdot R_{thj-a}$, and obviously we leave out the $R_{thj-a}$ because it is the same on both sides of the equation.
- The test set-up puts forward current through the 3 diodes but only blocks one, the thermal resistance may not be the same however. That may be the reason why some of the measurement performed by group in Europe may have showed that $P_r > P_f$.
- Per Uchida-san there would be some difference. But that the difference would be expected small, because the heat dissipation characteristics will not change so quickly after the interruption of the forward current $I_f$.
- More tests can be performed on axial and SMD diodes, they can be assembled in a box - and verify/validate test results: check the thermal runaway and $P_f/P_r$ ratio at thermal runaway.
A. background information
A junction box used in the plant flooded, causing the diode to fail.

B. Visual inspection

<table>
<thead>
<tr>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.jpg" alt="Image" /></td>
<td><img src="image2.jpg" alt="Image" /></td>
<td><img src="image3.jpg" alt="Image" /></td>
</tr>
</tbody>
</table>

Plastic material damaged
C. Electrical test:
Graphic test confirmed: DW4822 transistor tester
Test conditions: 10V / cell, 0.1mA / cell

<table>
<thead>
<tr>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
</table>

![Waveform Images]

Testing report:
1, #1, #3 adverse product reverse waveform Short.
2, #2 sample reverse waveform without exception.

D. X-Ray test:

<table>
<thead>
<tr>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
</table>

![X-Ray Images]

Testing report:
The X-Ray test, #1, #2, #3 total 3pcs sample plastic material without carbonation.
2. select #1, #3 samples to the chip:

<table>
<thead>
<tr>
<th>Number</th>
<th>chip</th>
<th>Partially enlarged chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
<tr>
<td></td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
<tr>
<td></td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
<tr>
<td>#3</td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
<tr>
<td></td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
<tr>
<td></td>
<td>![chip image]</td>
<td>![enlarged chip image]</td>
</tr>
</tbody>
</table>

**testing report:**

1. #1 sample chip protection ring edge of the continuous small melting point;

2. #3 sample chip edge appears continuous, larger melting point.
From the anatomical analysis of diode chip failure mode, you can see the more obvious and more serious multiple burns traces. From the failure mechanism analysis, the burn point is generated by the electrical power consumption which seriously exceeds the limit of the diode. In particular, it reflects the instantaneous multi-peak reverse power consumption, resulting in local breakdown of the chip at high temperature, silicon melting signs.

Compare this chip failure mode with the previous chip failure mode as follows:

<table>
<thead>
<tr>
<th>The chip failure mode</th>
<th>Past lightning failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td></td>
</tr>
<tr>
<td>#3</td>
<td></td>
</tr>
</tbody>
</table>

The chip has a number of firing more serious breakdown point, usually caused by lightning. Because the lightning produces extremely strong multi-peak energy, the first breakdown of the chip is still in the ultra-high temperature state (the silicon presents a high resistance state in the molten state), followed by the arrival of the second peak energy, causing the chip second Point burn breakdown. Therefore, a preliminary analysis suggests that lightning strikes lead to diode breakdown failure.
### Diode Field Failure Data from India

#### Source: All India Survey 2016, NCPRE, IIT Bombay

<table>
<thead>
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<th>Category</th>
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<tbody>
<tr>
<td>Modules Inspected for Diode Failures</td>
<td>348</td>
</tr>
<tr>
<td>Modules with Diode Failures</td>
<td>2</td>
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<tr>
<td>Percentage</td>
<td>0.57%</td>
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<tr>
<td>Failures in PPM of Modules</td>
<td>5700</td>
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<tr>
<td>Predominant Failure Mode</td>
<td>Short Circuit</td>
</tr>
</tbody>
</table>

#### Source: On-site Field Testing 2017-2018, PV Diagnostics, India

<table>
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<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules Inspected for Diode Failures</td>
<td>38,308</td>
</tr>
<tr>
<td>Modules with Diode Failures</td>
<td>~270</td>
</tr>
<tr>
<td>Percentage</td>
<td>0.7%</td>
</tr>
<tr>
<td>Failures in PPM of Modules</td>
<td>7000</td>
</tr>
<tr>
<td>Predominant Failure Mode</td>
<td>Short Circuit</td>
</tr>
</tbody>
</table>

- Many sites with diode failures also had significant cell cracking problem. Mismatch due to cracking could lead to ‘always on’ diode, thus leading to premature failure.
- Significant amount of diode failures were also observed in plants that had experienced lightning strikes.
EL Images of Modules with Short Circuit Diode Failures in Field

Source: All India Survey of PV Module Reliability: 2016, NCPRE, IIT Bombay

- Diode Failures were confirmed by I-V and EL Images.
- Since modules could not be brought to the lab, detailed failure analysis could not be performed on the diodes.
Future tests recommended

\textit{a) Temperature Over-stress in Forward Bias}

- When the PV module is partially shaded, bypass diode turns ON and its temperate begins to increase due to power dissipation in forward bias. If this condition persists for long duration, diode temperature eventually stabilizes as the diode reaches a steady state. If the diode temperature exceeds the maximum rated temperature, the diode may undergo failure due to this single event of temperature over-stress.

- Gaps: The current bypass diode test is performed at 75 °C ambient temperature and its first part involves passing current equal to short circuit current of the module through the diode for 1 hour and monitoring if the diode temperature exceeds maximum rated temperature. These test conditions are acceptable for rack mounted modules in moderate climates. However, these days modules are increasingly being deployed in hot climates and also in roof mounted configurations, in which the test conditions experienced in field are much harsher. We need to reflect this reality and reduce the occurrence of false positives under the current test when the module is deployed in hot climates.
Future tests recommended

b) Long Term High Temperature Operation in Forward Bias

• If partial shade scenario persists for long duration, and is a daily occurrence, diodes may end up spending significant amount of time at high temperature in forward bias. This may lead to diode failure due to continuous operation at high temperature. This type of behavior is not assessed by thermal runaway test which only tests for diode at elevated temperature for a total of 2 hours.

• Gaps: Currently there is not standard to test the susceptibility of junction boxes against failure due to long term operation at high temperature in forward bias.
Future tests recommended

c) Long Term High Temperature Operation in Reverse Bias

When the module is not subjected to partial shading, the diodes are reverse biased. When the modules are deployed in moderate climates / in rack mounted configuration, the temperature of bypass diodes in reverse bias is not considerably high. However, for the case of modules deployed in hot climates and / or roof mounted configurations, the diodes may operate at elevated temperatures (but at a temperature less than necessary to cause thermal runaway) for long duration and may undergo failure. Prolonged temperature exposure may lead to degradation of material properties and eventually inferior electrical performance.

- Gaps: Currently there is not standard to test the susceptibility of junction boxes against failure due to long term operation at high temperature in reverse bias.
Future tests recommended

d) Thermal Cycling

- PV modules are tested for their robustness for thermal cycling during the tests in IEC 61215. However, when the diodes are forward biased due to recurrent partial shading, the $\Delta T$ experienced by the diodes is much higher than that experienced by the modules. In this case, the large temperature fluctuations may cause diode failure by thermal cycling. We have seen cases in a Lab setup where die fatigue has occurred during thermal cycling involving large temperature fluctuations.

- Gaps: Currently there is no standard to test the susceptibility of junction boxes against failure due to long term operation at forward bias during cyclic thermal stresses.
New Designs to focus
Schottky Technology – die shrink improves Temp Cycle performance

Size Reduction!

100% 56%

Same Performance?
Lower Leakage Current due to die shrink
Process Improvements over the years improved ESD

ESD test according IEC 61000-4-2

30 kV are now possible!
Integration into a solar panel and challenges

• Packages with a profile lower than 1.1mm difficult due to thermal resistance / thickness of the die

• Integration into the module via soldered diodes (die) integrated into strips needs cooperation between module and semiconductor supplier. Products need to be tested after integration. Thermal resistance change from 30K/W to 5K/W.

• Die should preferably have mechanical protection against moisture / mechanical stress

• Mismatch in thermal coefficients is higher in a solar panel vs a Junction Box: Temperature Cycling more complex

• Diotec one of the TG4 participating members is available to jointly develop process / manufacturing
Conclusion

• Some progress has been made in developing standards through PVQAT Task force #4

• Diode issue is still prevalent and need to be investigated further. Further field failure information would be very helpful.

• Scope still exists to further develop standards. High temperature standards for hot climate may include some of the diode tests proposed. Kent Whitfield is leading the group for such hot climate standard 63126.

• Focus may have to be on New technology diode designs as old designs become obsolete and so does the test standards recommended.

• Request for more participation from PV industry in the group.
Acknowledgement

• Thanks to
  • Uchida –san and Kent Whitefield for their work on writing the standard.
  • Jos-Van Loo from Diotec
  • Support from Paul Robusto (Miasole), IEC and NREL team.
  • Narendra Shiradkar, formerly Jabil now with IIT Bombay for leading the testing efforts while in US.
  • Jabil Management support.
The Development and Research of PVQAT TG13

Hao Jin, Ning Li, Xinyu Zhang, and Qi Wang

02-28-2018
Contents

1. PVQAT TG13 Introduction
2. The Research of TG13
3. Summary and Plan of TG13
The Photovoltaic Quality Assurance Task Force (PVQAT) leads global efforts to craft quality and reliability standards for solar energy technologies.
1.1 PVQAT TG13 Introduction

### The development course of PVQAT TG13

- **Setting up**
  - The First Standard Meeting had been held on March 2016 in Shanghai

- **Spring Meeting**
  - There are two IEC standards and four new proposals had been discussed in TG13 Spring Meeting, at the same time, building the core member institution

- **Core member of PVQAT TG13**
  - Sarah, who initiated the TG13, issued > 20 certificates for TG13 at SNEC 2017 to encourage more PV experts from China to participate the cell standard research

- **PVQAT TG13 Fall Meeting**
  - This meeting discussed IEC 60904-1-2, IEC 60904-11 and EL standard. At the same time, UV degradation, Capacitance effect, specification of silicon wafer and others potential topics had been discussed too.

### The Plan activity in 2018

- The meeting arrange:
- F2F meeting: twice a year
- Tele-conf technical discussion

Next meeting will add new topics:
- Specifications for the silver paste that is used to contact N+ diffusion region of c-Si solar cells
- LeTID
- (PV) Cell - Type Approval Standard

2017年5月SENC展会上，Sarah作为PVQAT重要的发起人之一，为TG13组20多名专家颁发了核心委员证书，并希望更多的中国专家能加入到电池标准研究中。
1.2 PVQAT TG13 Meetings

- Held
  - Nov, 2016 – Shanghai, China
  - Mar, 2017 – Shanghai, China
  - Sep, 2017 – Wuxi, China

- Planned
  - Apr, 2018 – Wuxi, China
  - Sep, 2018 – TBD, China
# 1.3 Members of PVQAT TG13

<table>
<thead>
<tr>
<th>No.</th>
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<td></td>
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International

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<td>Andrew Tay</td>
</tr>
<tr>
<td>2</td>
<td>Amir Abdallah</td>
</tr>
<tr>
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<td>Leonardo Corrales Vargas</td>
</tr>
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<td>Kristen Nicole</td>
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<td>9</td>
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<td>Elias Urrejola</td>
</tr>
<tr>
<td>11</td>
<td>Dinesh Amin</td>
</tr>
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</table>

National
1.4 Technical Areas for TG13 Standards

To research on non-concentrating, terrestrial photovoltaic cells and related materials.

- Photoelectric performance
- Environmental test
- Quality assurance
- Quality assessment
- Durability of PV cells
- Material property characterization
1. PVQAT TG13 Introduction
2. Researches
3. Summary and Plan
2.0 PVQAT TG13 Researches

Activities

• IEC 60904-11: LID Test – (ACDV by Nov. 2017)
• PNW TS 82-1357 ED1: EL of PV Cell--- (PRVN by Feb. 2018 )

Researches

• Measurement of current- voltage of bifacial photovoltaic
• Measurement of UV degradation in crystalline silicon solar cells
• Capacitance effect in high efficiency crystalline silicon solar cells
• Specification for silicon wafers for use in photovoltaic solar cells
2.1 IEC 60904-11: LID test

- Measurement of initial light-induced degradation of crystalline silicon solar cells
2.2 PNW TS 82-1357 ED1 : EL test

- Electroluminescence of photovoltaic cells
2.3 Work from QA Task Force -- Silicon wafer

- Silicon wafer standard series classification

**IEC/TC82 Nara Meeting**

- Photovoltaic silicon wafer and other related materials is an important part for solar cell performance, but there are no standards to evaluate their property characterization in IEC standard system.
- It may be better to propose a wafer series standard.

**Hexagonal Diagram**

1. Specification for Silicon Wafers
2. Geometry test methods
3. Electrical Parameters test methods
4. Chemical Characteristics test methods
5. Crystal Characteristics test methods
6. Surface Quality test methods
7. Package of silicon wafers
2.3 Work from QA Task Force--Silicon Wafer

- Work in progress
  - Part 1: Measurement of dimensions

### Dimensions included

1. Geometric dimensions
   - wafer side length
   - chamfer length
   - chamfer angle
   - right angle

2. Thickness and total thickness variation (TTV)

### The main contents of this document

<table>
<thead>
<tr>
<th>Section</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><strong>Scope</strong></td>
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<tr>
<td>2</td>
<td><strong>Normative references</strong></td>
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<td>3</td>
<td><strong>Terms and definitions</strong></td>
</tr>
<tr>
<td>3.1</td>
<td>Thickness</td>
</tr>
<tr>
<td>3.2</td>
<td>Total Thickness Variation (TTV)</td>
</tr>
<tr>
<td>4</td>
<td><strong>Apparatus</strong></td>
</tr>
<tr>
<td>4.1</td>
<td>Geometric dimensions test equipment</td>
</tr>
<tr>
<td>4.2</td>
<td>Thickness and total thickness variation tester</td>
</tr>
<tr>
<td>5</td>
<td><strong>Sampling</strong></td>
</tr>
<tr>
<td>6</td>
<td><strong>Measurement</strong></td>
</tr>
<tr>
<td>6.1</td>
<td>Measurement environment</td>
</tr>
<tr>
<td>6.2</td>
<td>Geometric dimensions test</td>
</tr>
<tr>
<td>6.3</td>
<td>Thickness and total thickness variation test</td>
</tr>
<tr>
<td>7</td>
<td><strong>Report</strong></td>
</tr>
<tr>
<td>7.1</td>
<td><strong>Annex A:</strong> Recommendations for dimensions</td>
</tr>
</tbody>
</table>

---

*Note: The image contains a visual representation of the document's contents*
2.4 Work from International QA Task Force– Bifacial Solar Cell

- The History of IEC 60904-1-2

<table>
<thead>
<tr>
<th>Stage</th>
<th>Document</th>
<th>Downloads</th>
<th>Decision Date</th>
<th>Target Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>PNW</td>
<td>82/1044/NP</td>
<td>331 kB</td>
<td>2015-10-23</td>
<td></td>
</tr>
<tr>
<td>ANW</td>
<td>82/1081/RVN</td>
<td>492 kB</td>
<td>2016-02-05</td>
<td>2016-03</td>
</tr>
<tr>
<td>ACD</td>
<td>82/1081/RVN</td>
<td>547 kB</td>
<td>2016-02-06</td>
<td>2016-02</td>
</tr>
<tr>
<td>ADTS</td>
<td>82/1081A/RVN</td>
<td>763 kB</td>
<td>2017-03-31</td>
<td>2017-04</td>
</tr>
<tr>
<td>A2CD</td>
<td>82/1081B/RVN</td>
<td>442 kB</td>
<td>2017-05-05</td>
<td>2017-05</td>
</tr>
<tr>
<td>CD</td>
<td>82/1289/CD</td>
<td>476 kB</td>
<td>2017-05-12</td>
<td>2017-05</td>
</tr>
<tr>
<td>PCC</td>
<td>82/1325/CC</td>
<td>459 kB</td>
<td>2017-08-04</td>
<td>2017-08</td>
</tr>
<tr>
<td>ADTS</td>
<td>82/1325/CC</td>
<td>239 kB</td>
<td>2017-08-11</td>
<td>2018-02</td>
</tr>
<tr>
<td>TDTN</td>
<td></td>
<td></td>
<td></td>
<td>2018-02</td>
</tr>
</tbody>
</table>

- Research of cell

The main test method of bifacial solar cell in current production line and Lab: (1) Traditional single-side measurement method, (2) Double-side measurement method with two light sources, (3) Double-side measurement method with reflectors. The (2) and (3) measurements had been finished at SIMIT Lab in Shanghai, China.
2.4 Work from QA Task Force—Bifacial Solar Cell

- **Research result**
  - Comparison of equivalent single-side illumination and double-side illumination method

  ![Graphs showing current-voltage characteristics under different illumination methods](image1)

  - N-type, $\frac{I_{SC-r}}{I_{SC-f}} = 0.518$
  - P-type, $\frac{I_{SC-r}}{I_{SC-f}} = 0.823$
  - HJT, $\frac{I_{SC-r}}{I_{SC-f}} = 0.913$

- **Effects of measurement chuck**

  ![Image of measurement chuck](image2)

  Gold plating shows a higher Isc (~1%).

<table>
<thead>
<tr>
<th>Bifacial cell</th>
<th>Golden</th>
<th>Black</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jsc (mA/cm²)</td>
<td>37.36</td>
<td>37.01</td>
</tr>
</tbody>
</table>
2.4 Work from QA Task Force– Bifacial Solar Cell

**Planned**

- Apr, 2018 – New standard proposal, Wuxi, China
- Oct. 2018– standard draft, Busan Korea

**Future work**

1. Accumulation of measurement data
   - Bifaciality variations for $I_{sc}$, $V_{oc}$, and $P_{max}$;
   - Two types of bifacial photovoltaic modules (with cell sorting by front only or front and rear separately);
   - Comparison of indoor I-V measurement of both modules;
2. Improvement of the measurement method;
3. Summarize the standard.
2.5 Work from QA Task Force– UV Degradation

- Experimental process

Temperature: 60 ± 5°C
Wavelength: 280-400nm
UV Density: less than 200-220W/m²
Testing interval: 15KWh/m²
2.5 Work from QA Task Force—UV Degradation

**Experiment Result**

- Industrial solar cells are deteriorated by UV irradiation

- UV degradation is independent on LID process
- UV-degradation of module could be relevant on that of solar cells. The corresponding relation is been studying.
2.5 Work from QA Task Force— UV Degradation

The research plan:

<table>
<thead>
<tr>
<th>No.</th>
<th>Action</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Study of UV-degradation of solar cells (Surface passivation, ARC)</td>
<td>2017.12.01-2018.04.30</td>
</tr>
<tr>
<td>2</td>
<td>UV-degradation test of N-type solar cells</td>
<td>2017.12.15-2018.02.15</td>
</tr>
<tr>
<td>3</td>
<td>The effect of temperature on UV-degradation</td>
<td>2018.03.01-2018.03.31</td>
</tr>
<tr>
<td>4</td>
<td>The UV-degradation test of solar cells supplied by different vendor</td>
<td>2018.02.01-2018.02.28</td>
</tr>
<tr>
<td>5</td>
<td>The relation between UV degradation of solar cells and that of modules</td>
<td>2018.01.01-2018.03.31</td>
</tr>
</tbody>
</table>
3.0 Summary and Plan

- **Summary of Pvqat**
  - Revise the IEC 60904-11 LID standard CD version draft
  - Revise the WD version draft when EL proposal had been approved
  - Discussion the silicon specification and UV degradation draft
  - Accelerate the bifacial solar cell research
  - Standard meeting: **Apr, 2018 – Wuxi, China**

- **New challenges**
  - Measurement error of photovoltaic (PV) current-voltage characteristics due to capacitance effect
  - Measurement for the p-n junction depth of crystalline silicon solar cell – method of electrochemical capacity voltage (ECV)
  - The certification standard of solar cell
  - Specification for the silver paste which is used to contact the N+ diffusion region of c-Si solar cells
  - Others
IEC TC Working Group 8:

Photovoltaic (PV) cells

Thank you for your attention
Understanding PV Module Durability through Analysis of Fielded Modules and Sequential Accelerated Testing

T. John Trout
Global PV Reliability R&D Manager
DuPont Photovoltaic Solutions
February 28, 2018

For over 40 years
our material innovations have led the photovoltaics industry forward, and helped our clients transform the power of the Sun into power for us all. Today we offer a portfolio of solutions that deliver proven power and lasting value over the long term. Whatever your material needs, you can count on quality DuPont Photovoltaic Solutions to deliver the performance, efficiency and value you require, day after day after day…
Understanding PV Module Durability
– Through Analysis of Fielded Modules and Accelerated Sequential Testing

Models for module and component degradation
- What do we see in the field?
- What are we trying to predict in accelerated testing?

Understanding Module Durability Begins in the Field
- Understand both degradation of modules and components
- Global Field Program to assess degradation and aging
- 2017 Analysis and Case Studies
- Analysis of Backsheet Erosion
- Glass / Glass Operating Temperature

Accelerated Tests must Match Field Degradation
- Formalism: Sample / Stress / Measurement
- Sequential Tests Development and Results

Future Directions
Conclusions
DuPont PV Reliability: Global Organization – Broad Capabilities

**Labs**
- Experimental Station, Wilmington, DE
- Chestnut Run, Wilmington DE
- China Technical Center, Shanghai
- KSP Technical Center, Japan

**People**
- US, Europe, India, China, Japan

**Module Reliability**
- Fielded Module Evaluation and Analysis
- Outdoor Field Exposures – Fla, De
- PV module Fabrication and Characterization
- Accelerated Testing and New Test Method Development
- Broad Analytical Capabilities
- Fundamental Material and Polymer Science
Model for Module and Component Degradation

1. Overall module performance – power loss
2. Degradation of components – degradation leading to defects seen in the field

IEA International Energy Agency, PVPS report
T13-01:2014

Power Loss in the Field (Mean) ~ 0.5 – 0.8% / year
- Desert = 1.2%
- Tropical = 0.8%
- Temperate = 0.6%

Two distinct regions for P loss
- Baseline degradation ~ 20%
- End of life Failure > 50%

Mean = 0.8%/year
- 25 years = 20%
- 30 year = 24%

Module Component Degradation

1. Overall modules performance – power loss
2. Degradation of components – degradation leading to defects seen in the field

Degradation builds over time until critical point is reached
- Polymer degradation increases – backsheetwork yellowing, loss of mechanical properties, loss of molecular weight, erosion, acetic acid formation
- Eventually point of degradation is high enough that failure occurs
  - Retained properties < stresses
  - Resulting in visual defects: cracking, delamination, yellowing, loss of thickness

EVA
- Acetic Acid Formation
- BackSheet
  - Increase in Yellowing
  - Loss of Mechanical Properties
  - Loss of Polymer Mwt
  - Crack Growth and Propagation
Understanding Module Durability Begins in the Field

Use modules from the field to understand both the aging performance and degradation of modules and critical components and materials

- Excellent literature for power performance - NREL
- Few studies on components – especially backsheets

DuPont Field Assessment Program
- Study module and component degradation
  – develop data for backsheets
- Developed Visual inspection protocols
- Statistical analysis of fields and aggregate data
- Analysis and learning from case studies
- Select modules for extensive analytical analysis
- Collaborations with field partners
DuPont Global Field Assessment Program

Multi-step Inspection Protocol
- Documentation of location, age, climate, module, energy production, visual imaging, thermal imaging, IR spectroscopy,
- Defect categorization
- Select modules for further analysis

Defect Analysis and Statistics

Thermal Imaging IR camera identifying hot spots in modules

Backsheet identification and degradation using FTIR spectrometer
DuPont 2018 Field Analysis and Database - Overview

2018 Analysis
1+ GW inspected

- 77.7%
- 9.5%
- 12%
- 1.3%
- 0.4%

Data size more than doubled from 2016 to 1 GW
- All defects 22.3%
- Cell related defects 12%
- Backsheet defects 9.5%

<table>
<thead>
<tr>
<th></th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installations</td>
<td>286</td>
</tr>
<tr>
<td>Number of panels</td>
<td>4,234,324</td>
</tr>
<tr>
<td>Average age (years)</td>
<td>3.3</td>
</tr>
<tr>
<td>GW</td>
<td>1.047</td>
</tr>
</tbody>
</table>

Climate sample sizes 2018
Analysis of Climate on Defects Rates

Cell and Metalization show less or small effect with Climate
Polymer Components (Backsheet and EVA) show stronger trend
• Hot arid > Tropical > Temperate
• Use Defect Rates to determine “harshness” of Climates?
• Dominant factors are likely Temperature and UV

1 Temperate cell defects are dominated by Snail Trails, likely due to sampling
Analysis of Defect Rates for Roof vs Ground Mounted Systems

Overall Higher defect rates for roof vs ground installations
• Backsheet defects are > 2.5X higher on roof systems
• Cell defects are similar for Roof and Ground

Differences are likely due to higher temperatures for roof systems
• Roof Systems are typically 15 °C higher than Ground Mounted\(^1\)
• This trend with temperature is similar to the effect seen in climates

---

Analysis of Defect Rate vs Backsheet

Backsheet defects increased by 27% vs 2016 Analysis

- Polyamide increased by 18%
- PVDF increased by 51%
- Glass / Glass starting to show up
- Tedlar rate unchanged
Analysis of Backsheet Defects vs Age

Tedlar® makes up the oldest installations with lowest percentage of defects
- Defect rate is low and not increasing over time
PVDF and Polyester defect rate is high and is increasing with time

Tedlar® in the field (35yrs)
PET (16yrs)
PVDF (9 yrs)

- Front side yellowing due to inner layer chemical treatment
- TPE, Weak inner layer adhesion led to delamination
- Slight Front side yellowing
- BS delamination

1 2 3 4 5 6 7
Polymers degrade and lose thickness over time

Tedlar® PVF-based backsheets show erosion is 0.34 µm per year

- Both 25µm and 38µm thick Tedlar® film layers will last over 30 years.

Other backsheets, have erosion rates 3-5 times larger

- Erosion rates for PVDF and PET are statistically different from PVF rate
- Variation in rates for PVDF and PET could be due to different film compositions
- A 25 µm PVDF outer layer is expected to erode below an acceptable protective level in 8 yrs

Erosion measured by comparing SEMs from “under label” to exposed areas
Polymer Erosion in Space – Measured Erosion

38 polymer samples loaded on exterior of the US Space Station
Samples faced into the direction of travel
Constant exposure to reactive atomic oxygen, UV, X-Rays for 4 years
PVDF, PET, PA and PMMA eroded significantly
Lowest erosion with white Tedlar® PVF

<table>
<thead>
<tr>
<th>Backsheet Polymers</th>
<th>Erosion Yield (X10^{-25})</th>
</tr>
</thead>
<tbody>
<tr>
<td>White PVF</td>
<td>1.01</td>
</tr>
<tr>
<td>PVDF</td>
<td>12.9</td>
</tr>
<tr>
<td>PET</td>
<td>30.1</td>
</tr>
<tr>
<td>PA-6</td>
<td>35.1</td>
</tr>
<tr>
<td>PMMA</td>
<td>56.0</td>
</tr>
</tbody>
</table>

Erosion Yield = \frac{\text{Mass Loss (g)}}{\text{Area (cm}^2\text{)} \times \text{density (g/cm}^3\text{)} \times \text{fluence (atoms/cm}^2\text{)}}

White Tedlar® PVF showed the least erosion
• Similar trend to rate found from PV modules

http://www.asi.it/sites/default/files/attach/evento/de_groh_misse.presentation_italy_5-10-16_30_min.pdf
Backsheet Field Case Studies:

PVDF 5 Years: Cracking and Delamination
- 69 installations, N America, 1 MW
- Linked to loss of PVDF Mech Props

PET 9 Years: Cracking, Delamination, P loss
- Arizona, 35 kW
- Linked to polymer degradation

Polyamide 6 Years: Cracking, Yellowing
- China, 22 MW
- Cracks progressed in severity 1-4 yrs

Glass 10 Years: Cracking, Delamination
- Arizona, 4 kW
- Safety hazard

Glass 1 Year: Higher Operating Temp
- China, 40 MW
- Lower power output due to higher temp
Reduced Glass-Glass Power Output: Field Case Study in South China

- Initial year of operation: 2016
- Service Time: 13 months
- Location: Xuwen, Guangdong
- Date of inspection: Aug, 31, 2017
- # of modules: 150945
- System size: 40MW (4.8 G/G; 35.2 G/B)
- Mounting configuration: Ground open rack
- Fixed tilt or tracking: Fixed Tilt
- Backsheet: Glass; Polymer Backsheet
- Module Maker: Same for both types
- Technology: Poly-Si
- Surface: Grass/water
- Climatic conditions: Tropical

Summary
- Lower power generation for Glass-Glass modules
- G-G module shows some bending/bowing ~10%
- Transparent pinholes found in G-G module with white EVA

Unframed G-G modules with 4 pads parallel to long edge
Analysis of Monthly Cumulative Power Generation Data

Data obtained for
a. Three G-G blocks: block 11, 13, 15
b. Two G-B blocks: block 12, 14

Time Period
Jan 1 to Aug 30, 2017

- The standard deviation in power data is too high to show any differences
Comparing Daily Cumulative Power Data

**Jan-Apr**
Mean efficiency difference between G-G and G-B modules is **not statistically significant**
(p=0.103 > 0.05 in paired t-test; difference of means = -4.7)

**May-Aug**
Mean efficiency difference between G-G and G-B modules is **statistically significant**
(p=0.000 < 0.05 in paired t-test; difference of means = 65.14)

- Peak Eff Δ in summer: 2.3%
- Avg Eff Δ in summer: 0.95%
- Avg Irradiation Δ: (May-Aug) − (Jan-Apr) = +40%

**Avg Eff Δ of 0.95% ➞ Operating T difference of G-G vs G-B modules: 1.95°C-matches modelling results**

Temperature coefficient of $P_{\text{max}}$ for the G/G module*: -0.488%/°C, *Source: SAM, NREL & California Energy Commission
Connecting and Comparing the Field to Accelerated Tests – Sample / Stress / Measurement

Stress and Response Formalism – Response for Field and accelerated stressors

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stresses</th>
<th>Response [Measurement]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
<td>Field Exposure</td>
<td>Power loss, IV curve, EL, Visual, Insulation</td>
</tr>
<tr>
<td>Cell</td>
<td>DH, UV, TC, HF, ML,...Sequential Tests</td>
<td>Contact Resistance, SEM, EL Image, Visual</td>
</tr>
<tr>
<td>Backsheet</td>
<td>Mechanical Properties, Adhesion, Color, Molecular Weight Change, Gloss, Visual</td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>Color, VA content, Acetic Acid concentration, Visual</td>
<td></td>
</tr>
</tbody>
</table>

How can we Assess or Predict the Field Performance of New Materials?

<table>
<thead>
<tr>
<th>Field</th>
<th>Accelerated Test</th>
<th>Develop and validate new tests by correlating to the field Test using old (or as close as possible) materials and structures.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Materials</td>
<td>X → X</td>
<td>Compare performance in accelerated tests of new materials / structures to predict / estimate field performance</td>
</tr>
<tr>
<td>New Materials</td>
<td>? → Y</td>
<td></td>
</tr>
</tbody>
</table>
DuPont Sequential Tests

### Test 1
- **UV / DML / TC / HF**
- **Rationale:** Combines UV and Temperature cycling with the dynamic stresses of Dynamic Mechanical Load (DML).

### Test 2
- **DH/TC**
- **Rationale:** Combines two important stress factors in a shorter test not requiring expensive UV equipment. Appropriate for full-size module testing.

### Test 3
- **Xenon Weatherometer: ASTM G155 or SAE J1960 protocols**
- **Rationale:** Combines UV and rainfall simulation, common weathering test conditions in commercially available weatherometer.

### Test 4
- **UV / DH / 3x (TC / UC)**
- **Rationale:** Our #1 Test. Combines the most important stress factors in the field. Appropriate for component, minimodule, or full-size module testing.
Module Accelerated Sequential Test (FAST MAST)

- **6 months duration**
- **Damp Heat**
  - 1000 hours
- **UVX**
  - 542 hours 90°C BPT
- **Thermal Cycling**
  - 200X
  - 542 hours 90°C BPT
  - UVX
- **UVX**
  - 50 hours 90°C BPT

**Shortened MAST Sequential Test**
- Higher intensity UV Xenon exposure
- Higher 90°C BPT with shortened time
- Results are equivalent to original MAST.

1000 Hours in a Humidity Chamber
Amounts to > 25+ years worth of stress

600 Thermal Stress Cycles
Mimics thermal stresses seen in the field

1676 Hours in a UVX Chamber
Amounts to ~20 years desert dose of UVA

600 Thermal Stress Cycles
Mimics thermal stresses seen in the field
Sequential Test Results Compared to Field Results for Backsheets

- Polyamide backsheet: Cracking
- PVDF backsheet: Cracking
- PET backsheet: Yellowing

Field:
- Cracked, 5 yrs (Spain)
- Cracked, 5 yrs (Canada)
- Yellowing, 15 yrs (Japan)

DH 85C/85%RH UVA 1.2W/sqm (340nm), 70C BPT, TC 85°C <-> -40°C, per IEC 61215
## Comparison of Stress Tests to Field Results for Backsheet Degradation

<table>
<thead>
<tr>
<th>Stress</th>
<th>PPE</th>
<th>KPE</th>
<th>PolyAmide</th>
<th>TPT/TPE</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>Yellowing Mech Prop Loss</td>
<td>Cracking Front Side Yellowing</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>Low defects</td>
<td>Effects of simultaneous and sequential stresses</td>
</tr>
<tr>
<td>Damp Heat (1000 hrs)</td>
<td>Slight Yellowing</td>
<td>No Change</td>
<td>Mech Prop Loss</td>
<td>No Change</td>
<td>Misses UV degradation</td>
</tr>
<tr>
<td>UV (4000 hrs)</td>
<td>Yellowing Mech Prop Loss</td>
<td>No Change</td>
<td>Mech Prop Loss</td>
<td>No Change</td>
<td>Misses hydrolysis and moisture</td>
</tr>
<tr>
<td>DH/UV/TC (MAST Sequential Test)</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>Cracking Front Side Yellowing</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>No Change</td>
<td>Combines key stresses Gives best correlation</td>
</tr>
</tbody>
</table>

### Sequential Tests correlate better with degradation seen in the field
- Combine most important stress factors
- Use Stress levels / dosages that match field exposures
- Accelerate with highest temperature but do not produce degradation not found in the field
New Accelerated Sequential Dynamic Mechanical Load Test

Designed to better simulate the Field by combining Sequential Testing and with Dynamic Load

**Protocol**
- **UV exposure**: 65kWh/m² on the front
- **DML 1**: 1000 cycles of ±1500 Pa of loading @ 1/6 Hz
- **DML 2**: 1000 cycles of ±1500 Pa of loading @ 1 Hz
- **TC200** = Thermal Cycling, -40°C ↔ 85°C, ramp and hold *per IEC62782*, 200 cycles
- **HF30** = Humidity Freeze, 30 cycles
- **DML 3**: 1000 cycles of ±1000 Pa of loading @ 4 Hz (Optional)

*Tests by independent 3rd party testing lab DNV-GL, USA*
## Summary of Results

<table>
<thead>
<tr>
<th></th>
<th>G/G modules</th>
<th>G/Backsheet modules</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UVA</strong></td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td><strong>DML 1</strong></td>
<td>No change</td>
<td>No change</td>
</tr>
<tr>
<td><strong>DML 2</strong></td>
<td>Slight delamination on front</td>
<td>No change</td>
</tr>
<tr>
<td><strong>TC 200</strong></td>
<td>Delamination on front, encapsulant voids on back</td>
<td>No change</td>
</tr>
<tr>
<td><strong>HF 30</strong></td>
<td>Severe delamination on front, multiple encapsulant voids on the back</td>
<td>Slight yellowing along the edge, no delamination</td>
</tr>
</tbody>
</table>

*DML 3 not performed*

Glass-Glass modules show delamination induced by mechanical load combined with UV exposure, thermal cycling and humidity.
- Due to rigidity and non-breathability allowing trapping of degradation products

- **DML Sequential Test**: Fielded Glass Module: 21 yr (JRC)
Future Directions

Field Investigations

• Continue to expand data sets and analysis to understand failures and degradation mechanisms
• Deeper understanding of degradation mechanisms through chemical and physical analysis of fielded modules and comparison to accelerated testing
• Analysis of component / material degradation and power loss

Accelerated Testing

• Continue to use field results to develop new and better accelerated tests
• Develop shorter, more highly accelerated and predictive sequential tests

Materials and Components

• Use field results and accelerated tests to better understand component and module performance and design better backsheets and films
Conclusions

To understand PV Module durability and performance over time
• Consider – module, components, and materials
• All of the components of a module must be durable and perform over time
• Fundamental importance of field results
  • Understand degradation, aging mechanisms, and defects
  • Basis and guide for accelerated test development
• Importance of carefully designed accelerated tests
  • Correlate to the field (not induce new degradation modes)

Combining field results with accelerated tests to evaluate and give insights on how today’s new material will perform in the future

Using these tools can result in even better modules, components, and materials that will last and perform longer that those we are studying from the field today.
DuPont PV Reliability R&D Group

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John Trout
Bao Ling Yu
Factory Excursion and Lifetime Prediction

Michael Kempe, Dirk Jordan
National Renewable Energy Laboratory

Many other authors/contributors who could not be mentioned for confidentiality reasons

NREL Photovoltaic Reliability Workshop
March 28, 2018

Outline

- **Background**
- **Root Cause Analysis**
- **Model Parameters**
  1. Baseline Degradation
  2. Discrete Affected Area
  3. Degradation Rate of Affected Area
  4. Eyring Dependence on Temperature and RH
- **Model Results**
- **Conclusions**
Project Background:

- A developer constructed a utility scale photovoltaic power plant located in a dry desert environment.
- The bill of materials for the modules was put together by the developer and manufactured by a third party.
- The module design passed the qualification tests IEC 61730 and 61215.
- However, routine inspection of modules, performed after manufacturing, discovered a susceptibility to “damp heat” exposure in a subset of modules.
Motivation for Study

48 Modules were selected by a third party testing laboratory from the project and placed into stress testing. TC and HF samples indicated no issues.

IEC 61215 performance limit after 1000 h of 85°C and 85% RH

Four modules out of the 16 samples tested in Damp Heat indicated an issue.

- Cell A, Late, Blue
- Cell A, Late, Light Blue
- Cell B

IEC 61215 performance limit after 1000 h of 85°C and 85% RH
IR Images Consistent with Reduced Current

Typical unexposed, unaffected module.
Heating along tabbing due to high current in tabs and slightly higher recombination current near tabs.

Typical exposed sample.
Reduced heating near tabbing.
Changes in characteristic heating patterns.

Cells Type B, Unaffected Module

Cell type A, Affected Module
Module Categories – Frequency of Occurrence

All the different types of modes and bins were mixed together in the strings when deployed. Weighting of data by the fraction of field modules of each category is taken into account in the final model presented later.

These subcategories of modules were found to have different levels of susceptibility to the particular degradation mode of this study.

Modules constructed later and with light blue color were found to be the most susceptible.
Root Cause:

• For cells coming from one of two different cell manufacturers, the lighter blue colored cells manufactured later in the manufacturing run were highly susceptible to El-darkening through an interaction with solder flux.

• Unencapsulated cell level tests indicate moisture is needed to drive this degradation.

• Degradation produced a thinning of the already thinner light-blue cells, an increase in the series resistance of the cells, and a loss/reduction of current collection from some areas of the cells.
Project Scope and Objectives

• The manufacturer has figured out the root cause of the degradation mode.
• Our objective is to:
  – Assess the impact on the field. There was a desire to do service life prediction, but that is unrealistic to do with accuracy.
  – Propose corrective action or mitigation strategy. A complete replacement of all affected modules was proposed which would have cost millions.
• Our approach was to:
  – Rather than predict performance, we evaluated the additional impact of this degradation mode.
    • Determine upper and lower bounds for degradation attributable to this mechanism.
    • Estimate the most probable outcome.
    • Determine the reduced probability that the system will not achieve contract agreements that is attributable to this degradation mode.
  – This approach to data interpretation provided quantitative numbers focused only on this discovered failure which could easily be used by the banker and the developer to renegotiate the contract under an increased financial risk scenario.
Primary Model Assumptions

1. There is a baseline field degradation \( (R_{field}) \) upon which we will add a mechanism specific component.

2. There is an affected area \((A_i)\) of the cell impacted by a degradation not represented by 1, that is constant by module category.

3. The change in efficiency of the affected area is proportional to its efficiency at some time \( t \).

4. The constant of proportionality for the degradation rate in 3 is assumed to have an Eyring relationship with temperature \((T)\) and relative humidity \((RH)\).

\[
P_{System}(t) = P_o \left( 1 - R_{field}t \right) \sum_{i=\text{category}} W_i \left[ 1 - \frac{A_i}{A_o} \left( 1 - e^{-ct} \right) \right]
\]
Assumption 1: Modules survive TC-600 + HF-30

- Because the modules can survive TC-600 and HF-30, we believe the tabbing is good, delamination is unlikely, and the overall quality is high.

48 Modules Selected by the third party testing laboratory from the project and equally placed into stress testing. TC and HF samples indicated no issues.

This testing is well beyond IEC 61215 requirements of 200 and 10 cycles respectively for these tests.
Assumption 1: Estimate $R_{\text{field}}$

- With the exception of the fluxing process specific to a subset of modules, all indications are that the modules are constructed using materials and methods that perform consistent with historic values for the developer using the same bill of materials.

- We estimate that the background field degradation rate will be about 0.3%/y with a log-normal distribution around the mean.

- Because we are looking at the additional degradation relative to the base case, this is not as much of a critical assumption as one might initially assume.
Reported Field Degradation is Lognormal

• We fit a lognormal distribution to have the same mean and median as Dirk’s survey*. 

• Then we shifted the data by 3/5 to make the median be 0.3 %/y and the mean be 0.48 %/y.

Assumption 2: Affected Area by Module Category

Original EL image

Set threshold to highlight the darken area

Select the active area and calculate the dark area percentage
Assumption 2: Degradation Area is Limited

<table>
<thead>
<tr>
<th>Modules</th>
<th>T0</th>
<th>DH250</th>
<th>DH500</th>
<th>DH700</th>
<th>DH800</th>
<th>DH900</th>
<th>DH1000</th>
<th>DH1100</th>
<th>DH1200</th>
<th>DH1300</th>
<th>Average last four</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell A, Early, Light Blue</td>
<td>0.12</td>
<td>3.77</td>
<td>3.29</td>
<td>4.87</td>
<td>6.35</td>
<td>1.95</td>
<td>3.38</td>
<td>8.19</td>
<td>4.31</td>
<td>4.38</td>
<td>5.06</td>
<td>2.13</td>
</tr>
<tr>
<td>Cell A, Late, Light Blue</td>
<td>0.06</td>
<td>3.59</td>
<td>4.07</td>
<td>4.22</td>
<td>6.00</td>
<td>3.39</td>
<td>19.71</td>
<td>30.98</td>
<td>19.01</td>
<td>23.09</td>
<td>23.2</td>
<td>5.48</td>
</tr>
<tr>
<td>Cell A, Early, Blue</td>
<td>-0.34</td>
<td>1.81</td>
<td>1.87</td>
<td>3.69</td>
<td>1.95</td>
<td>0.31</td>
<td>4.10</td>
<td>8.21</td>
<td>3.87</td>
<td>3.86</td>
<td>5.01</td>
<td>2.13</td>
</tr>
<tr>
<td>Cell A, Late, Blue</td>
<td>-0.01</td>
<td>1.51</td>
<td>1.75</td>
<td>8.68</td>
<td>1.89</td>
<td>3.73</td>
<td>6.66</td>
<td>11.41</td>
<td>10.50</td>
<td>10.04</td>
<td>9.65</td>
<td>2.08</td>
</tr>
<tr>
<td>Cell B</td>
<td>-0.21</td>
<td>1.60</td>
<td>1.36</td>
<td>1.42</td>
<td>3.30</td>
<td>0.35</td>
<td>1.06</td>
<td>0.57</td>
<td>1.33</td>
<td>0.57</td>
<td>0.88</td>
<td>0.38</td>
</tr>
<tr>
<td>Cell B</td>
<td>0.11</td>
<td>1.41</td>
<td>1.24</td>
<td>1.96</td>
<td>3.46</td>
<td>0.70</td>
<td>0.76</td>
<td>0.85</td>
<td>3.20</td>
<td>1.27</td>
<td>1.52</td>
<td>1.14</td>
</tr>
<tr>
<td>Control</td>
<td>0.04</td>
<td>0.48</td>
<td>1.00</td>
<td>0.00</td>
<td>0.44</td>
<td>0.98</td>
<td>0.65</td>
<td>1.15</td>
<td>1.27</td>
<td>0.76</td>
<td>0.96</td>
<td>0.30</td>
</tr>
</tbody>
</table>

85°C and 85% rH test Dark area vs. Time

Average of the last four readings used to establish A/Ao by category along with its variability.
Assumption 3: Consequence of Affected Area

Across the different module categories large changes in FF correlate to the fraction of the affected dark area.
Assume the degradation mechanism occurs in the affected area in proportion to its remaining functionality.
Assumption 3 - Affected Area Behavior

- This allows us to relate the Fill Factor change measured in test to estimate the overall module time constant, $c$, from the governing model:

- This implies an assumption that $I_{sc}$ and $V_{oc}$ losses (which are much less significant in the accelerated stress test) will be accounted for in the $R_{field}$ degradation values.

\[
P_{System}(t) = P_o \cdot (1 - R_{field} \cdot t) \cdot \sum_{i=category} W_i \cdot \left[ 1 - \frac{A_i}{A_o} \cdot (1 - e^{-c \cdot t}) \right]
\]

Relates to change in Fill Factor

\[
\left[ 1 - \frac{A_i}{A_o} \cdot (1 - e^{-c_{eff} \cdot t}) \right] \approx \frac{FF_{it}}{FF_{i0}}
\]

An effective constant $C_{eff}$ is used because RH is not a constant making $C_{eff}$ not a constant. $C_{eff}$ is the time, position, and kinetic average $C$.
Assumption 4 – Behavior of the time constant, $c$

- The time constant $c$, is assumed to behave according to an Eyring relationship for cell temperature and relative humidity that is defined as:

$$C = e^\left(\frac{\beta_1 - \frac{\beta_2}{k\times T} - \beta_3 \times RH}{\beta_1 - \frac{\beta_2}{k\times T} - \beta_3 \times RH}\right)$$

- Combining these two and linearizing the results by taking the natural logarithm yields:

$$\beta_1 - \frac{\beta_2}{k\times T} - \beta_3 \times RH = \ln\left\{ -\ln\left[ 1 - \frac{A_0}{A_i}\left(1 - \frac{FF_{it}}{FF_{i0}}\right)\right] \right\}$$

- This equation contains three unknown parameters that can be solved for using nonlinear regression on the data.
Assumption 4: Compensation for Moisture Ingress

- It takes time for moisture to enter the encapsulant in front of a cell. This was seen in the delay before the $FF$ began to drop.

**Relative Humidity Along Tabbing Ribbon**

\[
C(X, Y, t) = C_s - C_s \frac{16}{\pi^2} \left\{ \sum_{m=0}^{\infty} \frac{1}{2m+1} \sin \left( \frac{(2m+1)\pi X}{l} \right) e^{- \frac{D(2m+1)^2 \pi^2 t}{l^2}} \right\} \left\{ \sum_{n=0}^{\infty} \frac{1}{2n+1} \sin \left( \frac{(2n+1)\pi Y}{l} \right) e^{- \frac{D(2n+1)^2 \pi^2 t}{l^2}} \right\}
\]
Assumption 4: Calculation of Effective Humidity

- With the moisture content as a function of time ($t$) and position ($X$), we compute and average RH which at the test temperature will produce the same damage.

\[
RH_{\text{eff}} = -\ln\left(\frac{\int_0^t \int_0^x e^{-\beta_3 RH} \, dx \, dt}{X \times t}\right)
\]

This is an important consideration for the effect of humidity in an accelerated stress test. It is not a constant but a function of time and position.

\[
c_{\text{eff}} = e^{\left(\beta_1 - \frac{\beta_2}{k \times T} - \beta_3 \times RH_{\text{eff}}\right)}
\]
Assumption 4: RH$_{\text{eff}}$ Results

There is a significant amount of time required for moisture to diffuse over the front surface of the cell, between the glass and the illuminated cell surface. The effective average relative humidity is significantly lower than the chamber set points over the course of the experiment.
Assumption 4: Excluded Data

• The 75°C data did not always exhibit significant \( FF \) loss and was thus often excluded from the regression analysis for data points resulting in irrational numbers.

• This indicates that the critical mechanisms are fairly highly thermally activated and thus not very likely to be significant.

75°C and 85% RH
Parameter Solution

• The regression analysis weighted the solution by the product of $A/A_0 \cdot \text{Time}$.
• Various weighting systems were tried giving results from 0.75 to about 1.05 eV. Choosing one at the lower end results in higher modeled degradation.
Modeled Data Compared to Actual

- The data is fairly scattered, leading to some uncertainties in the acceleration factors.
- A wider temperature range and wider humidity range is needed.
- However, it would appear that at 75°C the degradation mode of interest was starting to be masked, limiting the ability to use lower temperatures.
- Similarly, higher temperatures could activate new, higher activation energy processes.
FF Loss is Not the Only Degradation Process

Δ$P_{\text{max}}$

Power shows a continuous signal associated with multiple degradation modes

Δ$FF$

Fill Factor begins to change coincident with appearance of dark areas in EL

There are some degradation process affecting $P_{\text{max}}$ initially, but it takes a while for FF to be affected. This indicates that there are multiple degradation processes occurring, but it is not clear that FF losses are only attributable to this flux induced mechanism.
Monte Carlo Results by Category

- Because of the large high degradation rate tail in the $R_{\text{field}}$ distribution, the 97.5th percentile estimate is quite high.
- However, the difference between the base, no flux-AR interaction case and the different categories is relatively small.

<table>
<thead>
<tr>
<th>Module Category</th>
<th>Average Affected Area (%)</th>
<th>Percent of Field</th>
<th>Category 20 y degradation.</th>
<th>Difference in 20 y degradation compared to No-Flux-AR interaction.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.5 Percentile</td>
<td>50 Percentile</td>
</tr>
<tr>
<td>Cell A, Early, Light Blue</td>
<td>4.2±3.3</td>
<td>5.96</td>
<td>1.5</td>
<td>6.8</td>
</tr>
<tr>
<td>Cell A, Late, Light Blue</td>
<td>19±3.9</td>
<td>11.51</td>
<td>3.1</td>
<td>9.5</td>
</tr>
<tr>
<td>Cell A, Early, Blue</td>
<td>6±3</td>
<td>8.56</td>
<td>1.7</td>
<td>7.0</td>
</tr>
<tr>
<td>Cell A, Late, Blue</td>
<td>11±1</td>
<td>34.25</td>
<td>2.3</td>
<td>8.0</td>
</tr>
<tr>
<td>Cell B, Site 1</td>
<td>0.82±0.35</td>
<td>19.86</td>
<td>1.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Cell B, Site 2</td>
<td>2.7±2</td>
<td>19.86</td>
<td>1.3</td>
<td>6.4</td>
</tr>
<tr>
<td>Control</td>
<td>0.96±0.3</td>
<td>0.00</td>
<td>1.1</td>
<td>6.1</td>
</tr>
<tr>
<td>Overall Field Degradation</td>
<td>7.3±2.03</td>
<td>100</td>
<td>2.0</td>
<td>7.3</td>
</tr>
<tr>
<td>No Flux-AR Interaction</td>
<td></td>
<td></td>
<td>0.93</td>
<td>5.9</td>
</tr>
</tbody>
</table>
Monte Carlo Simulation with Flux Interaction

- Now, accounting for:
  - Flux failure mode
  - Probability distribution for degradation rate
  - Uncertainty in affected area

- The probability of not meeting the design loss rate is higher by **1.8%** because of this failure mechanism.

- Alternatively, to have the same likelihood of failure as for the unaffected case, a **0.05%/y** increase in the loss rate would be used.

- This provided quantitative data for the project financing team to use.

Poorest Performing cells:
Cell A
Late production
Light-blue cells

Estimated performance histogram after 20 y of field exposure.

After several years of exposure, this failure mode is not discernably affecting the project.
Conclusions

• Failure of a Damp heat test does not necessarily predict failure in the field.
  – Extreme conditions highlight highly activated processes which are far less likely to be relevant.
  – In this case it predicted an additional 1.4% degradation after 20 y.

• One cannot simply use chamber settings for exposure conditions of modules.

• As opposed to an inaccurate service life prediction, the data was used to estimate a 1.8% decreased probability of achieving the project goals or the need to increase the maximum allowed degradation rate by 0.05%/year.
Acknowledgements

• Unfortunately to protect the identity of the project and of those who made the modules and constructed the field there were many people who should have been identified as authors but could not.

• Sarah Kurtz, John Wohlgemuth, Peter Hacke, and David Miller for many useful discussions in this work.
Outdoor and Indoor Luminescence Imaging of Photovoltaic Modules

Ziv Hameiri, Raghavi Bhoopathy, Iskra Zafirovska, Oliver Kunz, Mattias Juhl, Thorsten Trupke

PV Reliability Workshop, NREL
28/2/2018
Outdoor photoluminescence measurements of photovoltaic modules under full sunlight illumination

SHORT COMMUNICATION

Outdoor photoluminescence imaging of photovoltaic modules with sunlight excitation

Raghavi Bhoopathy | Oliver Kunz | Mattias Juhl | Thorsten Trupke | Ziv Hameiri
Background

• It is desirable to operate photovoltaic (PV) power plants at its maximum capacity

• PV modules degrade during transportation, installation and operation

• There is a need for a characterization tool that can be used outdoors for inspecting these modules.
Existing methods

- **Visual assessment**
  Capable of detecting only optical degradation such as discoloration, delamination, glass breakage

- **Current-voltage measurements**
  Provides only performance data of entire string/module

- **Ultraviolet (UV) fluorescence**
  Detects only cracks with long-time exposure to UV dose

- **Infrared (IR) thermography**
  Mainly limited for hot-spots detection

- **Luminescence imaging**
  - Operates only when ambient sun light is low
  - Requires special hardware
  - Imaging cell-by-cell
Aims

• To obtain outdoor photoluminescence (PL) images using the sun as the sole source of excitation (no additional light source)

• To obtain these images contactlessly

• To obtain high quality large area images
Methodology

Open circuit
No carriers are extracted
Maximum PL

Short circuit
~All carriers are extracted
~ No PL

Subtracted image

\[ PL + \text{Ambient} \]

\[ \text{Ambient} \]

\[ PL \]
Methodology

PL: ~2% of ambient signal

Enlarged by 100 times

AM 1.5 solar spectrum
PL spectrum
Methodology

- All the cells that are connected to the same bypass diode, are connected in series.
- The cell with the lowest light-induced current limits the current.

![Diagram showing the connection of test cells and a control cell, with a bypass diode connected to each test cell. The control cell is highlighted as the current limiter.]
Methodology

Control cell: Fully illuminated

Fully shaded

Sun

MPP condition

OC condition

No shading

Fully shaded

Sun

100% $I_{mpp}$

0% $I_{mpp}$

100% $I_{mpp}$

0% $I_{mpp}$

9
Proof of concept

Short circuit (SC) condition

Open circuit (OC) condition

InGaAs spectrometer

Cardboard
Proof of concept

Spectrum measured at OC and SC

- Two slightly distinct spectra was observed
- Silicon luminescence spectrum was extracted by subtracting the SC spectra from OC
Experimental setup
Experimental setup

![Graph showing the AM 1.5 solar spectrum, PL spectrum, and filter transmission. The graph highlights the BP 1137 nm (25 nm) wavelength.](image-url)
Outdoor PL image

Optical image:

**PL image:**
Reveals cracks and other electronic defects.

Image acquisition frequency = 25 Hz

Total measurement time = 1 sec (40 images)
Outdoor PL image Vs Indoor EL image

Outdoor PL

Indoor EL

Intensity (a.u.)
How many images are required?
Sequential measurement

- **50 image-pairs**
  - 2 seconds

- **500 image-pairs**
  - 20 seconds
Sequential measurement

5 image-pairs

20 image-pairs

10 image-pairs

50 image-pairs

(PERC)
Batch measurement

- 50 image-pairs in 2 seconds
- 500 image-pairs in 20 seconds

Graphs showing average counts and SNR as a function of the number of image pairs.
Isolated regions
The isolated regions are not connected to the busbar; therefore not affected by the recombination caused by shading and metal-Silicon interface.
The isolated regions are not connected to the busbar; therefore not affected by the recombination caused by shading and metal-Silicon interface.
The isolated regions are not connected to the busbar; therefore not affected by the recombination caused by shading and metal-Silicon interface.
Can be used to identify the severity of the isolation.
Distinguishing extent of isolated areas

Differential PL images obtained by switching between $V_{OC}$ and any operating voltage greater than the $V_{MPP}$

Simulation

Experiment
Bypass Diode
Detection of bypass diode OC failure

Normal operation

(a)

Intensity (a.u.)

5000
3750
2500
1250
0

100mm

(b)

Control cell

Control cell

OC failure
Conclusions

Module characterization tool was developed that can identify defects:

- Under normal operation in the field
- Contactlessly without requiring any modification to the PV field installation
- Using the sun as the sole source of illumination
- Can be applied to identify extent of isolated areas and OC bypass diode failure.
Suns-PL
Implementation

\[ \text{PL} \approx e^{V_{i,\text{cell}}} \]

Irradiance = \( I_{\text{cell}} \)
Comparison to light I-V and Suns-$V_{oc}$
JPV: Detection of finger interruptions in silicon solar cells using line scan photoluminescence imaging

Iskra Zafirovska, Mattias K. Juhl, Jürgen W. Weber, Johnson Wong and Thorsten Trupke
Line scan PL imaging

- Performed using a prototype module line scan imaging tool developed at UNSW

- Open-circuit PL imaging:
  Uniform photo-excitation, full area imaging

- Line scan PL (PLLs) imaging:
  - Imaging restricted to a thin line spanning width of sample
  - Photo-excitation localised to this line
  - Individual “line” images continuously captured in sync with sample motion

Schematic of prototype line scan imaging tool [1].

Line scan PL imaging

- Currently EL imaging is typically used during module manufacturing
- Prototype can acquire $PL_{LS}$ and EL images of full area modules with up to 72 cells

Line scan PL ($PL_{LS}$) image of a commercial module containing many cells with finger interruptions ($R_S$ defect).  
EL image of the same module.
**PL\textsubscript{LS} for defect detection**

- Reliable defect detection is more effective using PL\textsubscript{LS} imaging due to an inverted contrast
- Can easily differentiate \( R_S \) defects and sites of high recombination, which is especially important in mc-Si material

<table>
<thead>
<tr>
<th>Technique</th>
<th>Excitation</th>
<th>( R_S ) defects</th>
<th>High recombination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit PL imaging</td>
<td>Full area illumination, no driving force for lateral current flow</td>
<td>Not visible</td>
<td>Lower intensity</td>
</tr>
<tr>
<td>EL imaging</td>
<td>Current injected at terminals and flows outwards</td>
<td>Lower intensity</td>
<td>Lower intensity</td>
</tr>
<tr>
<td>Line scan PL imaging</td>
<td>Localised line illumination, current flows from illuminated to non-illuminated regions</td>
<td>Higher intensity</td>
<td>Lower intensity</td>
</tr>
</tbody>
</table>

Comparison of the appearance of high recombination sites and \( R_S \) defects for different luminescence imaging techniques.
PL\textsubscript{LS} for defect detection

- Grain boundary (high recombination) centred over region with five finger interruptions (R\textsubscript{S} defect)
- Single finger interruption (R\textsubscript{S} defect)
- Finger with two interruptions (R\textsubscript{S} defect)
- Rectangular region of high recombination centred over a finger

Comparison of defect types from luminescence images simulated using Griddler 2.5 Pro.

(a) Open-circuit PL image  
(b) EL image  
(c) PL\textsubscript{LS} image
Advanced defect detection

The most comprehensive defect characterisation can be achieved by combining PL$_{LS}$ and EL images, in order to utilise the advantages of both techniques.

Ratio images: intensity of PL$_{LS}$ image divided by intensity of EL image. Areas of high recombination suppressed whilst even very subtle R$_S$ defects enhanced.

Images of a single cell cropped from a module image.

(a) PL$_{LS}$ image
(b) EL image
(c) Ratio of PL$_{LS}$ and EL image
Carrier induced degradation (CID) study

- Investigating the use of implied voltage from luminescence ($iV_{\text{mod}}$) vs direct terminal voltage measurements ($V_{\text{mod}}$), for the characterisation of voltage changes due to CID
- Luminescence intensity ($\phi$) directly correlated to terminal voltage [2, 3]:
  \[ \phi = C \exp \left( \frac{V}{V_T} \right) \]

![EL images of mc-Si PERC module used for CID experiment. CID achieved by light soaking module at elevated temperatures.](image1)

![PL$_{LS}$ images of module in the left figure](image2)

---


Carrier induced degradation (CID) study

- $iV_{\text{mod}}$ less sensitive to variations in measurement environment, specifically temperature
- $V_{\text{mod}}$ measurements: Difficult to separate real voltage degradation from temperature variation

Comparison of direct voltage measurements and implied voltage calculated from EL images during light soaking at elevated temperatures.
Conclusions

- $\text{PLL}_\text{LS}$ is a powerful imaging technique
- Can be used to classify various defects and faults in PV modules

Schematic of prototype line scan imaging tool [1].
Acknowledgements

• The entire Photoluminescence Team at UNSW

• The Australian Renewable Energy Agency (ARENA), the Australian Center for Advanced Photovoltaics (ACAP) and the Australian Research Council (ARC)
We are happy for collaborations

Please contact me
Thank you!

Question?
Contactless extraction of implied I-V curves of individual solar cells in fully assembled modules using photoluminescence

Aim:
To extract the current-voltage characteristics of a cell encapsulated in a module by a contactless and non-destructive method using photoluminescence.
Simulating line scan imaging

- *Griddler 2.5 Pro* [2] in conjunction with a custom developed software suite
  - Single Griddler simulation represents a “snapshot” in time of the line scan process
  - Line images are extracted from many simulations, and combined to form the final image
- Highly valuable for further exploration of concepts observed during experimental work

Solar System Uptime And Field Services Optimization -- Driven By Predictive Analytics

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• Predictive analytics on Predix
• Solar Asset Performance Management platform (APM)
GE Digital Industrial Transformation
Leader in industrial-strength analytics, physical + digital, integration and big data

The Predix Platform was built for the Industrial Internet.
It is a Platform-as-a-Service for developing, deploying, and operating
Industrial apps — turning insights into business outcomes.
Connectivity Architecture
Designed to easily connect your industrial assets

PV Arrays \rightarrow Solar Inverters \rightarrow Site SCADA System \rightarrow Site Firewall/Router \rightarrow Internet

OPC UA, Modbus TCP, etc. \rightarrow HTTPS

Mini Field Agent/Field Agent \rightarrow HTTPS

HTTPS

Predix Cloud

Perf. Engineer, Fleet Manager

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# Solar Inverter - Failure Prediction

## DETECTION METHOD

<table>
<thead>
<tr>
<th>V</th>
<th>A</th>
<th>°C</th>
<th>B</th>
<th>l/m</th>
<th>W/m²</th>
<th>Data sheets</th>
<th>Vib.</th>
<th>Time</th>
</tr>
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## TECHNOLOGY (MV/LV)

<table>
<thead>
<tr>
<th>LV</th>
<th>MV</th>
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<table>
<thead>
<tr>
<th>DC Bus</th>
<th>DC Caps Lifespan</th>
<th>DC Pre-charge Time</th>
<th>AC Caps Bulging</th>
<th>Caps Failure (post analytics)</th>
<th>Cap Lifespan</th>
<th>IGBT Heatsink Clogged</th>
<th>Cooling Leak (Pump Fault)</th>
<th>Pump Health</th>
<th>Cooling Leak</th>
<th>Fan Health</th>
<th>IGBT thermal cycle lifespan</th>
<th>IGBT power cycle lifespan</th>
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V – Voltage  
A – Current  
°C – Temperature  
B – Cooling Pressure  
l/m – Cooling Flow  
W/m² – Irradiance  
Vib. – Vibration  
LV – Low Voltage  
MV – Medium Voltage

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Cooling system health
- System alerts on **Day 0**
- Severity increases on **Day 79**  
  <- de-rated 33 days
- Inverter fixed on **Day 112**

Capacitor health
- System alerts on **Day 0**
- Severity increases on **Day 25**
- Inverter fails on **Day 39**

The output from physics based algorithms shown below are used in conjunction with empirical machine model for deviation detection.

Digital Solar solutions perform empirical machine modelling in real-time to predict the values of what all real and calculated variables should be at any operating point and environmental condition.

Typically current inverters and tools do not raise an alarm until failure. With the use of machine learning to train the model, as data is ingested alerts are generated well before component failure.
GE’s Solar APM Platform

Financial Cycle

Intelligent asset Strategies

Execution Cycle

Decision Cycle

PREDIX

Time Series

Analytics

Alerts

Cases & Recommendations

Evidence Expertise

Service Request

Work Order

Schedule Dispatch

Perform Capture

Servicemax

From GE Digital
Morning Newspaper – Fleet Manager

• Fleet level KPI

• Key site trends

• Availability (w/ or w/o fixes)

• Energy production (w/ or w/o fixes)

• Alarm & alert risk heat map overview
• Specific component impacted

• Detailed cost and time to repair

• Revenue and availability impact

• Parts availability (inventory)
Analysis details
Recommendation and Case creation
Resource Dispatch

- Seamless case to service order creation
- Service order detail and recommended instructions.
- Drag & Drop service order scheduling
- ServiceMax mobile app integration
What is an intelligent asset strategy

An IAS combines the risk and criticality of an asset and then develops the appropriate asset strategy to manage, execute, evaluate and track the performance and effectiveness of the asset.

The intelligent asset strategy is based on single source of truth, real time information, failure history, industry data and other standard methodologies.

- Identifies why an asset could fail and the best actions to prevent
- Links risk to organizational & business objectives
- Enables complete visibility to the health of the asset
- Continuously monitors for increased operational risk
- Is constantly measuring for effectiveness to objectives
- Forecasts what might happen in the future
- Enables true lifecycle cost analysis
Intelligent asset strategy
1. Focusing on prevent un-expected downtime, optimize maintenance activities

2. Achieved by developing predictive analytics on sub-component levels

3. Asset Performance Management system provide an integrated interface for decision making.
General Monitoring Structure

Southern Company Solar Fleet Monitoring

- Inverter Operation (ACDC Ratio)
- Site Output (Irradiance-Loud)
- APR Models
- Automated Review
- Manual Review
- Daily
- Inverter Operations Dashboard
- Inverter Alarms Dashboard
- DC Amps per String
- Internal Cabinet Temperature

Periodic (In development)
- Annual
- Monthly
- Performance Ratio
- Soiling Ratio
Manual Review
Solar Dashboards

• General screen flow is consistent across each solar facility
• Core dashboard screens are:
  • Site overview
  • Inverter overview
  • Site alarm summary (If possible)
Example of Site Overview Dashboard
Example of Inverter Overview Dashboard
Site Alarm Summary
(Not available for all sites)
Inverter Alarm Summary
(Not available for all sites)
Automatic Review
SCGen Core APR Models for Solar Monitoring

Only building three core model types at this point
• Site AC Generation model
• Site DC Generation model
• Inverter AC/DC Power Ratio model
Example of a Site Generation APR Model
Questions

Identify

Decision Made

Investigate Change

SCGEN M&D Center
One Team

Feedback from Plant

Communicate Observation

Plant Verification
PV Reliability Workshop: Single Framework Characterization

Steve Voss (steve.voss@powerfactorcorp.com) – 3/1/18
WHO WE ARE

- California-based company
- Founded in 2012 by power industry veterans
- Specialized in data intelligence
- +40 subject matter experts in solar, wind, traditional generation, and software dev
- +235 years of combined experience
  (First Solar, Calpine, SunEdison, First Wind, SunPower)
THE OBJECTIVE

• How can we use data from operational PV power plants to drive continuous improvement?

• Opportunities:
  • Design optimization
  • O&M optimization
  • Reliability improvements
  • Risk reduction

https://www.getvetter.com/posts/129-define-continuous-improvement-8-experts-definitions
THE OPPORTUNITY (OR PV DATA AT ITS FINEST)

- 500 commercial power plants
- 4 months of data
- Each data point represents 1 plant-month
- Correlation between Predicted (PVSyst Simulation) and Actual is essentially non-existent
- Too many convoluted effects

![Predicted vs. Actual Performance Ratio graph](image)

\[ y = 0.18x + 61.36 \]

\[ R^2 = 0.15 \]
HOW DO WE EXTRACT INFORMATION FROM THIS DATA?

• Many potential approaches: machine learning, predictive analytics, etc.
• One approach: Single Framework Characterization
  • Takes advantage of the fact that PV systems are simple
  • Statistically simple
  • Isolate single dependent to independent variable relationships
  • Nominal (spec sheet) values serve as anchor points for reference
SINGLE FRAMEWORK CHARACTERIZATION

• **Event losses:** Any performance impacting occurrence with a start and end time:
  - Outage, clipping, shading, curtailment

• **Operational losses:** Impact all operational intervals:
  - Thermal, inverter efficiency, soiling, current, voltage

• **Requirements:**
  - Full characterization from Nominal to Actual power
  - Direct comparison between Predicted and Actual production
EXAMPLE CHARACTERIZATION: DC VOLTAGE

- Traditional data presentation;
- Information content is near zero
EXAMPLE CHARACTERIZATION: DC VOLTAGE

- Voltage vs Temperature provides more information;
- Still too many competing effects.
EXAMPLE CHARACTERIZATION: DC VOLTAGE

Filters:

• Sun Height > 0
• Events
• Irradiance > 200 W/m²
EXAMPLE CHARACTERIZATION: DC VOLTAGE

Filters:

- Sun Height > 0
- Events
- Irradiance > 200 W/m²
EXAMPLE CHARACTERIZATION: DC VOLTAGE

• Full characterization of DC Voltage – independent of Events (aka convoluting effects);
EXAMPLE APPLICATION

- High volume tracking of (event free) evolution of indicative performance characteristics over time for degradation characterization

![Normalized Voltage vs Irradiance](image1)

![Predicted vs. Actual Performance Ratio](image2)

VS

\[ y = 0.1823x + 61.363 \]

\[ R^2 = 0.1467 \]
THE OBJECTIVE

• How can we use data from operational PV power plants to drive continuous improvement?

• Opportunities:
  • Design optimization
  • O&M optimization
  • Reliability improvements
  • Risk reduction

https://www.getvetter.com/posts/129-define-continuous-improvement-8-experts-definitions
PV Reliability Workshop: Single Framework Characterization

Steve Voss (steve.voss@powerfactorcorp.com) – 3/1/18
New Discoveries in Soiling of PV Modules

2018 PV Reliability Workshop


February 27-March 1, 2018
Contents

- Introduction/overview
- Review of soiling adhesion mechanisms
- Electric Field Induced Soiling
- Cementation
- Microbial
- Summary
- Acknowledgements
What Causes Soiling?

Many literature questions still need to be more fully addressed, e.g.:

• If gravity or wind brings dust to the surface, what makes it stick?
• What role does humidity and electrostatics play?
• What are the relative strengths between the different forces?
• What is the effect of surface properties and dust composition?
  • Surface roughness?
  • Surface Energy?
• Dust that has been on the surface for a while tends to be harder to remove, why?
• Dew seems to increase soiling.
• Is roughness observed on modules due to weathering from chemical etching of the glass or surface deposits?
• Why are soiling rates higher in cities?
• Why is soiling not uniform?
• How much do biofilms contribute to soiling?
• One of the main forms of enduring soiling is cementation.
  • What is cementation?

van der Waals may be most important initial adhesion mechanism that holds dust on the surface continuously.

Both tend to be weaker effects than predicted.

Capillary forces are a major issue in early morning with dew formation.

Need to understand and differentiate hydrogen bonding from van der Waals. Understanding critical to the development of mitigation strategies.

Cementation: All mechanisms adhere dust to surface to enable longer term “chemical” bonding.

Take home: surface energy only affect initial adhesion a little, probably more important for cleaning.

Need to understand how daily cycling with water and heat impacts cementation.
Initial Adhesion Mechanisms: Different Size Dust Particles

Modeling for spherical particles indicate vdw and capillary forces increase with particle size. Mechanics of Particle Adhesion, Jürgen Tomas, Otto-von-Guericke-University, 2004

Due to surface roughness, real dust particles have surface contact areas much smaller than expected based on the particle diameter and therefore vdw and capillary adhesion does not increase proportionally as particle size increases.

While longer-range forces may increase with the size of real dust; the adhesion of real dust from short-range forces does not increase for larger particles. Explains why larger particles blow off PV.
Comparison of the contact area between a glass surface and (a) a real 20-μm diameter dust particle and (b) a 20-μm diameter glass sphere. We are considering a 1-nm thick water layer with a 10-nm thick meniscus due to the relative humidity. The scale is the same for both images.

For short range forces (e.g., vdW and capillary) as expected adhesion forces are controlled by surface contact areas; not correlated with particle diameter for real dust particles that have surface roughness.
**PV Cell Voltage at Module Glass Surface**

- Demonstrates that ~1000 V on PV cells results in nearly 1000 V at module glass surface.
  - One issue is that sodalime glass is somewhat conductive.
  - Electric field will propagate through glass anyway, even if glass was more resistive and the module surface potential was close to zero.
  - Note, leakage current highest close to frame, may increase cementation.

Shiradkar, et. al. Proc. of SPIE Vol. 8825 88250G-1
Electric Field Induced Adhesion: 20-μm SiO₂ Sphere on Glass Surface

- Adhesion force on a piece of c-Si module at various locations in simulating glass center and near-frame.
- 20-μm silica was used to simulate dust particle in a well-defined shape and composition.
- Force was measured with increasing negative bias voltage.
- Electric field force increased up to ~10,000 nN at V=350 V, dominating adhesion (~100,000 nN at V=1000 V).
- Van der Waals increase slightly with voltage, due to enhanced dipole interaction of sphere and glass with electric field.
Three-dimensional Electric Field Forces on Real Dust Particles

- $F_{es}$ decreases moving away from the glass surface.
- $F_{es}$ of dust #4 is ~1000 nN, 200 μm away with 1000 V, similar to that of $F_{vw}$.
- $F_{es}$ is ~300 nN, 500 μm away, still a significant force, due to the long range of the electric field.
- Because of the long time dust particles may spend over a PV module, even the weakest 3D electric field force may enhance soiling rate.
Electric Field Induced Soiling (EFIS)

- PV Cell Electric field Extends through glass
  - By far strongest attraction of dust in air found so far
    - Induce dipoles in dust
    - Some dust may be charged
    - Other mechanisms may occur
  - Charge glass surface
    - Generate chemical reactions
    - Induce Ion migration
      - (semi-permanent dipole)
      - Slow decay of attraction force seen
  - Plans: Use AFM and QCM
    - Need to quantify soiling loss with V
    - Demonstrate changes in bonds with V

Large electric field from PV cells producing up to 1500 V extends through PV glass and may attract dust far away from the surface. Also, ion migration and surface charging may occur.
Follow-On: Adhesion of Different Size Dust Particles

For real dust particles with surface contact areas much smaller than and not correlated with particle diameter, vDW and capillary adhesion does not increase proportionally as particle size increases.

The long-range electric field force increases with the size of real dust particles; but the short-range capillary and van der Waals forces do not increase adhesion on the limited contact area of real larger dust particles.
Mechanisms: EFIS, Outdoor Test System

- **Measure Enhanced Soiling Rates/Losses of Real Dust Particles**
  - System deployed and now operational in CA
    - Soiling rates pretty low right now (lots of rain)
  - Preliminary results confirm results from CO that there is an apparent increase in soiling with +/-1000 V applied.

- **High voltage arrays are increasing soiling losses, and when combined with soiling may accelerate PID. A lot more work is needed.**

“High voltages relative to ground may affect the rate of accumulation of dirt on some modules and top cover materials after extended exposure.”
Soiling Mechanism: Cementation

- Cuddihy first to characterize “cementation”

To understand cementation, we must first quantify the impacts of the individual components and conditions.

Humidity cycling increases rate of aging

Particle “aging” leads to more contact area that increases the stiffness (interaction) between the QCM surface and particles; causing the frequency to increase with time.

Onset of cementation is detected in **halite particles on QCM SiO$_2$ surface** with humidity cycling.

Transition from sliding contact to rigidly adhered particles.

Cycling between humid and dry air causes the halite particles to initially age, as did the silica spheres. However, at some point, the fundamental interaction between the halite and QCM surface transitions to where it transmits “shear.”

**The formation of rigidly adhered particles marks the formation of cementation.** As more particles become cemented the frequency continues to decrease. With cementation detected, we can now quantify the different processes involved.
Complex Soiling Mechanisms: Cementation

Onset of cementation is detected with several materials on QCM SiO$_2$ surface with humidity cycling. + Δf with glass, no cementation

Cycling turned on

Large - Δf means cementation

Some materials like iron oxide appear. To cement on contact with glass. Still working out details to make truly quantitative.

Created tool to test surfaces/coatings that prevent cementation.
Mechanisms: Simulated Soiling Processes

- Mimics dew, temperature, and electrostatics of real PV modules while controlling humidity and uniformly dispersing dust.

Comparison Between Edge and Center

Reproducible and uniform dust distribution on glass sample.

Dust particles deposit from the side, shoot up, and spread uniformly throughout the chamber, with a five minute settling period.

Conductive tape is applied to the perimeter of the glass coupon and grounded to mimic the grounded frame of a PV module.
Mechanisms: Halite and Palygorskite Soiling

- Halite and palygorskite dust uniformly deposited on glass
- At 90% RH, the sample was cooled to ~15°C where dew formed
- Then the sample was heated to ~60 °C and held for 1 hour.
- Initial tests had only one dust deposition followed by multiple dew/heating cycles.

Results:

- Halite crystals formed after 1 cycle & -1000 V
  - Electric field concentrates salt at surface accelerating cementation.
  - Suggests that hydrophilic and +1000 V cell voltages may help.
- No effect of dew cycle or voltage on Palygorskite.
  - Cements with first dew, not effected by water drops
  - Suggests that hydrophobic surface may not help.
Field Samples for Abrasion Standard

- First referenceable description of the field coupon study.
  - “PV Soiling and Abrasion: Initial Observations From 5-Year Module Glass Coating Study”, SOLMAT (submitted)
- Biological contamination (fungi): Sacramento coupon results (1y) compared to veteran modules from Germany & CA.
- Trapping of inorganic matter confirmed in EDS analysis.
- Multiple measurements: no observed etching of glass from fungus, yet.

- Early attempts at cleaning glass (including removing biological species) described.

- Cleaning methods compared in field study: roughness from dry brush > wet sponge/squeegee.
- Post examination confirms that much contamination remains after only rinsing.
- Similar trend observed for restoration of transmittance.

Comparison of T field coupons from Sacramento. The cleaning practices used on the coupons are abbreviated as: NC (never cleaned), DB (dry brush), WS (low-pressure water spray), or WSS (wet sponge and squeegee).
Biological species (e.g. fungi) have been observed on coupons and veteran modules throughout the world (e.g., Sacramento, CA; Argenbühl, Germany; Brazil; Mumbia, India; and even Dubai, UAE) in tropical and desert environments.

- Hyphae (filament growths) can extend for mm’s. Radial colony growth pattern.
- Colonies with organic & inorganic matter (nutrients or shelter?).
- Density distribution can be highly heterogeneous.
- DNA identified the alternaria genus of ascomycetous fungi.
- Presently working on a method to distinguish organic & inorganic contamination, to provide a “particle count” of each.

Representative images of: contamination on Dubai coupon (top); Sacramento module (middle); Sacramento coupon (right); cultivation of contamination for biological assessment (bottom).
Exploring the Cleaning of Veteran Modules

- 6 cleaning solutions: IPA; DI water; Simple Green cleaner; saturated NaCl; acetic acid (10%); bleach (5%).
- Procedures: soak + rinse -vs.- soak + wipe + rinse.
- Veteran module: Argenbühl Germany (6y).
- Image before and after cleaning at indexed location.
- Some solutions more effective on inorganic contamination only.
- Some solutions highly effective, especially with soak + wipe + rinse procedure.
- Some solutions left behind a residue (not necessarily bad).
- Aqueous based solutions generally more effective. Bleach most effective at removing fungi.

Example: bleach (5%) for soak + wipe + rinse procedure. Highly effective cleaning.

Example: Simple Green for soak + rinse procedure. Predominantly inorganic matter removed.

a. Clean to enable study of abrasion.
b. Interest in cleaning, to confirm result in literature.
Summary

- **van der Waals and Capillary Adhesion of Dust Particles**
  - Main mechanisms that cause dust to initially stay on module surface.
    - van der Waals forces in dry conditions may have similar magnitude to capillary for smooth surfaces
    - van der Waals and capillary forces are significantly reduced with increased surface roughness, but are significantly increased with contact area. Thus the soiling adhesion is very dependent upon the local topography.
  - Little effect of vdW adhesion with surface energy
  - Capillary adhesion not correlated well with surface energy; other factors?

- **Electric Field Induced Soiling**
  - Long range force that substantially increases attraction out at millimeters and even centimeters
  - Enhances adhesion forces and force increases with particle size
  - Induced dipole and charging effects can last well into the night
  - Increases soiling rates and thus soiling losses
  - Accelerates some soiling processes like salt cementation

- **Microbial soiling**
  - Fungus growths invisible to the naked eye, but appears to be on many PV modules around the world
    - May be included in enhanced “permanent” degradation rates assigned to modules in hot/humid climates?
  - Clearly fungus adhere and grow on hot PV modules, not removed with rain
  - Initial work suggests more cleaning with strong scrubbing. Dilute bleach solution soaks followed by scrubbing (e.g., squeegee) seems to work best so far.
  - Need to understand growth processes (e.g., environmental conditions, module surface properties, …) to prevent fungus soiling

- **Cementation**
  - Very material dependent, some cements immediately upon contact, dew cycle very important process with other dust types
    - Appears that some cementation may be related to increasing the contact area and thus adhesion, others may be bond formation
  - Dew cycle and cementation may be main issues to focus on to mitigate soiling losses
Critical Needs and Pressing Issues

• Need to understand better the processes (e.g., cementation) that lead to permanent soiling loss/module degradation

• Qualification standards for coatings and cleaning
  o Advanced coating cannot be warrantied for use in harsh environments or with some cleaning processes because there are no standards
  o Need to understand the impact of addressing one or two adhesion parameters but perhaps creating durability problems (e.g., roughening the surface reduces vDW and capillary adhesion, but may increase cementation bond strength. Surface energy not a good indication of adhesion, and also may change with surface contamination. Qualification standards may need to include active soiling/weathering to qualify effectiveness of film).
  o Advanced cleaning/robots must go through expensive and long qualification processes to not void module manufacturers warranties.
  o Need to quantify acceptable damage induced by cleaning, and efficacy requirements.

• Soiling is a very challenging cross-cutting problem that is having trouble finding a home. Some do not consider it a “module” problem, or a “reliability” problem, or a “durability” problem. Yet, soiling can cause rapid power loss (reliability), induce long-term damage (durability), and cause individual cells to stop working, taking out an entire string (module).
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- Rebecca Jones-Albertus
UL3741 PV Hazard Control
Reducing Hazards for Firefighters

What are we protecting against and how do we prevent it?

Tim Zgonena
UL LLC
March 2018

Olga Lavrova
Sandia National Labs
Two Big Questions - What are We Protecting Against and How do We Prevent It?

1. What are the hazards for firefighters working in and around PV arrays?
2. How do we keep firefighters out of hazardous current paths?
Significant Task Group Effort for Publication of Requirements for PVRS Equipment and Systems - UL1741 (Dec 22, 2017)

- Protection of Emergency Personnel
- Status Indicators, Initiators and Reset Devices
- PVRSS that Includes PV Disconnect Functionality
- Operational Tests PVRSS Verify levels Controlled Conductors.
- Verification Testing of PVRSS at Rated Extremes
- Power Supply Ride Through
- Inverters Certified as PVRSE
- PVRSS & PVRSE Functional Safety Using Solid State Controls
- Environmental Test Conditions for a PVRSS/PVRSE
- Environmental Stress Testing (based on UL991)
- Ratings, Markings and Instructions.

The new UL1741 requirements are only for electronic PVRS solutions. There is also a need for non-electronic solutions to reduce firefighter hazards.
New Name
New Standard & STP for
PV Rapid Shutdown Systems
PV Hazard Control
UL3741

• **PV arrays are safe** - Existing product safety standards and NFPA 70, the National Electrical Code (NEC) include requirements for PV systems that provide practical safeguarding against common hazards in normal use and foreseeable abnormal conditions.

• **Firefighting operations** - present a different and more severe set of conditions that are outside of those evaluated as part of a typical product safety certification.

• **UL3741** - This new Photovoltaic Hazard Control standard evaluates for specific, defined abnormal conditions and fault tolerance related to anticipated firefighter operations that exceed the criteria of existing product safety standards
UL3741 DOE (Sandia and UL) Supporting Research

HAZARD ANALYSIS OF FIREFIGHTER INTERACTIONS WITH PHOTOVOLTAIC ARRAYS

This new research project expands on original UL Fire Research project. We need science based data to replace the 80V guesstimate

1. Evaluate electric shock parameters for grounded and ungrounded/isolated PV arrays
2. Define safe states for PV systems operation under emergency conditions
3. Determine body impedance model for FF including PPE and tools.
4. Evaluate electrical enclosure protection from firefighting liquids
5. Harmonize safety standards and committee work
Sandia / UL Technical Report -Hazard Analysis of Firefighter Interactions with Photovoltaic Arrays

• This report information will be used to help develop the requirements limits and tests of the new UL Standard for Photovoltaic Hazard Control, UL 3741.

• Based upon this report and input from PV industry & firefighter communities, UL has developed a framework and seed draft for the UL 3741 Standard, which will be more fully developed through the consensus process.

• One of the tasks under this research project is to develop a body impedance model for firefighters that accounts for the electrical resistance of the personal protective equipment (PPE) which is used, as well as the foreseeable interactions with the PV array to determine potential electrical pathways that may be encountered.
Task 1: Firefighter Safety for Grounded and Ungrounded PV Arrays

• Modeling to compare grounded and ungrounded arrays relative to electric shock hazards.
  • In both grounded and ungrounded arrays, the current hazard has a direct correlation to array voltage.
  • Ungrounded arrays are significantly safer for reasonable module isolation resistances with fault currents up to three orders of magnitude smaller than for a grounded array counterpart.
  • Grounded array size does not affect the shock current hazard.
  • Ungrounded array - as PV arrays size increases, $R_{iso}$ decreases and electric shock current hazards increase.
  • The non-linearity of the array IV curve must be taken into account for body resistances below 600Ω and array voltages above 1000V for accurate fault current determination.
  • PV array isolation resistance, $R_{iso}$, has a significant effect on current hazard to the firefighter for ungrounded arrays, which is a huge benefit when compared to intentionally grounded arrays.
**THEORETICAL WORST-CASE EVALUATIONS**

\( R_{\text{eff}} \) determines the load line and the amount of current \( I_{\text{FF}} \) that flows.
THEORETICAL WORST-CASE EVALUATIONS

• Ungrounded Arrays

\[ R_{\text{iso}}^{\text{ungrounded}} \approx R_{\text{module}} \]
\[ = \frac{(S - 1)P}{R_{\text{leak}}} + \frac{2P}{2R_{\text{leak}}} = \frac{R_{\text{leak}}}{S \cdot P} \]

\[ R_{\text{Eff}} \approx 2 \cdot R_{\text{iso}} + R_{\text{FF}} \]

• Grounded Arrays

\[ R_{\text{Eff}} \approx \frac{1}{\frac{1}{R_{\text{iso}}} + \frac{1}{R_{\text{FF}}}} \]

As \( R_{\text{iso}} \gg R_{\text{FF}} \), reduces to:

\[ R_{\text{Eff}} \approx R_{\text{FF}} \]
Task 3: Report on Firefighter Body Resistance Model Under Various Field Conditions

- Adult males and females vs traditional shock limits based on children
- Firefighter PPE measured the resistance of representative firefighter PPE including gloves, turnout gear, knee pads, and firefighter boots
- Firefighter body resistance
  - The PPE resistance can be added to the firefighter body resistance model
  - Firefighter Interactions and likely current pathways through the firefighter body including foreseeable failure modes. Example - Firefighter falling forward with a metal tool in their hand.
- PPE resistance reduces nonlinearly relative to voltages increase.
- The data results included many variables and considerations specific to the PPE condition, firefighter interactions and environment. It is recommended that the UL3741 STP and task groups establish the thresholds including safety factors for the standard.
## Direct Current Thresholds

<table>
<thead>
<tr>
<th>Physiological Effects (DC)</th>
<th>Men</th>
<th>Women</th>
<th>Children</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception (Wet)</td>
<td>4 mA</td>
<td>2.5 mA</td>
<td>2 mA</td>
</tr>
<tr>
<td>Inability to Let Go (Wet)</td>
<td>60 mA</td>
<td>40 mA</td>
<td>30 mA</td>
</tr>
<tr>
<td>Inability to Let Go (Dry)</td>
<td>120 mA</td>
<td>80 mA</td>
<td>60 mA</td>
</tr>
<tr>
<td>Ventricular Fibrillation (Wet)</td>
<td>226 mA</td>
<td>150 mA</td>
<td>113 mA</td>
</tr>
</tbody>
</table>

* The limits for children has been historically used to establish the electrical shock threshold for safety standards. Understand there are no children firefighters, they are listed for reference.
* Perception and inability of let-go is derived from research work of Dalziel; Ventricular fibrillation is derived based on the IEC 60479-1.
* Ventricular Fibrillation (Wet) limits were calculated from the DC values in accordance with IEC 60479-1.
Human body impedance model(s)

Body impedance depends on:
- Current path
- Touch voltage
- Duration of current flow
- Frequency
- Degree of skin moisture
- Surface area of contact
- Pressure exerted
- Temperature

Body impedance reduces asymptotically with increasing touch voltage.
Human body impedance—contd

$R_{C1}, R_{C2}$ – Contact resistances (skin)

$R_T$ – Tool(s) resistance

$R_I$ – Internal body resistance

$R_{PPE}$ – PPE resistance

Hand-to-foot impedances are typically 10-30% lower than hand-to-hand.

GIZ, et. al., “Evaluación de los riesgos de incendios en plantas fotovoltaicas y elaboración de planes de seguridad que minimicen los riesgos”, March, 2015.
Fire Fighter (FF) Body Model Impedance

- Document Search
- Modeling/Simulation
- FF PV interactions and exposures to current flow
- Wet – water, sweat, sea water
- Actual measurements of FF PPE
  - Do wet FF PPE provide shock protection or make it worse?
- Account for common FF tools

\[
Z_{\text{Tool}} \quad \begin{cases} 
Z_{\text{Skin or Glove}} & \text{if Tool inserted} \\
Z_{\text{Skin or Glove}} & \text{if Tool not inserted}
\end{cases}
\]

\[
Z_{\text{Body}} \quad \begin{cases} 
Z_{\text{PPE}} & \text{if Tool inserted} \\
Z_{\text{Skin or Boot}} & \text{if Tool not inserted}
\end{cases}
\]

- Expanding on the existing data IEC/TS 60479-1 and other standards, to account for:
  - PPE clothing
  - Tools
  - Other relevant factors
- These could be evaluated with other variables:
  - PPE moisture
  - Skin moisture
  - Anatomical factors
Calculation of PV array hazards

For a grounded system without an inverter, the IV curves will look like this depending on where the firefighter contacts the array. (7+ indicates faulting above the 7\textsuperscript{th} module above ground….1+ indicates faulting above the 1\textsuperscript{st} module above ground, etc
Full Power Shock Hazard Assessment

The Pmax value will scale with the number of strings as well as the number of modules faulted. The SPiCE simulations (black dots) are fairly well described by the equation (colored lines):

\[ P_{\text{max\_fault}} = V_{oc} \cdot I_{sc} \cdot (S \cdot F - S + 1) \]

Where S is the # of strings, M is the number of modules/string, and F is the number of modules faulted.
Hazards level for firefighters

- These currents and power levels will not result in physical dangers to emergency personnel
Full Power Shock Hazard Assessment

• But: Array size has little effect on current/voltage hazard to firefighter
  • Load line crosses IV curve at $V > V_{mp}$
  • Array acts as voltage source

![Diagram showing current hazard as a function of firefighter body impedance for various array sizes. The graph indicates total FF impedance (body + PPE) (Ohm) and highlights the 600V $V_{oc}$ array size.]
# Thresholds for Men

<table>
<thead>
<tr>
<th>IEC Zone</th>
<th>Boundaries</th>
<th>Physiological Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-1</td>
<td>$I_{FF} &lt; 4$ mA</td>
<td>Slight pricking sensation possible when making, breaking or rapidly altering current flow.</td>
</tr>
<tr>
<td>DC-2</td>
<td>$4$ mA $\leq I_{FF} &lt; 50$ mA</td>
<td>Involuntary muscle contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.</td>
</tr>
<tr>
<td>DC-3</td>
<td>$50$ mA $\leq I_{FF} &lt; 565$ mA</td>
<td>Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.</td>
</tr>
<tr>
<td>DC-4</td>
<td>See below</td>
<td>Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage.</td>
</tr>
<tr>
<td>DC-4.1</td>
<td>$565$ mA $\leq I_{FF} &lt; 775$ mA</td>
<td>Probability of ventricular fibrillation increasing up to about 5%.</td>
</tr>
<tr>
<td>DC-4.2</td>
<td>$775$ mA $\leq I_{FF} &lt; 1225$ mA</td>
<td>Probability of ventricular fibrillation up to about 50%.</td>
</tr>
<tr>
<td>DC-4.3</td>
<td>$I_{FF} \geq 1225$ mA</td>
<td>Probability of ventricular fibrillation above 50%.</td>
</tr>
</tbody>
</table>

## Grounded (mA)

<table>
<thead>
<tr>
<th>5% Imp</th>
<th>Voltage Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td>80 1000 1500</td>
</tr>
<tr>
<td>Bare Hand</td>
<td>138 1729 2593</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>54 745 1269</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>

## Ungrounded (mA)

<table>
<thead>
<tr>
<th>5% Imp</th>
<th>Voltage Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td>80 1000 1500</td>
</tr>
<tr>
<td>Bare Hand</td>
<td>51 635 952</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>32 428 690</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>

## 50% Imp

<table>
<thead>
<tr>
<th>5% Imp</th>
<th>Voltage Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td>80 1000 1500</td>
</tr>
<tr>
<td>Bare Hand</td>
<td>103 1283 1924</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>47 648 1084</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0 0 0</td>
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</table>

## 50% Imp

<table>
<thead>
<tr>
<th>5% Imp</th>
<th>Voltage Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td>80 1000 1500</td>
</tr>
<tr>
<td>Bare Hand</td>
<td>45 563 845</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>30 394 632</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0 0 0</td>
</tr>
</tbody>
</table>
# Thresholds for Women

<table>
<thead>
<tr>
<th>IEC Zone</th>
<th>Boundaries</th>
<th>Physiological Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-1</td>
<td>$I_{FF} &lt; 2.7$ mA</td>
<td>Slight pricking sensation possible when making, breaking or rapidly altering current flow.</td>
</tr>
<tr>
<td>DC-2</td>
<td>$2.7$ mA ≤ $I_{FF} &lt; 33.2$ mA</td>
<td>Involuntary muscle contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.</td>
</tr>
<tr>
<td>DC-3</td>
<td>$33.2$ mA ≤ $I_{FF} &lt; 375$ mA</td>
<td>Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.</td>
</tr>
<tr>
<td>DC-4</td>
<td>See below</td>
<td>Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage.</td>
</tr>
<tr>
<td>DC-4.1</td>
<td>$375$ mA ≤ $I_{FF} &lt; 514$ mA</td>
<td>Probability of ventricular fibrillation increasing up to about 5%.</td>
</tr>
<tr>
<td>DC-4.2</td>
<td>$514$ mA ≤ $I_{FF} &lt; 813$ mA</td>
<td>Probability of ventricular fibrillation up to about 50%.</td>
</tr>
<tr>
<td>DC-4.3</td>
<td>$I_{FF} ≥ 813$ mA</td>
<td>Probability of ventricular fibrillation above 50%.</td>
</tr>
</tbody>
</table>

## Grounded (mA)

<table>
<thead>
<tr>
<th>Voltage Class</th>
<th>5% Imp</th>
<th>1000</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Hand</td>
<td>138</td>
<td>1729</td>
<td>2593</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>54</td>
<td>745</td>
<td>1269</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

## Un grounded (mA)

<table>
<thead>
<tr>
<th>Voltage Class</th>
<th>5% Imp</th>
<th>1000</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPE</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare Hand</td>
<td>45</td>
<td>553</td>
<td>952</td>
</tr>
<tr>
<td>Sweaty Gloves</td>
<td>32</td>
<td>428</td>
<td>690</td>
</tr>
<tr>
<td>Dry Gloves</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Comparison Against the 80 V Guesstimate “Limit”

<table>
<thead>
<tr>
<th>IEC Zone</th>
<th>Boundaries</th>
<th>Physiological Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-1</td>
<td>$I_{ff} &lt; 2.7 \ mA$</td>
<td>Slight pricking sensation possible when making, breaking or rapidly altering current flow.</td>
</tr>
<tr>
<td>DC-2</td>
<td>$2.7 \ mA \leq I_{ff} &lt; 33.2 \ mA$</td>
<td>Involuntary muscle contractions likely especially when making, breaking or rapidly altering current flow but usually no harmful electrical physiological effects.</td>
</tr>
<tr>
<td>DC-3</td>
<td>$33.2 \ mA \leq I_{ff} &lt; 375 \ mA$</td>
<td>Strong involuntary muscular reactions and reversible disturbances of formation and conduction of impulses in the heart may occur, increasing with current magnitude and time. Usually no organic damage to be expected.</td>
</tr>
<tr>
<td>DC-4</td>
<td>See below</td>
<td>Patho-physiological effects may occur such as cardiac arrest, breathing arrest, and burns or other cellular damage.</td>
</tr>
<tr>
<td>DC-4.1</td>
<td>$375 \ mA \leq I_{ff} &lt; 514 \ mA$</td>
<td>Probability of ventricular fibrillation increasing up to about 5%.</td>
</tr>
<tr>
<td>DC-4.2</td>
<td>$514 \ mA \leq I_{ff} &lt; 813 \ mA$</td>
<td>Probability of ventricular fibrillation up to about 50%.</td>
</tr>
<tr>
<td>DC-4.3</td>
<td>$I_{ff} \geq 813 \ mA$</td>
<td>Probability of ventricular fibrillation above 50%.</td>
</tr>
</tbody>
</table>

### Ungrounded (mA)

<table>
<thead>
<tr>
<th>Voltage Class</th>
<th>5% Imp</th>
<th>50% Imp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Hand</td>
<td>35</td>
<td>24</td>
</tr>
<tr>
<td>Sweaty Glove</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Dry Glove</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

### Grounded (mA)

<table>
<thead>
<tr>
<th>Voltage Class</th>
<th>5% Imp</th>
<th>50% Imp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Hand</td>
<td>62</td>
<td>35</td>
</tr>
<tr>
<td>Sweaty Glove</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>Dry Glove</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Task 4 - Evaluate Electrical Enclosure Protection from Incidental Handline Fire Hose Exposure

- Most PV equipment is only required to be evaluated for rain exposure. This is typically a NEMA 3R rating. Previous UL testing demonstrated 3R enclosures filled with water when exposed to incidental fire hose spray.
- Traditional 3R Raintight rated PV equipment exposure to a fire hose stream could allow water to enter and it is possible that water can come in contact with live electrical parts increasing risk of electric shock and reducing effectiveness of PVRS equipment and systems.
- Water ingress into the PV equipment can create other shock hazard current paths or ground reference ungrounded PV circuits that can compromise functionality and safety.
- This work evaluated higher rated IP and NEMA Type enclosures to determine if they were able to withstand the handline fire hose exposure that was intended to simulate incidental fire hose spray.
Task 4 – Enclosure Tests

• A few of the enclosures tested were not able to withstand the exposure (NEMA 3R and one NEMA 4 with a flat sandwiched gasket adhered to the cover)

• The enclosures with a labyrinth design and recessed captive gasket passed the exposures with no water ingress.
### Task 4 – Enclosure Tests

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mfr</th>
<th>Material</th>
<th>Dimensions</th>
<th>Enclosure Environmental Ratings</th>
<th>4'</th>
<th>2'</th>
<th>Str</th>
<th>4'</th>
<th>2'</th>
<th>Str</th>
<th>4'</th>
<th>2'</th>
<th>Str</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>Steel</td>
<td>12x10x5 in.</td>
<td>4, 13</td>
<td>Pass</td>
<td>Pass</td>
<td>Fail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>Steel</td>
<td>16x16x6 in.</td>
<td>4, 12</td>
<td>Fail</td>
<td>Fail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>B</td>
<td>Fiberglass</td>
<td>15.25x13.25x7 in.</td>
<td>4X, 12</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>5</td>
<td>C</td>
<td>Aluminum Alloy</td>
<td>200x230x110 mm</td>
<td>4, 4X, 12, 13, IP69</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
<tr>
<td>6</td>
<td>A</td>
<td>Steel</td>
<td>9x23.75x6.25 in.</td>
<td>4, 12</td>
<td>Fail</td>
<td>Fail</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>D</td>
<td>Steel</td>
<td>6x4x3 in.</td>
<td>4, 13</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pressure, PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
</tr>
<tr>
<td>75</td>
</tr>
<tr>
<td>100</td>
</tr>
</tbody>
</table>

- **Pattern**: 4' and 2' are tested for water tightness. Str (stream) is tested at 45° oblique angle.

For each result cell, the hose stream was directed both perpendicular to the cover and at a 45° oblique angle.

### Table 2 – Enclosure Test Results

The IP69, NEMA Type 4 and 4X enclosures did a much better job of keeping water out than NEMA 3R rated enclosures.
• PV modules, connectors and micro-inverters, no sample exceeded a 5 mA limit during continuous high-voltage testing while being sprayed by the fire hose.

• It was observed that the electrical leakage current increased as direct water spay hit portions of PV modules, inverters and electrical connectors and decreased after the hose stream was removed.
(2) Inside the Array Boundary.
The PV system shall comply with one of the following:

1. Provide shock hazard control for emergency responders through the use of a PV Hazard Control means listed for the purpose. The hazard control components shall be installed and used in accordance with the instructions included with the listing or field labeling. The PV array shall be listed or field labeled as a rapid shutdown PV array. Such a PV array shall be installed and used in accordance with the instructions included with the rapid shutdown PV array listing or field labeling.

   Informational Note: A listed or field labeled rapid shutdown PV array is evaluated as an assembly or system PV hazard control system may be comprised of either an individual piece of equipment that fulfills the necessary functions, or multiple pieces of equipment coordinated to perform the functions as described in the installation instructions to reduce the risk of electric shock hazard within a damaged PV array during emergency response operations for fire fighters, as defined in the installation instructions to reduce but not eliminate risk of electric shock hazard within a damaged PV array during fire fighting procedures. These rapid shutdown PV arrays are designed to reduce shock hazards by methods such as limiting access to energized components, reducing the voltage difference between energized components, limiting the electric current that might flow in an electrical circuit involving personnel with increased resistance of the conductive circuit, or by a combination of such methods.

2. Controlled conductors located inside the boundary or not more than 1 m (3 ft) from the point of penetration of the surface of the building shall be limited to not more than 80 volts within 30 seconds of rapid shutdown initiation. Voltage shall be measured between any two conductors and between any conductor and ground.

3. PV arrays with no exposed wiring methods, no exposed conductive parts, and installed more than 2.5 m (8 ft) from exposed grounded conductive parts or ground, shall not be required to comply with 690.12(B)(2).

The requirement of 690.12(B)(2) shall become effective January 1, 2019.
UL3741 - It Is Not Just the Voltage

While limiting voltage is one means to reduce electric shock hazards there are many other ways to reliably reduce shock hazards. This new UL3741 standard will develop commonly applied other protection methods for this PV Array application in a manner that is based upon engineering and science.
UL3741 STP Members

UL 3741, Standard for Safety for Photovoltaic Hazard Control,

### STP Balance Summary

Total Number of Voting Members: 31

<table>
<thead>
<tr>
<th>Interest Category</th>
<th>Number of members</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AHJ</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>Commercial/Industrial User</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Consumer</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>General</td>
<td>9</td>
<td>29</td>
</tr>
<tr>
<td>Government</td>
<td>3</td>
<td>10</td>
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<tr>
<td>International Delegate</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Producer</td>
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<td>32</td>
</tr>
<tr>
<td>Supply Chain</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Testing &amp; Standards</td>
<td>2</td>
<td>6</td>
</tr>
</tbody>
</table>

Updated: 2/7/2018
UL3741 Seed Document Draft

- The UL3741 draft has been developed as a seed document that can be used to accelerate the development of the standard.
- IEC format to speed international adoption.
- Being developed as a both US and Canadian national standards.
- UL is including experts in related areas to provide input on the technology and standards for equipment that provide some similar functions.
- The UL3741 seed draft was derived from the below identified groups and documents.
  - UL Fire Experts, North American fire fighters, fire protection experts, UL Fire Council, National and international fire experts, NFPA PV Fire Fighter Task Group and IAFF Experts
  - AHJs
  - UL/ SANDIA PV Fire Fighter Research Project report and staff
  - UL1741 PV Rapid Shutdown Task Group Members
  - SEIA Rooftop PV Systems and Firefighter Safety Report
  - Collaboration with experts in related standards
    - UL62109-2 Ground Fault Task Group
    - UL2231 Electric Vehicle Chargers
    - UL9540 Energy Storage Systems
    - GFCI, Fire Alarms, Industrial controls
    - Functional Safety Standards
Firefighters

• For the purposes of reducing shock hazards in UL3741 it is assumed that firefighters will have:
  • Required training for firefighter operations.
  • An established hierarchy of command and responsibility.
  • A minimum required PPE.
  • A minimum or common set of firefighting tools.
Draft UL3741 Evaluation Flowchart

Design Safety Analysis (e.g. FMEA)

Testing Required?

YES

PERFORMANCE TESTING

NO

INDICATIONS

RATINGS

MARKINGS

Component Usage
Existing Certifications
Component Redundancy
Inherent Voltage Thresholds
Construction Thresholds
Applicability to System Variations

See Next Slide
Draft UL3741 Testing Flowchart

1. **Array Operations/Interactions**
   - Walking, Tool Exposure, Falling, Ladders, Indirect Spray, etc.

2. **Test for Hazard Exposure**
   - Body Impedance Model(s), Modified by PPE (Gloves, Boots, Turnout Gear)

3. **Pass/Fail**

4. **Apply Failures and Faults**
   - Single-Point Equipment Failures Foreseeable System Level Faults

5. **Hazard Exposure Re-Test**

6. **Functional Safety Evaluation**
   - Severity of Shock Hazard Occurrence Risk of Interaction Occurrence Risk of Shock Hazard

7. **Pass/Fail**
Potential UL3741 Enhanced Protection Measures

Figure 1: PV Hazard Control Standard Functional Diagram

Note: Examples of systems, equipment and components include:

PVHCS: e.g. combination of specific mounting system (6), use of switching and array segmenting devices (5), and inverter control (3)(4).

PVHCE: e.g. Array combiner box with internal switching (2)

PVHCC: e.g. Switching component located mid string (5)
UL3741 Functional Safety Analysis
PVHC systems shall be provided with a safety analysis such as, but not limited to, a failure modes and effects analysis (FMEA) that identifies critical safety components and circuits of the system.

The analysis shall consider the compatibility of the parts of the PV system (e.g. modules, control devices, wire management systems, etc.) with regard to hazard reduction efficacy of the overall system.

The analysis shall consider the range of relevant single point failures and system level faults that have a likelihood of occurrence in the course of identified firefighter operations.

The analysis shall consider performance tests that may be bypassed based on construction and operational criteria thresholds.

The analysis shall be performed by the manufacturer of the PVHC system or the entity that integrates the components that comprise the PV/PVHC system.
Proposed UL3741 Task Groups

UL3741 Task Group Membership and STP, not all task group members are STP members.

1. Finalization of the Standard Scope;
2. Terms and Definitions;
3. Functional safety and risk assessment;
4. Firefighter interactions;
5. Firefighter body impedance model, current paths, PPE failures and thresholds/limits;
6. System tests (not covered by other standards).
Development of PV Standard for Compliance with the 2017 NEC 690.12

1) Listed PV array level protection system.
2) 80V, 30 Second Limit for controlled conductors internal to the array.
3) PV arrays with no exposed wiring methods, no exposed conductive parts, and installed more than 8ft from exposed grounded conductive parts or ground.

New science based research and leverage existing technology where we can.
UL3741 – Task Group Initial Goals

- Use of IEC format as this will likely become the seed document for an international standard.
- Make use of existing related work
  - UL2231 for EV protection.
  - UL9540 ESS – System designs and distributed protection.
  - Functional Safety 60730, 61508, UL1998, UL991
- Structured development to facilitate staged implementation
  - Develop first and publish ASAP
    - Scope and definitions
    - Firefighter interactions
    - limits and thresholds
- This foundational work will allow for a fast pass option for less complex products that comply due to inherent properties or operational limits that meet the requirements and intent of the standard.
- Parallel effort to develop the more challenging and time consuming requirements needed to evaluate more complex and involved solutions.
Timing for UL3741

- Align with 2020 NEC code proposals where possible (ongoing)
- Develop and publish the UL3741 Standard (ongoing)
- Develop educational material Do’s and Don’ts (future)

NEC 2017 690.12(B)(2) shall become effective January 1, 2019.

690.12 (B)(2) Controlled conductors located inside the boundary or not more than 1 m (3 ft) from the point of penetration of the surface of the building shall be limited to not more than 80 volts within 30 seconds of rapid shutdown initiation. Voltage shall be measured between any two conductors and between any conductor and ground.

UL3741 STP and Task Group agreement to fast track development and publication. Pushing for Q2/Q3 2017.
Thank you!

Olga Lavrova  Sandia National Labs
olavrov@sandia.gov

Tim Zgonena  UL LLC
Timothy.p.zgonena@ul.com

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http://corporate.ul.com/departments/fs/FE/fe_home.htm

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Resilient Microgrids

Examples of Customer-sited Resilient Solar+Storage Microgrid Systems

3/1/2018
Responsible energy, your choice

OutBack was Microgrids when Microgrids wasn’t cool

► Majority of the market has been focused on Grid Dependent PV
  ► Converting PV power (and now energy storage) direct to the grid
  ► Cannot operate without utility signal

► Our products create Grid Interactive Microgrids
  ► Our systems use batteries, aka energy storage
  ► Can operate both in parallel as well as independent of utility
  ► Built upon our historic strengths in off-grid and standalone applications

► Creating a new space called Grid Hybrid
“Here’s a $70,000 system sitting idle,” said Ed Antonio, who watched his 42 panels as well as those on several other houses in the area go unused since the power went out Oct. 29. “That’s a lot of power sitting. Just sitting.”
“Advocates say the system’s success during Irma — while a nearby school serving as a special needs shelter suffered a generator failure — proved solar power’s value at a time when 4.4 million Florida Power & Light customers lost service, many for days.”

Networked microgrid with li-ion, fuel cell and hydrogen storage

Pu‘uwa‘awa‘a Ranch and Blue Planet Energy

Site controller balances all generation and loads via Blue Planet energy management system and using AXS Port Modbus commands

https://greenmagazinehawaii.com/the-comforts-of-an-off-grid-home/
Large residential solar+ resiliency

SKYWIRE ELECTRICAL RESIDENTIAL INSTALLATIONS, OZARK MOUNTAINS

Grid/Hybrid living as a step-up in performance and aesthetics from conventional grid-tied installation, integrating solar electrical and solar thermal systems
Community emergency relief & church electrical power: Washington

LITTLE BROWN CHURCH, WHIDBEY ISLAND GRID/HYBRID SYSTEM

39 solar panels added to this church to enable it to function as an emergency shelter with back-up electricity for the island in the event of a natural disaster.

- System Power: 9.36kW
- Components: Radian Inverter/Charger, FLEXmax Charge Controllers, EnergyCell RE Batteries, Integrated Battery Rack enclosure, MATE3 system controller
Ranch water supply

Pure Power Solutions: Healdsburg CA

Containerized approach streamlined construction and deployment
Remote multi-purpose: California

Net-Zero Ranch in Southern California; Celebrity Installation

20 OutBack Radians in 160W configuration at the center of a power complex including PV, wind, three utilities, and 11 ton battery bank.
Agricultural electrical power: Caribbean

**Solar Nexus International Upgrade of St. Kitts, Caribbean Plantation**

Workshop installation on a sugar plantation using PV + storage to overcome the sporadic local grid and storm-related outages.
Agricultural/broadcast power: Iowa

Two separate Radian systems with high capacity storage and optics RE

Provides farm battery backup during emergencies and uninterrupted electricity to support ham radio communications and competitions

Produces 30,000kWh and supplies sufficient backup electricity for critical loads in the homestead with three days' autonomy

Owners can sell back surplus solar energy they create; saving $2,600 per year and resulting in a net zero electricity bill
Commercial electrical power & historical preservation: India

TeamSustain Project, Malankara Plantation, India

Historic building converted into India’s first net-zero office complex. System protects against frequent utility blackouts which were impacting business operations.
Rural community electrical power: Haiti

Solar Electric Light Fund (SELF) teamed with Partners in Health (PIH)

Electricity for hospitals and clinics throughout the country

► Seven hospitals
► Twelve health clinics
► Led to additional project to power seven schools serving 2,000 students

► One key finding: PV arrays sized to meet weekday loads can overheat battery on weekends and holidays.
► Led to development of Global Charger Output Control function
Additional success stories are available at:
http://www.outbackpower.com/outback-resources/case-studies

Thank you for your time

WWW.OUTBACKPOWER.COM
Design for Safety & Reliability
UL certified MLPE Rapid Shutdown Solution for NEC 2017

Danny Eizips, VP of Hardware
March 1, 2018
- Founded in 2007
- HQ in Silicon Valley, CA
- Sales and support offices worldwide
- Products certified across countries
- Installed at over 24,000 sites
- Over 2,200,000 units shipped
- Over 700TB of data collected
- Over 35 PV module manufacturers shipping TS4 products worldwide
- Trusted by leading brands:
Mission Statement

To increase customer ROI by delivering smart PV technology designed to yield maximum energy harvest at minimal cost.
Solution Overview
TS4 Platform: Cover & Base

Select functions as needed from six different TS4 covers for a junction box base.

TS4-D: Diodes
TS4-M: Monitoring
TS4-F: Fire Safety
TS4-S: Safety
TS4-O: Optimization
TS4-L: Long Strings
TS4 Platform: FLEX MLPE (Beyond MLPE)

Select functions as needed for reduced cost and increased ROI

- **TS4-D**: Diodes
- **TS4-M**: Monitoring
- **TS4-F**: Fire Safety
- **TS4-S**: Safety
- **TS4-O**: Optimization
- **TS4-L**: Long Strings

**Architecture 1: TS4 (Integrated)**

- The Smart Module: Built in Functionality
- Adopted by more than 35 module OEM’s!

**Architecture 2: TS4-R (Retrofit)**

- Add to any module, new or existing

Adopted by more than 35 module OEM’s!
TS4 Platform: FLEX MLPE (Rapid Shutdown)

Select functions as needed for reduced cost and increased ROI

- **TS4-D**: Diodes
- **TS4-M**: Monitoring
- **TS4-F**: Fire Safety
- **TS4-S**: Safety
- **TS4-O**: Optimization
- **TS4-L**: Long Strings

All include Rapid Shutdown
NEC 2017 Rapid Shutdown


Short Background

- The National Electric Code (NEC) is a book that’s published every 3 years and is the “bible” for electricians.
- NEC is published and driven by the National Fire Protection Association (NFPA).
- Chapter 690 is specific PV systems regulations, and 690.12 is an article that was introduced in 2014.
- While officially adopted only in North America, these codes tend to have an influence on regulatory bodies worldwide.
Article 690.12

2014
30 volts within 10 seconds 10 feet from the array

2017
Module conductors limited to 80 volts 30 seconds after rapid shutdown (anywhere within the array boundary)
NEC 2017: Requires MLPE

“350mm/1ft from the array in all directions”

- **Outside array boundary**
  - Controlled conductors limited to not more than 30 volts within 30 seconds

- **Inside array boundary**
  - Field labeling required
  - Controlled conductors limited to not more than 80 volts within 30 seconds
  - If no exposed wiring methods, conductive parts installed more than 2.5m/8ft from ground = no need to comply
Reliable Rapid Shutdown shipping for more than 3 years:

- **TS4-S**: Safety
- **TS4-O**: Optimization
- **TS4-L**: Long Strings
System Architecture

**TS4-S, TS4-O, TS4-L**

- Relies on the “Keep Alive” architecture
- Once AC is removed, within 30 seconds, modules are in shutdown mode
The ONLY UL Certified MLPE Rapid Shutdown Solution

**TS4-O, TS4-R-O, TS4-R-O-Duo, TS4-L**
- **SMA**
  - SMA STP 50-US-40

- **ABB**
  - UNO-7.6-TL-OUTD-S-US, UNO-8.6-TL-OUTD-S-US

- **Fronius**
  - Galvo 2.5-1
  - Primo 8.2-1

- **Ginlong Solis 5K-2G-US**
- **Huawei SUN2000-30KTL-US**
- **Ingeteam INGECON SUN 40TL**
- **KACO blueplanet 3.0TL1 M2**

**TS4-S, TS4-R-S, TS4-R-S-Duo**
- **SMA**
  - SMA STP 50-US-40

- **Fronius Primo 8.2-1**
- **Ginlong Solis 5K-2G-US**
- **Ingeteam**

- **Power-One PVI-4.2-OUTD-S-US-A**
- **Solectria Renewables**
  - PVI-5200TL
  - PVI-23TL-480
- **Sungrow SG60KU-M** Rated 1000Vdc input, 112A input
UL Certified with MANY Inverters

This new addition supports SunSpec Alliance’s Rapid Shutdown Signaling:
System Architecture

TS4-F

- Relies on the “Keep Alive” architecture
- Once AC is removed, within 30 seconds, modules are in shutdown mode
- Transmitter can be integrated into the inverter or external
- TS4-F available as a PV module integrated or add-on/retrofit
- Based on proven technology that has been shipping for more than 3 years
Rapid Shutdown Interoperability

- Tested with multiple transmitters – including SMA and Fronius
- Several PV vendors are currently certifying
- Multiple Inverter suppliers are currently integrating

Both rapid shutdown Receivers and Transmitters are available for integration from Tigo.
THANK YOU
Daniel.Eizips@tigoenergy.com

www.tigoenergy.com
Appendix
NEC 2014: Currently Enforced

- Only applies to PV conductors more than 1.5m/5ft in length within a building or more than 3m/10ft from a PV array
- Not more than 30V and 240 VA within 10 seconds
Module-Level vs. String-Level

- **Traditional Disconnect**
  - Inverter off, DC voltage still present

- **Module-Level Disconnect**
  - Individual modules at 0V
  - Home run cables are de-energized
Impact of PV Performance and Technology on Power Plant Financial Success

Jenya Meydbray
February 2018
PV Power Plant

Cash Generating Asset

- A PV power plant is just a cash generating asset
- Future cash flows can be financed (i.e. sold)
- In order to sell future cash flows they need to be understood
- Technical Inputs: PV Equipment, construction, weather file, contracts
- Influencing factors: Technical advisors, 3rd party reports, experience
About Cypress Creek

• Cypress Creek does development, construction and owns & operates solar projects
• Founded in mid-2014
• ~1.6 GWs of solar projects built
• ~1.4 GWs in our operating portfolio
• Mostly small-ish utility scale (5-10 MWs)
• Building ~1 GW this year and much more next year
PV Power Plant Players

Asset Management
- Purchase Equipment: modules, inverters, trackers/racking, cabling, monitoring system, transformers, substations, etc.
- Prepare the site and perform installation

Tax Equity Investors
- Covers 45-50% and is based on several factors including cost and income
- Take the tax credits and invest in some equity portion of the project
- After tax IRRs of 10-20% depending on structure

Banks
- Provide Debt to the project
- Covers 40-50% of project cost and is sized based on future cash flows
- Typically 4-6% at up to 25 years, can be 5 years beyond PPA term

Independent Engineering Firms
- Advise the lenders and investors on technical assumptions
Definitions

Value of Solar to Investors

Costs

- Development, Interconnection, Studies, Equipment, Land, Civil Work, Construction, Permits, Taxes, etc.

Net Present Value (NPV)

- the difference between the present value of cash in and the present value of cash out over a period of time

Illustrative Example

- Discount rate: 6%
- Requirements like > 10 cents NPV are common
- This project is worth doing

<table>
<thead>
<tr>
<th>Year</th>
<th>Net Income</th>
<th>Value Now</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(34)</td>
<td>(34)</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>9.43</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>8.90</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>8.40</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>7.92</td>
</tr>
</tbody>
</table>

NPV: $0.65
“Optimization”

NPV is the magic number

- Most stakeholders in PV projects are risk averse
- Most financial players rely heavily on the Independent Engineering view of the energy model
  - Weather file, equipment performance, degradation rates, availability, additional haircuts based on “risk,” O&M, etc.
- General rule of thumb is 1% of increased production is worth about 1-2 cents / Wp of NPV
  - This needs to be accepted by all parties
  - Difficult to monetize increases that are outside of pan files or OND files
- So if a widget increases lifetime production by an estimated 2% and costs 10 cents / Wp it’s not even worth considering.
- If it costs 2 cents / Wp then it is worth considering
Risk Analysis

• New technologies and new vendors are generally not easily accepted
• So how do we move technology forward as an industry?

Technical Qualification Process:

• Recent Bankability Report (within 18 months)
  • DNV GL, Black & Veatch are typical providers
• Recent Lab Testing (within 18 months)
  • DNV GL Product Qualification Program (PQP) does the trick well

• Every Project
  • Disclosure of BOM and factory locations
  • Production oversight to verify
    • Typically performed by CEA or SolarBuyer
Cost vs. Value

Relative Build Cost

- 0.07 0.04 0.04 0.05 (0.10) 0.06 0.07 0.11 0.14 0.08

Relative NPV

(0.02) (0.04) (0.06) (0.08) (0.10) (0.12) (0.14) (0.16) (0.18) (0.20)

Lowest Cost  Highest Cost
Additional Experiences with Technology

Whack a Mole

• Often one technology improvement creates problems (and cost) in other areas

• Some trackers are powered by the AC grid

• Depending on the voltage an additional transformer may be needed

• During high wind conditions trackers are supposed to stow.

• If grid goes down it can’t, this is a problem

• Some sites need an alternative source of power just for tracker stow support during grid outage – often a diesel generator

• One “low cost” tracker resulted in 6 months of delay in commissioning
  • Didn’t turn out to be lower cost in the long run
### NPV Impact of Technical Decisions During Financing

<table>
<thead>
<tr>
<th>Yearly Degradation (%)</th>
<th>Lifetime (years)</th>
<th>O&amp;M ($/KW-yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>0.25%</td>
<td></td>
<td>$0.04</td>
</tr>
<tr>
<td>0.50%</td>
<td>($0.13)</td>
<td>$0.00</td>
</tr>
<tr>
<td>0.75%</td>
<td>($0.04)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Yearly Degradation (%)</th>
<th>$5.00</th>
<th>$6.50</th>
<th>$8.00</th>
<th>$10.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25%</td>
<td></td>
<td></td>
<td></td>
<td>$0.04</td>
</tr>
<tr>
<td>0.50%</td>
<td>$0.02</td>
<td>$0.00</td>
<td>($0.02)</td>
<td>($0.06)</td>
</tr>
<tr>
<td>0.75%</td>
<td></td>
<td></td>
<td>($0.04)</td>
<td></td>
</tr>
</tbody>
</table>
Take Aways

- Optimize for yield per dollar **NOT** STC Wp per dollar
  - If split cell modules result in lower kWh/kWp then their value is lower per Wp
- Lowest cost is rarely highest value
- Need a lot of 3rd party validation for acceptance
  - Lack of sufficient 3rd party reports often leads to conservatism during financing
- Get new products in the field ASAP, start collecting real operating performance on customer sites
Uncertainty reduction of Performance Loss Rate Estimates

Philip Ingenhoven, Giorgio Belluardo, David Moser
11 Institutes including...

- Alpine Environment
- Applied Remote Sensing
- Regional Development and Location Management
- Renewable Energy
- Public Management
- Mummies and the Iceman
The Institute for Renewable Energy

5 research groups:

- URBAN AND REGIONAL ENERGY SYSTEMS
- SUSTAINABLE HEATING AND COOLING SYSTEMS
- PHOTOVOLTAIC ENERGY SYSTEMS
- ENERGY EFFICIENT BUILDINGS
- ENERGY RETROFIT OF HISTORIC BUILDINGS
Outlook and purpose of the work

Understand performance loss rates (PLR) of PV modules

• So far the standard for PLR is not published
• No method is agreed on

We analyzed
• Different technologies
• Different methods of determining the PLR
• Comparing the results for the different methods

We would like to
• Suggest (or at least contribute to the discussion of the) definition of the new standard for performance loss
Data used:

Production Data from inverters

26 PV arrays of 8 technologies monitored for 6 years from January 2011
Data used:

Dedicated Weather Station

Irradiance:
Direct, Diffuse, Global Horizontal, Global Tilted (POA)

Temperature:
Ambient, back of the module

Wind:
Direction, Speed
Recorded data

Weather station:
(every minute - 15 min average computed)
• Global horizontal Irradiance
• Direct Irradiance
• Diffuse Irradiance
• POA Irradiance
• Albedo
• Ambient Temperature
• Some Module Temperatures
• Wind speed + direction

PV data from inverter:
(every 15)
• Power AC
• Power DC
• Current PV
• Voltage PV
Data preparation

Compute the performance ratio PR every 15 minutes at time t

\[ PR(t) = \frac{P_{DC}(t) \cdot G_{STC}}{G_{POA}(t) \cdot P_n} \]

\( P_{DC} = \) DC power, \( G_{POA} = \) plane of array irradiance
\( P_n = \) nominal power, \( G_{STC} = 1000 \text{ W/m}^2 \)
Data preparation
Outlier and shading filter

Mode of the PR distribution

±2 σ interval
Data preparation

Define Monthly PR

\[ PR_{\text{month, DC}} = \frac{Y_a}{Y_r} \]

\[ Y_f = \sum_{\text{month}} \frac{P_{AC}(t)}{P_n}, \quad Y_r = \sum_{\text{month}} \frac{G_{POA}(t)}{G_{ref}}, \quad Y_a = \sum_{\text{month}} \frac{P_{DC}(t)}{P_n}, \]

Example polycrystalline Silicon
Performance loss

• Problem is the high seasonality of some data.
• How to find the trend?
7 Methods to reduce seasonality of PR data

- linear regression (over full years) of uncorrected PR
- fitting of uncorrected PR with single and double periodic functions
- classical time series decomposition on uncorrected PR
- STL decomposition of uncorrected PR
- linear regression of corrected PR (to standard test conditions (STC))
- linear regression of PVUSA
1. linear regression of uncorrected PR

Due to fluctuations large error

$$PR_{lin}(t) = a \cdot t + b,$$

Performance loss rate:

$$PLR = \frac{12a}{b},$$

Errors:

$$u_{PLR} = \sqrt{\left(\frac{12}{b}\right)^2 \cdot u_a^2 + \left(\frac{12a}{b^2}\right)^2 \cdot u_b^2},$$

mc-Si => PRL = -0.8 ±0.2 %/a
2.+3. periodic fitting

- Single and double periodic fitting

\[
PR_T = A_0 \cdot \sin \left( \frac{t}{\tau} \right) + B_0 \cdot \cos \left( \frac{t}{\tau} \right) + A_1 \cdot \sin \left( \frac{2t}{\tau} \right) + B_1 \cdot \cos \left( \frac{2t}{\tau} \right) + a \cdot t + b,
\]

- PLR:

\[
PLR = \frac{12a}{b},
\]

Error as above
- 1sin: PLR = -0.9 ± 0.1 %/a
- 2sin: PLR = -0.9 ± 0.1 %/a
4. Classical series decomposition:

Classical series composition:
(using R)

- Trend: symmetric 12 month moving average -> gradient used for PLR
- Seasonality: Average of each month over the years
- Rest: difference between

Problem: 12 month missing in trend 6 initial and 6 final month!

\[
PR_{\text{monthly}}(t) = T_t + S_t + R_t,
\]

\[
\text{PLR} = -0.9 \pm 0.1 \%/a
\]
5. Seasonal time series decomposition using local regression (STL)

Classical series composition: (using R)
- Trend: smoothing using moving averages and extrapolation over various loops -> gradient used for PLR
- Seasonality: Average of each month over the years
- Rest: difference between Problem 6 initial and 6 final month solved!

PLR = -0.9 ± 0.1 %/a
6. Corrected PR

Data filter:
• $G_{POA} > 800\text{W/m}^2$

PV corrected to standard test conditions
• Compute back of model temperature
• Adjust irradiance

PLR: $-0.9 \pm 0.1 \%/\text{a}$

Missing month in winter!
7. PVUSA

Data filter:
- $G_{POA} > 800 \text{W/m}^2$

PV power data is fitted each month to the conditions:
- irradiance $G_{POA} > 1000 \text{W/m}^2$
- ambient temperature $T=20^\circ \text{C}$
- wind speed $W=1 \text{m/s}$

$$P = G(a + b \cdot G + c \cdot W + d \cdot T)$$

PLR = -0.9±0.1 %/a

Missing month in winter!
Comparison of the Methods

- Simple regression: Quick and dirty with big error but usable PLR
- Periodic function fitting: very good accuracy and good PLR value
- Classical Series Decomposition: good accuracy, good PLR
  - But missing initial and final month
- Local Regression (STL): very good accuracy and good PLR
- PR corrected: larger error, sometimes bigger than benchmark, good PLR values. Missing months in winter due to extra filtering
  - Bad for thin-film with unclear temperature behavior
- PVUSA: larger error, sometimes bigger than benchmark, good PLR values. Missing months in winter due to extra filtering.

Conclusion: statistical methods outperform deterministic ones!
Comparison of the Methods

Average relative error for all technologies:

<table>
<thead>
<tr>
<th>Method</th>
<th>Linear reg</th>
<th>Periodic 1sin</th>
<th>Periodic 2sin</th>
<th>Classical series Decomposition</th>
<th>Series Decomposition Using local regression</th>
<th>Corrected PR</th>
<th>PVUSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average relative error</td>
<td>39.2%</td>
<td>14.7%</td>
<td>14.3%</td>
<td>13.2%</td>
<td>12.6%</td>
<td>17.4%</td>
<td>34.2%</td>
</tr>
</tbody>
</table>
Improvements on PR corrected

• Using measured outdoor temperature coefficients

• Statistical methods still better!
Comparison Results

Good agreement between methods and technologies especially for Crystalline based technologies

Large differences in thin film technologies due to different technology details

these Methods do not allow to find the reason for degradation...
Solar Train EU project

14 Marie Sklodowska Curie PhD Fellows investigate

areas of focus:
• climatic degradation factors,
• system analytics,
• material (polymer) parameters,
• service life & energy models,
• linking production to performance and
• performance enhancement by improved O&M.

This project is funded by the European Union’s Horizon 2020 programme under GA. No. 721452.

https://solar-train.eu/
Take Home Message

Statistical methods
• reach higher accuracy
• find similar performance loss rates
• Need less input data (only power + irradiance)

My humble opinion

Utilizing Statistical methods:
• data from more PV plants is accessible for the performance loss analysis
• Better overall predictions possible
Comparison of Statistical and Deterministic Smoothing Methods to Reduce the Uncertainty of Performance Loss Rate Estimates

Philip Ingenhoven, Giorgio Belluardo, and David Moser
Thanks for your attention

Contact us:

www.eurac.edu
Philip.Ingenhoven@eurac.edu
Annual degradation rates of recently produced c-Si PV modules under subtropical coastal climate conditions

Central Research Institute of Electric Power Industry (CRIEPI)

Tetsuyuki ISHII

This study was supported by New Energy and Industrial Technology Development Organization (NEDO) under Ministry of Economy, Trade and Industry (METI).
Outline

1. Introduction
   - Purpose of this study
   - Objective

2. Experimental method
   - Investigated PV modules and system configuration
   - Three indices used to evaluate PV performance

3. Results and discussion
   - Calculations of annual degradation rates using the three indices
   - I-V curves change of each PV module
   - EL images change of each PV module

4. Summary
Background of this study

- The cumulative installation of PV systems was about 400 GW
- The reliability and durability of PV systems is important
  a) Credibility of PV module manufacturers increase
  b) Power generation costs depend on usable years
  c) Precise estimation of power supply from PV systems

Electric companies must control power supply mainly using thermal power plants

Electric power from PV system is not stable
The purpose of this study

- c-Si PV modules are the dominant PV technology with about 90% of the market share
- Recently, various high-efficient PV cells are commercialized, such as SHJ, IBC, and PERC technologies
- However, there is little information available on the reliability and durability of these high-efficient PV modules

⇒ Here, recently produced c-Si solar cells are investigated

[PV test field at AIST Kyushu Center in Saga Prefecture, pictured in April 2017]
## Investigated c-Si PV modules

<table>
<thead>
<tr>
<th>Kind</th>
<th>Total Pmax [kW]</th>
<th>Array Configuration</th>
<th>Install Mon/Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1A</td>
<td>5.04</td>
<td>7S × 1P × 4A</td>
<td>9/2010</td>
</tr>
<tr>
<td>E-1B</td>
<td>4.9</td>
<td>5S × 1P × 4A</td>
<td>12/2012</td>
</tr>
<tr>
<td>E-2A</td>
<td>5</td>
<td>6S × 1P × 4A</td>
<td>9/2010</td>
</tr>
<tr>
<td>E-2B</td>
<td>5</td>
<td>5S × 1P × 4A</td>
<td>12/2012</td>
</tr>
<tr>
<td>W-2A</td>
<td>4.8</td>
<td>5S × 1P × 4A</td>
<td>12/2012</td>
</tr>
<tr>
<td>W-2B</td>
<td>4.68</td>
<td>6S × 1P × 4A</td>
<td>12/2012</td>
</tr>
<tr>
<td>M-3C</td>
<td>1.55</td>
<td>5S × 1P × 1A</td>
<td>06/2016</td>
</tr>
<tr>
<td>M-3D</td>
<td>1.89</td>
<td>7S × 1P × 1A</td>
<td>06/2016</td>
</tr>
<tr>
<td>W-1A</td>
<td>1.25</td>
<td>5S × 1P × 1A</td>
<td>06/2016</td>
</tr>
<tr>
<td>W-1B</td>
<td>1.05</td>
<td>5S × 1P × 1A</td>
<td>06/2016</td>
</tr>
<tr>
<td>W-1C</td>
<td>1.475</td>
<td>5S × 1P × 1A</td>
<td>06/2016</td>
</tr>
<tr>
<td>W-1D</td>
<td>1.45</td>
<td>5S × 1P × 1A</td>
<td>06/2016</td>
</tr>
</tbody>
</table>

- 11 kinds, 22 types of PV modules have been investigated
- These include 6 kinds, 12 types of c-Si PV modules
- Here, we show the performance of 6 types from 2013 to 2017

Mosaic image of test field pictured by a drone

Pictures of 6 types of c-Si PV arrays

- Each capacity is about 5 kW composed of 20~28 PV modules
An example system configuration (W-2B)

- Multiple (eight) string PCS with high frequency transformer
- DC circuit is not grounded
- Both four PV strings of SHJ (W-2A) and IBC (W-2B) are connected to the PCS
Outdoor I-V curve of every PV string, in-plain global solar irradiance, and back-side module temperature using T-type thermocouple are measured at 10 time intervals.

Every PV string is generally connected to electric power grid.
Indices based on outdoor measurements

- Three indices are used to calculate the annual degradation rates of the PV modules

- Index A) Annual energy production
  - To remove the influence of missing data, we only select the time intervals at which the powers of all the PV strings are more than 0 (W)

- Index B) Performance ratio corrected to 25°C ($PR_{T=25}$)
  - We use the data which were measured under stable and high irradiance ($\geq 700 \text{ W/m}^2$) conditions

\[
PR = \frac{P_{\text{MAX}}}{P_{\text{NOM (STC)}}} \cdot \frac{G}{1000} \\
PR_{T=25} = PR \times \frac{1}{1 + \gamma(T - 25)}
\]
Index based on indoor measurements

- All c-Si PV modules were measured by a pulsed solar simulator under the STC once a year
- Measured power output/Nominal (Labeled) power output
- Index C) Average over the normalize values of all PV modules

- Light source: Xe lamp
- Sweep direction: \( I_{SC} \rightarrow V_{OC} \)
- Sweep time: 100 ms
Index A) Annual energy production

- Normalized annual energy production of SHJ (W-2A) and IBC (W-2B) decreased by about 5.5% and 2.3% from 2013 to 2017, respectively.
Comparison between PR and PR_{T=25°C} reveals that the seasonal variations in PR mostly originated from seasonal variations in *module temperature* (not solar spectrum)
Index B) Monthly PR corrected to 25°C

- Annual average PR corrected to 25°C ($PR_{T=25°C}$)

- Annual average $PR_{T=25}$ of SHJ (W-2A) and IBC (W-2B) decreased by about 4.9% and 2.4% from 2013 to 2017, respectively

Normalized annual energy production (Index A) suggests performance decreases by 5.5% and 2.3%
The normalized indoor power under STC of SHJ (W-2A) and IBC (W-2B) decreased by about 3.9% and 2.9% from 2013 to 2017, respectively.
The investigated PV modules using p-type Al-BSF solar cells tend to show the lower annual degradation rates. The maximum value is about 0.3 %/year.

However, the investigated PV modules using n-type solar cells tend to show the higher annual degradation rates. The values range between 0.5 and 1.2 %/year.
Pictures of new 6 types of c-Si PV arrays

- Each capacity is about 1.5 kW composed of 5~7 PV modules
High efficiency c-Si PV installed in 6/2016

- The measurement period is too short!!
- p-type PERC sc-Si cells show clear light induced degradation (LID), but the decreases are different from W-1C to W-1D
# Summary of degradation rates (%/year)

## Index

<table>
<thead>
<tr>
<th>Index</th>
<th>01/2013~12/2017</th>
<th>06/2016~12/2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) Energy production</td>
<td>0.0</td>
<td>-0.4</td>
</tr>
<tr>
<td>(B) Outdoor PR</td>
<td>0.2</td>
<td>-0.1</td>
</tr>
<tr>
<td>(C) Indoor $P_{MAX}$</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**PV modules using p-type Al-BSF solar cells**

<table>
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<th>Index</th>
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</tr>
<tr>
<td>(C) Indoor $P_{MAX}$</td>
<td>0.1</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**PV modules using n-type solar cells**

---

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The performance of IBC (W-2B) modules under positive potential conditions decreased largely.

The system is not grounded.
Change in I-V curves of IBC (W-2B)
EL images of IBC(W-2B) in Dec. 2017

(a) W-2B (IBC) 1-1
(b) W-2B (IBC) 1-2
(c) W-2B (IBC) 1-3
(d) W-2B (IBC) 1-4
(e) W-2B (IBC) 1-5
(f) W-2B (IBC) 1-6

Electric potential − → Electric potential + →
EL images of IBC (W-2B) in Dec. 2017

(a) W-2B (IBC) 1-1
(b) W-2B (IBC) 1-2
(c) W-2B (IBC) 1-3
(d) W-2B (IBC) 1-4
(e) W-2B (IBC) 1-5
(f) W-2B (IBC) 1-6

Electric potential —
The contrast was changed

Electric potential +
Change in I-V curves of SHJ (W-1A)

(a) W-2A (SHJ) 2-1

(b) W-2A (SHJ) 2-5

Electric potential —

Electric potential +
Proposed degradation mechanisms (PID)

Conventional p-type c-Si

Naumann et al., SOLMAT 120 (2014) 383

n-type IBC

SunPower’s Report (2005)
Change in I-V curves of sc-Si (E-1A)
Change in EL images of sc-Si (E-1A)

Pictured in 2017

E-1A (sc-Si) 1-1  E-1A (sc-Si) 1-4  E-1A (sc-Si) 1-7

Pictured in 2014

E-1A (sc-Si) 1-1  E-1A (sc-Si) 1-4  E-1A (sc-Si) 1-7

Electric potential —  Electric potential +
Summary

- We investigated the annual degradation rates of recently produced PV modules installed in Saga prefecture in Japan using three indices.

- The results are consistent among all indices. The PV modules using p-type Al-BSF solar cells tend to show the lower annual degradation rates, although the PV modules using n-type solar cells tend to show the higher annual degradation rates.

- The performance of IBC (W-2B) modules would decrease due to “PID” of n-type IBC solar cells.
Thank you for your kind attention!!
Improved Reliability & Output from Solar Modules by Reduced Operating Temperature

Martin A. Green and Zibo Zhou, UNSW Sydney
Module T

\[ H_{t} = \mathcal{Q} \]

\[ H = \frac{750}{25} = 30 \text{ W/m}^2\text{K} \]
Rule of thumb

\[ \log (\text{degradation rate}) \]

\[ \frac{1}{T} \]

\[ X \]

\[ 2X \]

\[ 10^\circ C \]

\[ E_a = 0.5 - 0.6 \text{eV} \]
Rule of thumb

log (degradation rate) vs. $1/T$

- Leakage current, PID
- $E_a = 0.5 - 0.6 \text{eV}$
- $E_a = 0.75 \text{eV}$

$10^\circ \text{C}$ and $7^\circ \text{C}$

$\text{PIP 22,173}(2014)$
Rule of thumb

log (degradation rate) vs. $\frac{1}{T}$

- 12°C: Contact corrosion

- 10°C: Leakage current, PID
  - PIP 22, 173 (2014)

- 7°C
  - $E_a = 0.49 \text{ eV}$
  - $E_a = 0.5 - 0.6 \text{ eV}$
  - $E_a = 0.75 \text{ eV}$

$2X$
Decrease module temperature $T$ by $10^\circ C$, could increase output by 4-5%, halve degradation rates, double module life and energy output.
Compendium of photovoltaic degradation rates

Dirk C. Jordan¹*, Sarah R. Kurtz¹, Kaitlyn VanSant² and Jeff Newmiller³

Heat flows

\[ \text{free convection } Q_{\text{FF}} \]

\[ \text{radiation } Q_{\text{RF}} \]

\[ \text{wind convection } Q_{\text{WF}} \]

\[ \text{heat absorbing layer } Q_{\text{IN}} \]
Heat flows

\[ H = 30 \text{ W/m}^2\text{K} \]
\[ h_R \sim 15 \text{ W/m}^2\text{K} \]
\[ h_F \sim 7 \text{ W/m}^2\text{K} \]
\[ h_W \sim 7 \text{ W/m}^2\text{K} \]
\[ h_C \sim 1 \text{ W/m}^2\text{K} \]
Ideal reflectivity

![Graph showing reflectivity and emissivity vs. wavelength (µm)]
Ideal reflectivity

Reflectivity

Wavelength (μm)

Emissivity

16.4%
Ideal reflectivity

\[ \Delta T \sim 16.4\% \times 30^\circ C \sim 5^\circ C \]
Ideal reflectivity

\[ \Delta T \approx 16.4\% \times 30^\circ C \approx 5^\circ C \]

\[ \Delta T = 5.2^\circ C \]
Ideal reflectivity

PERC 42.38GW capacity end 2017
(EnergyTrend; ~ one-third total!)

Higher R
Ideal reflectivity

PERC 42.38GW capacity end 2017
(EnergyTrend; ~ one-third total!)

Higher $R$

$\Delta T = 1.7^\circ C$
Ideal reflectivity

300K b’body
Ideal reflectivity
Ideal reflectivity

Low iron glass

Fan et al. ACS Photonics 2017, 4, 774−782; Gentle & Smith, SOLMAT150 (2016) 39–42
Ideal reflectivity
Ideal reflectivity

Fan et al. ACS Photonics 2017, 4, 774–782
Ideal reflectivity

Increase $\varepsilon$ by 15-25%
$\Delta T = 2-3^\circ C$

Saint-Gobain
Module frame
Module frame

\[(\sum k_w) \nabla^2 t = Ht - \dot{Q}\]

\[L_{th} = \sqrt{\frac{\sum k_w}{H}} \approx \sqrt{\frac{1.1 \times 0.0032}{30}} = 0.01 \text{ m} = 1.1 \text{ cm}\]
Module frame

Heat to frame = \( L_{th}^2 H (t_{cell} - t_{frame}) / \min(S, L_{th}) \)
Module frame

Heat to frame = $L_{th}^2 H \frac{(t_{cell} - t_{frame})}{min(S, L_{th})}$

$L_{th} = 3.2\text{cm (Si areas)}$

$= 3.0\text{cm (100\text{um Al b’sheet})}$
Convection
Convection

\[ h_{RF} \]

[Graph showing convection with temperature distribution and heat transfer rate]

\[ Q_{RB} \]

[Graph showing surface heat flux distribution]
Convection

bottom to top of module
5°C lower MNOT (NOCT) seems possible by:
1. Increasing R (1.2- 2.5um)
2. Decreasing R (>4um)
3. Increasing rear convective loss
4. Increasing heat to frame

This could measurably increase output by 1-2% and life and energy production by 50%.
The search for root cause: status of LeTID in PERC modules

Mallory A. Jensen and Tonio Buonassisi
Massachusetts Institute of Technology (USA)

2018 Photovoltaic Reliability Workshop

February 27, 2018
An organized search for root-cause

Light and Elevated Temperature Induced Degradation (LeTID)
Multicrystalline LID PERC LID Carrier-Induced Degradation (CID)

WHAT  WHERE  WHO
WHEN  WHY  HOW
today’s focus
**WHAT** is LeTID?

### modules [1]

Degradation followed by regeneration under the **same conditions**

Accelerate timescale with higher temperature and illumination intensity

### cells [2]

**Figure adapted from [2]**

### wafers [3]


WHEN and WHERE does LeTID occur?

degradation conditions [1]-[7]

- Temperature: 50°C up to 140°C
- Illumination intensity: 0.15 up to 44.8 kW/m²

cell architecture [1]-[4]

- Enhanced in PERC vs. Al-BSF
- High temperature firing step required

substrates

- First observed in multicrystalline silicon
- Recent observations of similar behavior in Czochralski [8] and Float-Zone [9]
- Enhanced as-grown compared to after gettering [3], [10]-[11]

---

WHY does LeTID occur?

carrier-induced degradation (CID)

- Dependence on operating condition – faster degradation at $V_{oc}$ [1]
- Degradation rate directly proportional to excess carrier density [2]-[3]

PERC vs. Al-BSF

- Is PERC just more sensitive to bulk lifetime changes?
- Slower or no degradation in Al-BSF likely due to lower operating injection level

---

WHO – what defect is causing LeTID?

**recombination activity** *temperature- and injection-dependent lifetime spectroscopy*

possible defect parameters [1], [2]

---

**Significant difference** between undegraded and degraded recombination

**High** $k$ value [1]-[4] – positively-charged, donor-type defect

Recombination-active defect forms *early* in degradation and *increases* in concentration

Temperature-dependent $k$ *consistent* with reported values for Mo, but **not Ti or W**

*true defect may not yet be characterized*

---

WHO – what defect is causing LeTID?

**solubility and diffusivity** [1]

**Hypotheses:** metal impurity causes LeTID, metal impurity distributions change during firing, metal precipitates may be related to LeTID

---

---

Metal-rich particles **decrease in size** but **increase in density** after firing

**Solubility and diffusivity** required for sufficient interstitial increase consistent with **fast diffusers** like Cu and Ni, Co [2]-[3]

---

WHO – what defect is causing LeTID?

**Hypothesis:** Hydrogen is at the root cause of LeTID, either forming a recombination-active complex or associating/dissociating from the background bulk defect during degradation and subsequent regeneration.

- **Bulk hydrogen** (rather than firing time-temperature) is **necessary** for degradation to occur.

- **Bulk hydrogen** is **not the only prerequisite:** firing without hydrogen renders the defect inactive.

- **Excess hydrogen** (longer MIRHP times) leads to **lower** LeTID defect concentrations.


HOW does the LeTID defect cause degradation?

inspiration for a physics-based model [1]


For example...

<table>
<thead>
<tr>
<th>State</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>State 1</td>
<td>after firing, before degradation</td>
<td>$M_i$-$H_x$ complex</td>
</tr>
<tr>
<td>State 2</td>
<td>maximum degradation</td>
<td>$M_i$ and $H$</td>
</tr>
<tr>
<td>State 3</td>
<td>complete regeneration</td>
<td>$M_i$-$H_x$ complex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>... or $M_i$ to surface</td>
</tr>
</tbody>
</table>
HOW does the LeTID defect cause degradation?

inspiration for a physics-based model [1]

<table>
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<tr>
<td>state 3</td>
<td>complete regeneration</td>
<td>M_i-H_x complex</td>
</tr>
</tbody>
</table>

...or M_i to surface

possible physics-based model

- \( \Delta n \) change leads to changes in [2]-[3]:
  - Occupation probability
  - Charge state fractions
  - Defect complexes
- Possible spectroscopic value in assessing occupation probability in different states [4]-[5]

\[
\begin{align*}
E_c & \quad \text{H}^0/- \\
\text{H}^+/0 & \quad \text{H}^0/-
\end{align*}
\]

Summary and recommended next steps

**WHAT**

carrier-induced degradation, especially in higher efficiency devices requiring metallization firing

**WHEN**

well-defined by experiment

**WHERE**

**WHY**

- mobile component: bulk hydrogen
- metal impurity moves: Cu, Ni, or Co
- metal impurity stationary: Mo or other slow diffuser

**WHO**

**HOW**

- define solubility and diffusivity of mobile LeTID defect
- confirm observations of suppressed LeTID with increasing [H]
- define stability of defect/defect complexes in each state through experiment
- compare stability to DLTS studies (Ex. Co-H [1], Pt-H [2])
- possible modulation of occupation probability through carrier injection
- spectroscopic investigations of occupation probability – experiment and simulation

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  - Quantum Energy and Sustainable Solar Technologies (QESST) Engineering Research Center
- Harvard Center for Nanoscale Systems (NSF No. ECS-0335765)
- Advanced Photon Source at Argonne National Laboratory (U.S. DOE No. DE-AC02-06CH11357)
Questions?
Decoupling Optical, Recombination, and Resistive Losses with Luminescence Measurements

Kristopher O. Davis, Eric J. Schneller, Siyu Guo

External Collaborators: Andrew Gabor, Greg Horner, Josh Gallon, Steve Johnston
University of Central Florida
Role of Metrology in PV

Manufacturing setting
• Measure $P_{MP}$ to determine selling price (e.g., $I-V$ curves at STC)
• Identify manufacturing defects
• Accurately quantify the impact of the manufacturing defects on performance
• Identify the root cause of the defects
• Process control – improve performance on the line by actively using the metrology data in manufacturing
• Assist R&D team by gaining knew knowledge – hard to quantify, but potentially valuable

Benefits
• Catching manufacturing problems early prevents bad components from moving further downstream in production
• Efficiency gains possible via process control and tuning of the overall production line
• Quality improvements (e.g., performance, aesthetics) help branding and may results in price premiums (?)
• Drastically accelerate cycles of learning when introducing new materials and processes
• Better understanding by the R&D team may also accelerate technology development

Almost all of these can also apply to PV reliability and durability
J-V Characteristics

Al-BSF = aluminum back surface field

Front side ARC and passivation layer(s)

Front contacts

n⁺ emitter

p⁺ BSF

Rear contact layer

Al-BSF = aluminum back surface field
Loss Mechanisms – Rules of Thumb

Optical losses lower $J_{SC}$

Resistive losses lower the FF

Recombination losses lower $V_{OC}$, $J_{SC}$, FF

$J_G \quad J_1 \quad R_{SH} \quad R_S \quad V$

Graph showing $J$ (mA cm$^{-2}$) vs $V$ (mV) with labels $J_{SC}$, $J_{MP}$, $V_{OC}$, $V_{MP}$, and $P_{MP}$.
Optical Losses – PV Cells

- Front surface reflectance ($R_{ext}$)
- Absorption within the ARC ($A_{ARC}$)
- Internal back reflectance ($R_{r1}, R_{rn}$)
- Free carrier absorption ($A_{e,FCA}, A_{BSF,FCA}$)
Recombination Losses – PV Cells

- Saturation current density \( (J_0) \) dictates \( V_{oc} \)
- Total \( J_0 \) of the cell is \( \approx (J_{0f} + J_{0b} + J_{0r}) \)

Front metal coverage \( \approx 6\text{-}10\% \)

Rear metal coverage = 100\%
Resistive Losses – PV Cells

• Shunt resistance \( (R_{SH}) \)
• Series resistance \( (R_{S}) \)

Core Metrology for PV Cell Loss Analysis

- Illuminated $I-V$
- Dark $I-V$
- Suns-$V_{oc}$
- Quantum efficiency and reflectance
- PL imaging

![Graphs showing $J$ vs $V$, $EQE$ vs $\lambda$, and PL image](image)
Calibrated PL Imaging

Quantum Efficiency and Reflectance

\[ J_{sc} = \int SR(\lambda) \cdot I_{AM1.5}(\lambda) d\lambda \]

$J_{SC}$ Loss Analysis by Mechanism

Loss Analysis for PV Modules?

- Illuminated $I-V$
- Electroluminescence (EL) imaging
Loss Analysis for PV Modules?

- Illuminated $I$-$V$
- Electroluminescence (EL) imaging
- Suns-$V_{OC}$
- Calibrated EL vs. injection current for dark $I$-$V$ analysis
- Calibrated EL and local voltage analysis
- High-resolution PL imaging at open-circuit with a small field of view
- Non-contact QE using an optically induced EL
**I-V + Suns-$V_{OC}$ Measurements of Modules**

- See Eric Schneller’s poster tomorrow

Results from Sinton Instruments FMT-350

**Case 1: 10 Year Deployment in Florida**

- Smaller loss in efficiency at lower irradiance for $R_S$ related degradation

**Case 2: Potential Induced Degradation**

- Larger loss in efficiency at lower irradiance for $R_{SH}$ related degradation
Determining Individual Cell Voltage from EL images

- T. Potthoff, et al. (ISFH) developed a technique to convert EL images of modules using the EL signal to weight the voltage
  - Take EL image of module
  - Use brightest spot within each cell to weight voltages
  - Use simple summation and division to extract voltage of each cell

Calibrated EL vs. Injection Current

- Determine the operating voltage of each cell
- Repeat at different currents (i.e., sweep)
- Construct dark I-V curves for each
- Perform curve fitting of each cell
- Now you have $J_0$, $R_S$, and other parameters for each cell!

Extracting Dark $I$-$V$ from Individual Cells within a Module

- Applied this approach to sister modules
- One was kept indoors and the other installed in the field in Florida for 10 years

Validation of the Calibrated EL vs. Current

- Technique seems to work well unless there is a serious shunt
Recombination and Resistive Losses of Individual Cells

- Silicon heterojunction modules from Dirk Jordan

Calibrated EL and Local Voltage Analysis

• Use the calibrated EL to get the local voltage distribution
• If you use EL cameras with sufficient spatial resolution, you can analyze the local voltage within specific regions
• Provides the potential to decouple recombination and resistive loss mechanisms of individual cells
Calibrated EL and Local Voltage Analysis

Cell Interconnects

Contact Resistivity

Broken Contacts

Contact Recombination

(a) (b) (c)
Contact Recombination

- Decoupling contact recombination from recombination in the passivated emitter region
- One method: make test structures with a varied contact fraction, then measure the Suns-$V_{OC}$ curve of each
- Fit $J_0$ (metal fraction)
  - $J_0$ (0%) is passivated region
  - $J_0$ (100%) is contacted region
High-Resolution PL Imaging at Open-Circuit

- HR PL with a voltage calibration over a small field of view can be used to separate passivated surface recombination from contact recombination.
- Can be applied to modules since it is an open-circuit technique and doesn’t require full module illumination.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Suns-V&lt;sub&gt;OC&lt;/sub&gt;</th>
<th>HR PL</th>
</tr>
</thead>
<tbody>
<tr>
<td>( j_0 ) at passivated area ( (j_{oe} + j_{ob}) )</td>
<td>409 fA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>534 fA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>( j_0 ) at metal area ( (j_m) )</td>
<td>6089 fA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
<td>6675 fA/cm&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Recombination ratio</td>
<td>14.9</td>
<td>12.5</td>
</tr>
</tbody>
</table>

S. Guo, et al. 45<sup>th</sup> IEEE PVSC. Submitted.
Non-Contact Quantum Efficiency Measurements

Non-Contact Quantum Efficiency Measurements

Non-Contact Quantum Efficiency Measurements

Cell under test: Multi Al-BSF
Calibration reference: Mono all back contact

Cell under test: Mono PERC
Calibration reference: Mono all back contact

Cell under test: Multi Al-BSF
Calibration reference: Multi Al-BSF

Cell under test: Mono PERC
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Loss Analysis for PV Modules?

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- Andrew Gabor, Ph.D. (BrightSpot Automation)
- Steve Johnston, Ph.D. (NREL)
- Funding from the DOE SunShot Program
- Funding from Tau Science
Other Posters from UCF

- Poster session II tomorrow
Reliability of Electrically Conductive Adhesives Used as Solar Cell Interconnections

Katherine Han | 2-27-2018
Overview

• P-Series and SunPower Reliability
• What is ECA?
• Benefits of ECA
• Reliability testing of SunPower P-Series
• Future work: Mechanisms of degradation
SunPower is a Leader in PV Reliability with our IBC Products

- A robust method to calculate solar panel degradation, developed in collaboration with NREL, was applied to 230MW spread across 149 sites, 560 inverters, and 800,000+ panels.

- SunPower® panels demonstrate 0.2%/yr annual power degradation.

- Conventional Panels, including conventional and heterojunction technologies, degrade at ~0.75%/yr.

Jordan, D. et al. “Robust PV Degradation Methodology and Application.” PVSC 2017 pre-print
P-Series: Shingled Front Contact Cells with SunPower Module Quality

- Multi- or mono-crystalline front contact cells
- Shingled design eliminates between-cell white space, improving efficiency
- ECA interconnection provides an opportunity for high-reliability joints with less stress on the cells than solder

- Performance Series provides higher quality than standard front contact modules with lower cost than current generation of SunPower IBC products
What is an ECA?

• Conductive metal filler mixed with an adhesive polymer matrix

• ECA components on the market (non-exhaustive list)
  – Polymer matrix
    • Epoxy
    • Acrylic
    • Silicone
  – Metal filler
    • Silver
    • Silver-coated copper

• Decades of demonstrated reliability in:
  – Vehicles
  – Hand-held electronics
  – Etc.

Benefits of ECAs as Solar Module Interconnections

- Processed at lower temperatures than solder
- Screen printable
- Rapid full module inline curing
- Lower Young’s modulus than solder joints can impart less stress on the cell and reduces stress build-up in thermal cycling
- Similar joint resistance as solder
- Improved module efficiency by reducing white space
- Redundancy of interconnections improves reliability

- ECAs provide a new wide range of material options for solar module interconnection
3rd Party (PVEL) Long Term Reliability Testing

TC Results on Conventional and SunPower Panels

- P-Series demonstrates exemplary reliability in chamber testing
Historically solder joint failure has been a major field reliability concern.
Mechanical- Lazy Installer Drop Loses Less Power

- P-Series module design and ECA utilization maintains power after mechanical damage

As Received

4.6% Power Loss

As Received

18.7% Power Loss
P-Series Is Mechanically Robust

- P-Series performed better during deflection after poor handling than CT1 (3BB)
Acceleration Factors and Field Correlation

• Demonstrated high reliability using accelerated testing that was developed for conventional solar modules
  – Demonstrates qualitative, but not quantitative good reliability performance

• Complicated acceleration factor estimation for thermal cycling
  – Material property dependent AF determined by amount of strain that builds up during each cycle
  – Cannot generalize AFs for all ECAs
Next Steps

1. Determine degradation mechanisms for various ECAs, develop new reliability testing if necessary
2. Develop method to determine acceleration factors for any new ECA based on mechanical or chemical properties
3. Develop limits of ECA specifications (Tg, elasticity modulus, conductivity, etc requirements) for use in solar modules
Thank You

Let’s change the way our world is powered.

Katherine Han, SunPower Reliability
Katherine.han@sunpowercorp.com
OBSERVATIONS OF PV SYSTEMS POST-HURRICANE

Eliza Hotchkiss
Recovery and Resilience Lead
Strategic Energy Analysis Center at NREL

February 27, 2018
Background

Like many remote islands the USVI is dependent on fossil fuel for the generation of electricity.

In 2010, the USVI established a goal to reduce fossil fuel-based energy use by 60% (based on a 2008 baseline) by 2025.

As a result, VIWAPA has been improving energy efficiency and diversifying energy resources: wind, solar, natural gas.

Photo source: www.seaglassvi.com/islands/us-virgin-islands/st-thomas/
Background

• Two Category 5 storms, Hurricanes Irma and Maria, damaged Saint Croix, Saint John, and Saint Thomas among other smaller islands.
  o Hurricane Irma hit the USVI on September 6 with the eye passing over St. Thomas and St. John.
  o On September 20\textsuperscript{th}, the eye of Hurricane Maria swept near St. Croix with maximum winds of 175 mph.

• Estimated damages $\sim$7.5 billion. Generation fared well, but $\sim$ 80-90\% of the power transmission and distribution systems in the USVI were damaged.

• November 2017 estimates were in the range of $\$850$ million in hurricane recovery funding to help “rebuild a more resilient electrical system.”
Background

- Wind speeds, direction and duration impact the performance of a PV array
  - Limited data due to weather stations and anemometers going offline

- Why did PV systems fail?
  - Was it poor workmanship or poor materials?
  - Was it a matter of needing to design differently?
  - Can systems be designed to resist 200 mph winds?
  - What are the costs of resilience improvements and are they worth it?
PV System Observations

**St Thomas**
- The PV installed at the airport (~385kW) along the runway only had a few panels damaged.
- The Donoe array (~4MW) was significantly damaged.
- Ron De Lugo rooftop and carport with various damages.

**St Croix**
- Spanish Town array (~4MW) had about 17 panels damaged in Hurricane Maria.
- Almeric had a ground mounted system (470kW) that was severely damaged.
  *Designs referred to ASCE 7-10 code and wind speed of 145/165 mph.*
- Rooftop solar on all islands had various survival rates.
St Thomas

Dedication of 4.2 MW PV plant in USVI (February, 2015)

Array pre-Irma (*DOE photo*)
PV Failures

Same plant after Hurricane Irma, December, 2017

Photo credit: Eliza Hotchkiss, NREL
PV Failures

Photo credits: Eliza Hotchkiss, NREL
PV Failures

Photo credits: Eliza Hotchkiss, NREL
Wind Direction and Speeds

Image Source: Google Maps
St. Thomas Airport PV plant

- Inverter 1 – 135 kW
- Inverter 2 – 250 kW
- Last data received at 11:32am Sept 6, 2017

Weather station stopped responding

The whole PV plant stopped responding

Data from September 6, 2017, provided by Vahan Gevorgian, NREL

Photo credit: top left, VI Office of Economic Opportunity top right, Eliza Hotchkiss, NREL
Rooftop PV systems

Photo credit: Eliza Hotchkiss, NREL
Roof Mounted PV Arrays

- Roof mounted PV prevalent across USVI
- Wind load criteria is included in ASCE 7-16 (residential and commercial)
- Performance varied greatly
  - Failure mainly due to clips that attach to rails
  - Panels became windborne debris
  - Panels also damaged due to debris (e.g. collapsed antennae)

Photo credits: Left photo (FEMA MAT); Right photos (Andy Walker and Ran Fu, NREL)
Rooftop PV system

Photo credits: Eliza Hotchkiss, NREL
Mobile PV system

Photo credits: Eliza Hotchkiss, NREL
Lessons Learned: Uplift

Uplift was seen with modules hanging out over parapet walls (e.g. windward side of building during the storm) and modules were totally detached from the rack in the storm.

Recommendation:
- On existing arrays remove front row of modules, avoiding area of wind exposure.
- On new arrays, account for uplift and site panels to avoid overhang

Photo credits: Andy Walker and Ran Fu, NREL
Lessons Learned: Bolts and Torqueing

Bolts were missing from some brackets.

Recommendation:
- Install missing bolts and tighten to torque specifications
- Confirm torque specification during commissioning

Photo credits: Andy Walker and Ran Fu, NREL
Lessons Learned: Clamping

A commonly observed problem was that clamps holding the modules in position did not withstand sustained winds. Several end clamps were found in a bent condition indicating that bending of the end bracket released a module, creating motion/vibration, which then disengaged the next center clamp which held two modules down.

Materials:
- Center clamp was stainless steel, marked 1R HA14, 70 psf, ETL UL
- End clamp was made of aluminum and unmarked

Photo credits: Andy Walker and Ran Fu, NREL
Lessons Learned: Clamping

The clamps shown indicate the main failure (bent clamps) and a contributing factor related to the lateral braces which were held in place by only 2 self-tapping screws instead of four through-bolts. The frame on the right indicates a bolt ripping out of the framing.

Recommendation:
- Consider through-bolting rather than clamping module frames.
- A combination of clamps and through-bolts may be used.
- Use the adequate number of clamps per module, per specifications.

Photo credits: left, Andy Walker and Ran Fu, NREL, right, Eliza Hotchkiss, NREL
Lessons Learned: Electrical

Recommendation:
- For immediate deployment, move unbroken modules onto rack space where they are contiguous with modules of the same type and can be connected together electrically.
- Use stainless steel cabinets with multiple door attachments rather than single rod closures to prevent water intrusion.

Table. Results of string testing

<table>
<thead>
<tr>
<th>Condition</th>
<th>Number of Strings</th>
<th>Affected Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>35</td>
<td>420</td>
</tr>
<tr>
<td>Okay</td>
<td>55</td>
<td>660</td>
</tr>
<tr>
<td>Total</td>
<td>90</td>
<td>1080</td>
</tr>
</tbody>
</table>

Photo credits: Andy Walker and Ran Fu, NREL
How Can PV Become More Resilient?

We understand systems won’t be 100% resilient 100% of the time, however, there may be some low-cost best practices or standards to improve resilience of PV systems:

- Standards and design specifications such as materials used in PV modules and racking systems (qualification testing, UL1703 IEC61215, NEC code)
- Installation verification (torqueing with a torque wrench, assembly, connections, acceptance tests (static and dynamic load tests – 300W panel 2mx1m)
- Maintenance of components (e.g., torqueing pre-hurricane season, electrical testing, etc.)
- Siting and design: differences in topography (sail or chimney/stack effect), racking installation (e.g., piers), soil conditions, overhang location, etc.
- Operational procedures, such as adjusting tilt of arrays pre-storm or cover with protective materials
- Costs and benefits associated with all of these measures
Thank you

eliza.hotchkiss@nrel.gov
www.nrel.gov/resilience-planning-roadmap/

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.
### Wind and PV Generation

<table>
<thead>
<tr>
<th>Island</th>
<th>Location and Resource Type</th>
<th>Capacity MW of AC</th>
<th>Estimated Annual Energy Production (MWh/year)</th>
<th>Condition Post Hurricane Season 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>St Thomas</td>
<td>Estate Donoe Solar Farm (solar PV)</td>
<td>4.2 MW</td>
<td>7,897</td>
<td>Unsalvageable</td>
</tr>
<tr>
<td></td>
<td>Port Authority</td>
<td>0.45 MW</td>
<td>978</td>
<td>Minimal damage from flying debris impact</td>
</tr>
<tr>
<td>St Thomas - St John</td>
<td>“Net Metering”</td>
<td>6.86 MW</td>
<td>17,011</td>
<td>Good condition</td>
</tr>
<tr>
<td>St Croix</td>
<td>Estate Spanish Town (PV)</td>
<td>~4 MW</td>
<td>8,633</td>
<td>Good condition (17 panels were reported to have impact damage)</td>
</tr>
<tr>
<td></td>
<td>Federal Courthouse Installation</td>
<td>0.469 MW</td>
<td>963</td>
<td>Unsalvageable</td>
</tr>
<tr>
<td></td>
<td>“Net Metering”</td>
<td>5.8 MW</td>
<td>15,006</td>
<td>Good condition</td>
</tr>
</tbody>
</table>


*In 2011, more than 1,800 PV panels were installed along the runway of the Cyril E. King Airport, totaling 451-kilowatt (kW)—one of the largest solar PV systems in the Caribbean. The 451-kW PV system flanking the airport’s landing strip was funded by a $2.9 million DOE grant through the Recovery Act. At 1,500 feet long and 14 feet wide, the installation is the largest solar project in USVI and will produce approximately 15% of the airport’s energy needs, or 600,000 kWh annually.*
TS 63126: Guidelines for Qualifying PV Modules, Components and Materials for Operation at High Temperatures

Status

Kent Whitfield, UL
IEC TS 63126 – What is it?

This project intends to provide guidance on the modification of tests in:

- IEC 61215, Module performance
- IEC 61730, Module safety
- IEC 62790, Module jboxes
- IEC 62852, Module connectors
- IEC 62930, Module cables

To take into account modules operating at high temperatures due to:

- Ambient air temperatures in excess of 40°C
- Mounting systems that restrict cooling.

By modifying individual tests contained in those standards through

- Increasing testing temperatures, or
- Increasing testing duration, or
- Increasing number of cycles.
Status of IEC TS 63126

New work item proposal approved 31 March 2017

First group meeting in Neuchatel Switzerland, 3 October 2017

Five conference calls since then

Participation:

• 30 members, 10 countries

• Extra effort to find participation from Middle East areas such as Saudi Arabia and Arab Emirates

Goal is to

• CD by October 2018
• DTS May 2019
• Complete work by May 2020
Approach thus far

Understanding module operating temperature as a function of installation location and installation style using modelling

- Includes sensitivity analysis for wind speed, irradiance, ambient temp, albedo, installation angle, and azimuth

Supporting model by experiment (or real data if available)

Create an easy to understand standard reference environment that

- Meets or exceeds actual “hot” locations studied
- Supports modifying product temperature test results

\[ T_{\text{module}} = \text{Irradiance} \times e^{(a+b \times \text{WindSpeed})} + T_{\text{ambient}} \]

\[ T_{\text{cell}} = T_{\text{Module}} + \frac{G}{1000 \text{W/m}^2} \Delta T \]

<table>
<thead>
<tr>
<th>Module Type</th>
<th>Mount</th>
<th>a</th>
<th>b</th>
<th>\Delta T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass/cell/glass</td>
<td>Open rack</td>
<td>-3.47</td>
<td>-.0594</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/glass</td>
<td>Close roof mount</td>
<td>-2.98</td>
<td>-.0471</td>
<td>1</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Open rack</td>
<td>-3.56</td>
<td>-.0750</td>
<td>3</td>
</tr>
<tr>
<td>Glass/cell/polymer sheet</td>
<td>Insulated back</td>
<td>-2.81</td>
<td>-.0455</td>
<td>0</td>
</tr>
</tbody>
</table>
Example for a Hot-Climate

Difference between Maximum and 98-percentile
Choice is 98% since time-at-temperature is an important consideration
98-Percentile - Meaning

Expect ~ 175 hours at or above this temperature per year.

Although the exposure time tends to be lumped into the summer season.

Results in several days with 3hrs or more exposure to elevated temperature

- Coincides with Solar ABC’s approach for determining regulatory compliance for high-temperature as part of an Expedited Permit Process for PV Systems (2012)
What the outcome might look like

Although not finalized, the outcome of this effort is expected to result in modifications to existing tests such as shown below:

<table>
<thead>
<tr>
<th>IEC 61215 (MQT)</th>
<th>IEC61730 (MST)</th>
<th>From</th>
<th>To (NP)</th>
<th>Model Suggests open-rack (50°C amb)</th>
<th>Model Suggests close-roof (50°C amb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MQT 09 Hot spot endurance</td>
<td>50°C</td>
<td>Tcon-10°C</td>
<td>Tcon-20°C</td>
<td>60°C</td>
<td>Tcon-20°C</td>
</tr>
<tr>
<td>MQT 10 UV preconditioning</td>
<td>60°C</td>
<td>Tcon-10°C</td>
<td>Tcon-10°C</td>
<td>70°C</td>
<td>Tcon-10°C</td>
</tr>
<tr>
<td>MQT 11 Thermal cycling</td>
<td>85°C</td>
<td>Tcon</td>
<td>Tcon-10°C</td>
<td>90°C</td>
<td>NC</td>
</tr>
<tr>
<td>MQT 18 Bypass diode testing</td>
<td>90°C</td>
<td>Tcon</td>
<td>NC</td>
<td>50°C</td>
<td>50°C</td>
</tr>
<tr>
<td>MST 21 Temperature Test</td>
<td>40°C amb</td>
<td>max amb</td>
<td>see MQT 09</td>
<td>see MQT 09</td>
<td></td>
</tr>
<tr>
<td>MST 22 Hot spot endurance</td>
<td>see MQT 09</td>
<td>See MQT 18</td>
<td>See MQT 18</td>
<td>See MQT 18</td>
<td></td>
</tr>
<tr>
<td>MST 25 Bypass diode thermal</td>
<td>See MQT 18</td>
<td>See MQT 18</td>
<td>See MQT 18</td>
<td>See MQT 18</td>
<td></td>
</tr>
<tr>
<td>MST 37 Material creep test</td>
<td>105°C</td>
<td>Tcon or 105°C</td>
<td>NC</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>MST 51 Thermal cycle</td>
<td>See MQT 11</td>
<td>See MQT 11</td>
<td>See MQT 11</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>MST 54 UV test</td>
<td>See MQT 10</td>
<td>See MQT 10</td>
<td>See MQT 10</td>
<td>NC</td>
<td></td>
</tr>
<tr>
<td>MST 56 Dry heat conditioning</td>
<td>105°C</td>
<td>Tcon or 105°C</td>
<td>NC</td>
<td>NC</td>
<td></td>
</tr>
</tbody>
</table>

* - >200 cycles with no change to temperatures
Next steps

Complete modeling effort.

Begin continuous simulator and outdoor experimental validation test

Seek actual module temperature (focus area is KSA)

Modify test temperature or cycles as necessary – October of this year
  • Feedback from member countries
  • CDV by May 2019

Interested in participating?
Send me an email at kent.whitfield@ul.com

Especially seeking testing labs for experimental validation and anyone with high temperature data!
Developments in IEC 61730

Nancy Phillips

February 28, 2018
DuPont Photovoltaic Solutions

For over 40 years
our material innovations have led the photovoltaics industry
forward, and helped our clients transform the power of the Sun
into power for us all. Today we offer a portfolio of solutions
that deliver proven power and lasting value over the long term.
Whatever your material needs, you can count on quality
DuPont Photovoltaic Solutions to deliver the performance,
efficiency and value you require, day after day after day…
IEC 61730
PV Module Safety

New versions published in 2016

- Part 1: Requirements
- Part 2: Test Methods

Amendments in progress

- Part 1: CD circulating for comment (Phillips)
- Part 2: CD in preparation (Volberg)
1. **Instructions for reporting of Isc for bi-facial modules** *(Section 5.2.2.1)*

2. **A requirement for Class 0 modules** (for use in restricted access areas), so that they are not required to meet the glass breakage test, MST 32 *(Section 5.4)*

3. **Weathering requirements for relied-upon insulation.** *(Section 5.5.1)*

4. **To Section 5.6.4:**
   - a component level test for assessment of distance through insulation (dti) for use with thermally deformable materials *(Section 5.6.4.3)*
   - Clarification to Table 3
   - Clarifications to Table 3 and 4 *(Section 5.6.4)*
   - Clarification of Figure 4 *(Section 5.6.4)*
   - Thickness requirements for glass/ceramic insulating materials (allows for <3.5 mm glass in 1500V modules)
   - An alternative minimum distance through insulation (dti) requirement for frontsheets used in flexible modules.

5. **To Annex B:**
   - Clarifications on the usage of CTI values *(Section B.2)*
   - Correct mistakes in Table B.4 *(Section B.8)*
   - Clarification on creepage distance requirements *(Section B.6)*

6. **Related to definition of “Open Rack”**
Proposal for an amendment for IEC 61730-2 ed.2

Important changings:

- Modification of testing tree concerning clarification of several test sequences and relevant samples.

- Clear specification concerning the peak value of impulse voltage test.

- Alignment of test procedures under consideration of definition of “Open rack” installation and/or “High temperature application” in IEC 61730-1 Amd 1.

- Better explanation (and supplement of drawing) for ignitability test.

- Alignment of test plan if IEC 61730-2 with IEC 61215 (not only concerning mandatory and optional tests).
Insulation thickness requirement

Current IEC 61730-1 IS
- Minimum thickness requirement for relied-upon insulation defined in Tables 3 and 4
- Thickness of relied upon insulation is checked by insulation thickness test (MST 04) in final application...

Modification to allow for prequalification: or by dti test according to IEC TS 62788-2 on component level.

Narrow exception:
- for flexible modules (as defined in IEC 61215 amendment in progress), using thin film technology where the surface against the front sheet is protrusion free. Single layer polymeric ETFE (>95 % ETFE) frontsheets of Material Group I with system voltages ≤1000 V shall have a minimum thickness of 50 μm
Definition of “Open Rack”

Question: How open is “open”?

Real issue is with low air flow applications in high T environments

- **61730 Scope: Environmental Temperature**
  - All PV modules shall be suitable for operation in outdoor non-weather protected locations, exposed to direct and indirect (albedo) solar radiation, in an environmental temperature range of at least −40 °C to +40 °C and up to 100% relative humidity as well as rain.

- **Reference to “open rack”**
  - RTI requirement defined by module temperature test MST 21 or 90 °C, whichever is higher.
  - For open rack mounted PV modules, the normalized measured maximum PV module operating temperature can be assumed to be 90 °C, so the insulation RTE/RTI or TI rating shall be at least 90 °C.

- **Considering recommendation to**
  - Remove reference to “open rack”
  - Limit scope to a maximum module operating temperature (98 %-ile metric)

Discussions proceeding in IEC 63216 project team

(Testing of PV Modules Operating at High Temperature)
61730-1 backsheet weathering requirement

Weathering Requirement in 61730-1 AMD1

5.5.2.2.2 Laboratory Weathering Exposure

Air-side and sun-side weathering specimens shall be exposed as described in exposure A3 in Table 1 of IEC TS 62788-7-2. (White and clear backsheets)

For black or colored backsheets, air-facing side and sun-facing side specimens shall be exposed as described in exposure A2 in Table 1 of IEC TS 62788-7-2

Specimens shall be exposed for 2000 hours, with an additional set of samples exposed for 4000 hours if using the alternate pass/fail criteria.

5.5.2.2.3 Evaluation Tests, Criteria for Qualification

Sun-side exposed specimens shall be evaluated by visual inspection as described in the table. Air-side exposed specimens shall be evaluated by both visual examination and % Elongation described in the Table.

5.5.2.2.4 Backsheet qualification limitations

If exposure type B, E, or G is used for the backsheet weathering exposure, the backsheet qualification is limited to modules using an encapsulant with the same or higher UV cut-off (as defined in IEC 62788-1-4) reported for the filter of the weathering specimen for exposure of the sun-facing side of the backsheet.

---

IEC 62788-7-2 A3:
- Xe, 0.8 W/m2/nm, ChT 65°C, BPT 90°C

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Exposure Specimen</th>
<th>End-point Passing Criteria</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual Examination (using standard and backlit lighting)</td>
<td>Both sun-facing and air-facing specimens</td>
<td>No visual signs of degradation on air-facing side or sun-facing side when viewed under standard laboratory lighting and backlit lighting. No cracks, bubbles, or delamination</td>
<td>MST-01</td>
</tr>
<tr>
<td>% Elongation</td>
<td>Air side specimen</td>
<td>50% retention* after 2000 hours AND 25% minimum value, OR 25% minimum value after 4000 hours</td>
<td>IEC TS 62788-2</td>
</tr>
</tbody>
</table>

*Supplier may request preconditioning of the sample for up to 100 hours at up to 100°C as requested by supplier (no additional humidity added)
61730-1 backsheets weathering requirement

Weathering Requirement in 61730-1 AMD1

5.5.2.2.2 Laboratory Weathering Exposure

Air-side and sun-side weathering specimens shall be exposed as described in exposure A3 in Table 1 of IEC TS 62788-7-2. (White and clear backsheets)

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---

**Test Method** | **Exposure Specimen** | **End-point Passing Criteria** | **Ref**
--- | --- | --- | ---
Visual Examination (using standard and backlit lighting) | Both sun-facing and air-facing specimens | No visual signs of degradation on air-facing side or sun-facing side when viewed under standard laboratory lighting and backlit lighting. No cracks, bubbles, or delamination | MST-01

% Elongation

<table>
<thead>
<tr>
<th>% Elongation</th>
<th>Air side specimen add sun-side specimen</th>
<th>50% retention* after 2000 hours AND 25% minimum value, OR 25% minimum value after 4000 hours</th>
</tr>
</thead>
</table>

*Supplier may request preconditioning of the sample for up to 100 hours at up to 100°C as requested by supplier (no additional humidity added)

---

IEC 62788-7-2 A3:
- Xe, 0.8 W/m²/nm, ChT 65°C, BPT 90°C
Weathering Requirements for Relied-upon insulation

Ongoing discussions:

Test method consistency – experiments in progress
- ETB Test method consistency
- Weathering exposure consistency

Technical issues to resolve
- Exposure T
- Pass/Fail criteria
  - R-ETB and/or ETB
- Thermal preconditioning
- Specimen design for sun-side exposures
Test Method consistency
Elongation at break

WPET Data (unweathered)

• Lab A
  • Random samples
• Lab B
  • Cross-web samples

WPET - Lab A
%E: mean = 133, stdev = 28

WPET, Lab B
% E: mean = 96.0, stdev = 4.7

• Test method can be done with good repeatability
• Need to define Best Practices
  • Materials sampling, preparation, equipment, method, etc.

In progress:
• Survey on test method details in progress
• Round robin testing (10 laboratories) in progress
Test Method Consistency
Weathering exposure

Weathering exposure round robin:

- Reference material – selected to observe degradation after 500-2000 hours A3 exposure
- High % Elongation variability in unweathered samples made quantitative analysis difficult
- After 2000 h, good consistency at 6 of 9 laboratories
- Working to understand sources of variability

Survey on test method details:

- Notable differences:
  - Fixed v. rotating rack
  - Sample back: open, or on rack
  - Optical filter (Boro/Boro v. RightLight/Daylight/Quartz)
  - Black Panel (Insulated v. non-insulated)
- Temperature round robin

Weathering Exposure temperature measurements:

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</table>

1 standard deviation 9 4 2 2

New PVQAT TG 5 Round Robin weathering experiments in progress
Pass/fail criteria – Elongation at break after weathering

Default criteria, after 2000 h exposure
- 50% retention* (RETB) AND
- 25% minimum value (ETB)

Alternate criterion, after 4000 h exposure
- 25% minimum value (ETB)

General Philosophies (UL model)
- Minimum value at end of life (minimum ETB)
- Limited change in materials (minimum RETB)

Balancing approaches:
- Disallow known and potential bad materials
- Allow new innovations in materials

Discussion Questions:
How to include a safety margin in the minimum value; the known bad data observed (15% ETB after 2000 hours), is below the minimum value; raise to include a higher minimum value, plus a safety margin

Minimum value at 2000 hours should be higher than at 4000 hours
Optional thermal preconditioning step

*Supplier may request preconditioning of the sample for up to 100 hours at up to 100 °C as requested by supplier (no additional humidity added)*

Prompted by a desire to allow for new polyolefin materials
- Polymeric materials can hold residual stress (morphology), properties can change from thermal equilibration (no bond breaking)
- “Hypothetical” example:
  - ETB (initial) ~1000%
  - ETB after thermal treatment ~400%
  - ETB after 2000 hours A3 exposure ~300
- Data for PO backsheet (table)

Alternate proposal:
- Use lamination conditions (15 min @150° C) as a reference point, use rule of thumb to adjust time and temperature (table)
  - 75C for 50 hours
  - 100C for 8 hours

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</tr>
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</table>
Gaps noted from other discussions _will be addressed in next draft_

- How to approach “manufacturing excursions”? (e.g. multiple BOMs for one “model”)
  - Include requirement for alternate BOMs follow IEC 62915, Module Retest Guidelines

- Extended reliability:
  - Recognized that 61730 qualification does not represent 25 year reliability in all “covered” locations … How to address?
    - Some national standards addressing this with additional requirements for qualification
    - Solutions in process in other standards
    - Additional statements in 61730?
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The miracles of science™
Activities and Goals of PVQAT

Tadanori Tanahashi (AIST)
PVQAT: We are...

PVQAT OPEN FORUM (Volunteers)
- Collaborative Research
- Discussions on Current Issues
- Data Collection and Comparison of Results

IEC Support
Establish Standards

PV Reliability WSs Support

Will Collaborate?

Tasks 13 + others(?)
PVQAT: Approach

- A rating system to ensure **durable design** of PV modules for the climate and application of interest.

- A guideline for factory inspections and quality assurance (QA) during **manufacturing**.

- A comprehensive system for **certification** of PV systems, verifying appropriate design, installation, and operation.
PVQAT: Task Groups

Task Group 1: Manufacturing Consistency (IEC TS 62941 -> IS)
Task Group 2: Thermal and Mechanical Fatigue (IEC 62892)
Task Group 3: Humidity, Temperature, and Voltage (IEC 62804s + C-AST)
Task Group 4: Diodes, Shading, and Reverse Bias (IEC 62979 +)
Task Group 5: UV, Temperature, and Humidity (IEC 61730 + IEC 62877s)
Task Group 6: Communication inactive
Task Group 7: Snow and Wind Loading inactive
Task Group 8: Thin-Film Photovoltaic Modules (IEC 63140)
Task Group 9: Concentrator Photovoltaic Modules (CPV) inactive
Task Group 10: Junction Box Connectors
Task Group 11: System Verification and Power Electronics Testing (Mar. 1)
Task Group 12: Soiling and Dust
Task Group 13: Cells
### PVQAT: Regional Activities

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**Details:** Please visit Poster # 77

**Japan**

Combined TGs (TG2/3/5) -> Focus on Safety Issues
Issues to be discussed (in my opinion)

Re-confirmation
- Goal (Final Destination): Healthy Growth of PV Community via Standardization
- Most Optimized Approach:
  Necessity of Addition / Improvement of Approach(s)

In Practical
- Necessity of Addition / Re-Organization of Task Group(s)
Goal and Activities Task Group 5 (UV, T, RH)

- IEC qualification tests (61215, 61646, 61730-2) presently prescribe up to 160 days field equivalent AM 1.5G TUV dose. This is \(< 25 \text{ years!}

- **Goal**: develop UV- and temperature-facilitated test protocol(s) that may be used to compare PV materials, components, and modules relative to a field deployment.

**Core Activities:**

1: Consider weathering **literature** and **climate meteorology** (*location-dependent information*).
   - *e.g.*, known benchmark locations...Miami, FL; Phoenix, AZ

2: Leverage **existing standards**, including other industries.
   - √ *Summary exists from Kurt Scott et. al.

3: Improve understanding of existing PV UV tests.

4: Improve understanding of module durability.
   - 4-1 Collect information about **field failure modes**.
     - *e.g.*, the literature, site inspections, industry feedback
   - 4-2 Confirm appropriate **UV weathering models**.

5: Consider suitable **artificial UV sources**.
   - √ *Summary of module capable equipment from David Burns et. al.*

6: **Generate test procedure for accelerated UV weathering.**
   - Presently performing experiments to provide technical basis & confident decisions.

7: Perform **laboratory verification** of proposed test standard/failure mode.
   - - mini-module study (Japan), SoPhia round-robin (Europe), interlaboratory “study 1” (TG5 X)
Important Considerations Related to UV Weathering

**Steady-state weathering** (e.g., discoloration, gloss loss, embrittlement)

- A high fidelity, duration-relevant weathering test for PV materials did not exist.

- **Commercial equipment** cannot practically accommodate module specimens ($$$). Examples: automotive, paint, textile industries use representative **coupon specimens**.

- Representative **specimen geometry** is not always known. Examples: BS polymer sheet vs. laminated coupon. Different chamber specimen temperature of transparent, white, and black specimens.

- Limited understanding of key considerations ($E_a$, action spectrum, reciprocity). How do you prescribe & interpret weathering tests?

- **Correlation between artificial and natural weathering** remains to be established. Location specific; diurnal & annual variability of weather; monitoring UV ($\lambda$’s);... Benchmark natural weathering required in other industries for material acceptance.

**Complex weathering** (e.g., cracking of backsheet)

- Some damage modes do not readily manifest using steady state weathering, e.g. PA backsheet.

- Many considerations for steady-state also apply to complex weathering.
IEC TS 62788-7-2 Weathering Standard

History

• Developed for coupon and component specimens.
• Consider: maximum terrestrial UV intensity; module temperature (85\textsuperscript{th} percentile); %RH in PV application w.r.t. lower chamber control limit.
• Published 2017/9/06.

Implementation

• Other (referencing) standards would identify:
  - Specimen geometry.
  - Exposure from a menu of options in 62788-7-2.
  - Product requirements (pass/fail), if applicable.
  - Test duration (1000, 2000, 4000 hours typical).
• Xe chamber is reference method.
• UVA-340 fluorescent chamber may also be used. Verify your results!

Proposed weathering conditions for Xe chambers.

Comparison of artificial test and natural (terrestrial) temperature & humidity conditions.
Related research efforts: PVQAT TG5 Study 1 (encapsulants & edge seals)

**TG5 X, Study 1**
Considerations: type artificial UV source, temperature, humidity, natural weathering, $E_a$...

- Discoloration of encapsulants
- Attachment strength of encapsulants
- Strength & adhesion of edge seals

References:
Kempe et. al., Proc SPIE, 2016, 9938-03.

$E_a$ on order of $\sim 50$ kJ·mol$^{-1}$ (0.5 eV) estimated for EVA.

**Schematic and photo of wedge specimen (edge seals).**
Compressive shear test used to examine the attachment of EVA.
Change in strength of attachment with Xe weathering at 3M.
Specimens on outdoor rack, in Golden, CO at NREL.
Specimens after 618 MJ·m$^{-2}$ in Xe chamber, at Fraunhofer CSE.

Results for Xe aged wedge specimens.
An alternate weathering regime was identified for the hottest experiments based on:

- Inflection in $\Delta \tau$ & YI data.
- Loss of UV absorber in $\tau$ spectra.
- Formation of voids at specimen periphery.
- Disparate fluorescent spectra (different product species).

• Chamber temperature of $\sim 60^\circ$C recommended.

• $\Delta \tau$ of 2% suggested for evaluation.
- Consistent with 0.25-0.33%/y degradation rate for EVA discoloration from the literature, with modest acceleration factor for first $\sim 5$y field use.


- Shown applied here for EVA-B (subsequent generation product).

Miller et. al., in preparation.
TG5 Weathering Questionaire

• Do you work with UV weathering?
• We have a Questionnaire for you! 😊

We are interested in identifying the industry practices to improve IEC TS 62788-7-2.

Topics
• Weathering Chamber
• Specimen fixture & mounting
• UV source
• Temperature verification
• Humidity verification

Key findings to date
• Use of rotating- vs. fixed-rack. Issues: use of sample blanks, sample replacement.
• Use of different UV filters, e.g., ASTM D7869/quartz vs. s-boro/quartz.
• Need to verify specimen temperature (chambers models designed differently).
• Use different black panels (uninsulated vs. insulated). Frequency BP replacement.
• Use of backing substrate (air or metal backplate).

• Contact: nancy.h.phillips@dupont.com, David.Miller@nrel.gov
• More rigorous qualification test for UV durability (field equivalence not yet correlated).
• Covers encapsulants, frontsheets, and backsheets (transparent, used like frontsheets in bifacial modules).
• **Test will combine transmittance (62788-1-4) and weathering (TS 62788-7-2) standards.**
• A pass/fail criteria ($\Delta \tau > 2\%$) will be specified for change in transmittance. Additional pass/fail based on defects, e.g. delamination.
• Result required in IEC 62788-1-1 to be reported in encapsulant datasheets.

**Timeline:**
NWIP #1060 $\rightarrow$ CD #1190 $\rightarrow$ CDV #1360 (due 2018/3/09) $\rightarrow$ FDIS $\rightarrow$ STD published (future, after R-R)

**Legacy:**
transferred from IEC 62892-3 to IEC 62788-1-7.
PVQAT TG5 Study 2: 62788-1-7 Optical Durability R-R

Test materials (3 replicates)
1. Contemporary EVA (commercial product, UV cut-off 360 nm)
2. Contemporary EVA (commercial product, low PID, UV cut-off 360 nm)
3. Contemporary EVA (commercial product, low PID, UV cut-off 230 nm)
4. A9918 EVA (known bad benchmark material)
5. TPO (R&D formulation, thermoplastic, low crystallinity)
6. TPO (R&D formulation, thermoplastic, high crystallinity)
7. TPO (commercial product, thermoplastic)
8. POE (R&D formulation, thermoset, with UVA)
9. POE (R&D formulation, thermoset, without UVA)
10. PVB (commercial product, BIPV material)
11. Transparent backsheet (commercial product) air side
12. Transparent backsheet (commercial product) sun side
13. PS reference (weathering reference material, SAE J2412, or SAE J2527)
(14.) Reference material (1 replicate coupon, do not weather)

Goals
1a. Quantify r & R of IEC 62788-1-7 (SS weathering).
1b. Verify pass/fail criteria for IEC 62788-1-7.
2. Quantify activation energy of contemporary materials.
3. Quantify acceleration factor in benchmark locations.

Participants (artificial weathering)
1. 3M
2. Borealis (A5)
3. CREST (Loughborough University)
4. DNP
5. Dow-Chemical
6. DuPont
7. Eye Applied Optics
8. Fraunhofer CSE
9. NREL (A3 & A4)
10. RenewSys (QUV, B3)
11. Suga
12. Sun Power

Participants (natural weathering)
a. ATLAS (Miami)
b. ATLAS (Phoenix, 1x)
c. ATLAS (Phoenix, EMMA)
d. KACST (Riyadh)
e. NIST (Gaithersburg)
f. NREL (Golden, 1x)
g. NREL (Golden, EMMA)
h. Q-Lab (Cleveland, 1x)
i. SERIS (Singapore)

Contact:
David.Miller@nrel.gov
Future Efforts For TG5 X

Materials

- To date TG5 X has largely focused on encapsulants.
- We are looking ahead to other materials & components, e.g., backsheets, cables, clips.
- Characteristics of interest, e.g., embrittlement/cracking, adhesion, ...
- Give us your feedback on what is relevant & most needed.
- Could examine material interactions.

Methods

- Improve methods and understanding for other materials/components (benchmark test T, E<sub>a</sub>, r&R).
- Methods for hot climates (desert or tropical locations, i.e. aid IEC 63126).
- Correlating artificial and natural weathering.
- Use of water spray during UV weathering.
- Combined stress testing, e.g. Köhl et. al.
- Diurnal based accelerated test sequence (similar to ASTM D7869).
- Accelerated aging test sequence, e.g., MAST at DuPont.
Getting Involved… Including Regional TG5 Efforts

There are three regional TG5’s. Each group focusing on different supporting activities (experiments). You may participate/follow more than 1 of the groups. 😊

- TG5 “X” (encapsulants; now also looking ahead).
  We welcome participants from other regions!
  Contact: David MILLER <David.Miller@nrel.gov>

- TG5 China (encapsulants & backsheets).
  Contact: Carol CHEN <chenxinx@cei1958.com>

- TG5 Japan (sequence of tests; MiMo study; encapsulant delamination).
  Combined work with TG2 & TG3.
  Contact: Tsuyoshi SHIODA <Tsuyoshi.Shioda@mitsui-chem.co.jp>

See: http://www.pvqat.org (PVQAT effort) also: http://pvqatastaskforceqarating.pbworks.com (minutes, references, attachments, meeting recordings)
There has been fantastic participation in TG5.

Thank you to the many participants for your ongoing support!!

- If interested in TG5 activities or the experiments, please contact the corresponding regional leader. (See regions slide)

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

Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.
“PVQAT TG12: The Contamination (Soiling) of Solar PV”

David Miller

PV Reliability Workshop
Denver West Sheraton
February 28, 2018, 5 minutes.

*See also: PVRW Session10 (Soiling). Thurs March 1, 10:00-12:00.*
Task Group 12-1 (sensors and the monitoring of soiling)
• Contributed to IEC 61724-1 (quantifying effect of soiling on PV systems).
• Contact: YuePeng DENG <Yuepeng.Deng@FIRSTSOLAR.COM>.

Task Group 12-2 (solutions for cleaning)
• Much recent interest. Goal: module cleaning standard (manual & robotic methods).
• Contact: Lin SIMPSON <Lin.Simpson@nrel.gov>.

Task Group 12-3 (antireflective and/or anti-soiling coatings)
• Recent focus on abrasion.
• Web study group, including abrasion and characterization methods.
• Goal: abrasion test standard, e.g., suite of PV specific methods.
• Goal: artificial soiling test standard, e.g., used for R&D purposes.
• Contact: David MILLER <David.Miller@nrel.gov>

Task Group 12-4 (modeling/analysis of effects of soiling on PV systems)
Example: analysis of power production data from PV installations
Contact: Leo MICHELI <Leonardo.Micheli@nrel.gov>
TG12-2 Develop Broad Based Cleaning Standard(s)

Identify and develop the scientific basis and methods for qualifying cleaning practices for PV modules

Expand and augment as needed present methods:

- PV Module Abrasion, *e.g.*, IEC 62788-7-3. Abrasion Test for PV
- Module Integrity, *e.g.*, IEC 61215 (2016) represents a quality characteristic with regard to the module's mechanical stability and compliance with electrical parameters.
  - *E.g.*, IEC 61730 PV module requirements for electrical and mechanical operating safety during its entire expected service life.
- Window Cleaning, *e.g.*, ASTM work item WK58123 https://www.astm.org/DATABASE.CART/WORKITEMS/WK58123.htm.

In general, cleaning by hand, high pressure water, dry brushing, or using robots all have intrinsic advantage and disadvantages. *Ultimately, the industry needs agreed upon best practices and perhaps standards for PV module cleaning so that module and plant warrantees are jeopardized.*
TG12-3 Proposed IEC 62788-7-3 PV Abrasion Standard

Suite of Proposed methods:

• **Falling sand test, *e.g.*, DIN 52348.**
  Simulate abrasion resulting from common low velocity impact events.

• **Forced sand impingement, *e.g.*, MIL-STD-810G or ASTM G76.**
  Simulate abrasion resulting from infrequent, intense storms.

• **Machine abrasion (dry & slurry, linear & rotary), *e.g.*, ASTM D2486**
  Simulate abrasion resulting from field use (especially cleaning).

**Machine abrasion** of primary concern for AR/AS coatings (most damage from cleaning).
Simulate abrasion resulting from field use (especially cleaning).

**Sand tests** anticipated to be of concern for backsheets.

**Contact:** David MILLER <David.Miller@nrel.gov>.
Site Locations for the Field Coupon Study

1. Sacramento, CA, Mediterranean agricultural location.
2. Mesa AZ, ASU, hot desert suburban location.
3. Mumbai India, IIT, tropical wet (monsoon) & dry with heavy urban soiling.
4. Kuwait City, KISR, hot desert with high sandstorm frequency.
5. Dubai U.A.E., DEWA, hot desert with dew cycles and sandstorms.

Many thanks to all the partner locations that have volunteered to support this effort!
Specimens & Treatment of the Field Coupon Study

- 10 different specimen types are being deployed (coated, uncoated references)

- 4 cleaning/treatment methods for the coupons (which is most abrasive?)

- Coupons return to NREL at years 1-5 to quantify degradation

- Coupons that are not cleaned will provide ability to analyze dust and to perform evaluation of coating effectiveness

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<tr>
<td>Dry brush clean monthly</td>
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<tr>
<td>Sponge/squeegee/water</td>
<td></td>
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<tr>
<td>Handheld pressurized</td>
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</table>
PV Modules May Be Contaminated By Biological Species!

- Biological species (e.g. fungi) have been observed on veteran modules (Sacramento, CA and Argenbühl, Germany) and field coupons (Sacramento).


- On PV, bio-species can collect organic & inorganic matter (nutrients or shelter).

- Literature: fungi can secrete acid, etch glass. Not observed to date in field study.

- On PV, bio-species affect accumulation, retention (cementation), and cleaning.

- DNA sequencing identified the alternaria genus of ascomycetous fungi.

- Will compare species population, contamination interactions, and efficacy of cleaning.
The 2018 Soiling Workshop

- **Previous events** have been in October, hosted by DEWA, Dubai (UAE)
- Will be sending out **survey by March 1, 2018** for site selection and date

**Potential hosts (volunteers, so far)**
- NREL, Golden CO, USA
- Arizona State University, Phoenix AZ, USA
- Research Institute for Solar Energy and New Energies (IRESEN) Morocco
- Others?

**Potential dates**
- In conjunction with other conferences?
- Fall 2018 (September, October, November?)

**Potential topics (including...)**
- Impact of soiling on PV performance
- Soiling related module reliability issues
- Reducing soiling impact on PV production
- Advanced coatings durability in deserts
- Manual and Robotic Cleaning Issues

**Contact:** Lin SIMPSON: Lin.Simpson@nrel.gov
The TG12 Monthly Webinar Series

- **TG12 webinars** constitute a online conference spread throughout the year.
- Organizers:
  - David MILLER (NREL), Greg SMESTAD (Sol Ideas Tech.), Russ JONES (KACARE), Mike VAN ISEGHEM (EDF)
- Presently >200 participants are following the webinars.
- References & recordings are shared through the PB Works website.
  See: http://pvqataskforceqarating.pbworks.com/w/page/109737652/Soiling%20and%20Dust%20Webinars

- FY18Q1 topics:
  - Cleaning of PV modules/ Drone cleaning (2018/1/09)
  - Studying soiling in an environmental dust wind tunnel/ Soiling monitoring (2018/2/13)
  - Satellite monitoring & subsequent accumulation analysis of airbourne PM (2018/4/10)

- We are looking for speakers on topics including:
  - Cleaning of PV, CSP
  - Economics of soiling
  - Experiences at installations in challenging locations
  - Monitoring of soiling
  - AR/AS coating technology

- Contact: Greg SMESTAD <smestad@solideas.com>
After years of interest, there has been fantastic participation in TG12. Thank you to the many participants for your ongoing support!!!

If interested in TG12 activities or the experiments, please contact the corresponding topic leader. (See topics slide)

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

Your questions and feedback are much appreciated! Please help me to cover the important details & perspectives.
2nd International Workshop on
the Sustainable Actions for “Year by Year Aging” under
Reliability Investigations in Photovoltaic Modules

SAYURI-PV 2017 Workshop Report

Keiichiro Sakurai
Tadanori Tanahashi
RCPV, AIST, Japan
SAYURI-PV 2017 had been held as a Satellite Meeting of PVSEC-27.

Date: November 11th – 12th, 2017

Venue: Ryukoku University, Seta Campus (Building 8)
1-5 Yokotani, Seta Oe-cho, Otsu, Shiga 520-2194, JAPAN

Topics: We've focused on the evaluation methods of materials (including PV cell, polymers, metallization, and others) to assure the long-term reliability of PV modules.
SAYURI-PV 2017

[Agenda / Topics]
Session 1: Field Experience
  Annual Degradation Rates of Recent c-Si PV Modules
Session 2: Cell
  PID / IQE Mapping [Rear Side] / EL + I-V for Diagnostics / CIGS
Session 3: Metallization
  Al Paste for PERC Cells / Corrosion Mechanisms [DH / Acetic Acid]
Session 4: Polymer (1)
  Material Interaction / PAL Spectroscopy/ Fielded Module Analysis
Session 5: Polymer (2)
  Bifacial Modules / Degradation Behavior in Thailand & Japan / Quantification of Adhesion Strength
Session 6: General Discussion
Questions to Participants

- how to elucidate the “Equivalent Yearly Damage” in the materials used in PV modules?

- how to understand the “Interaction / Matching” among the materials used in PV modules?

Answer from Participants

- Unfortunately, we have not yet sufficiently accumulated the data to support the estimation of “Equivalent Yearly Damage”, in particular, on polymer materials.
SAYURI-PV 2017

Thanks to all presenters and participants !!!

60 Participants, 18 Oral Presentations

(Proceedings available only for PVRW / SOPHIA / SAYURI WSs participants)

November 11th - 12th, 2017 at Ryukoku Univ. (Otsu)
SAYURI-PV 2018 will be held in autumn 2018.
Date and Venue: TBD
Detailed information will be available by late April.

Please Check for updates at https://unit.aist.go.jp/rcpv/cie/index.html

Contact us at: sayuri-pv-sec-ml@aist.go.jp
Understanding PV Module Durability through Analysis of Fielded Modules and Sequential Accelerated Testing

T. John Trout
Global PV Reliability R&D Manager
DuPont Photovoltaic Solutions
February 28, 2018

For over 40 years
our material innovations have led the photovoltaics industry forward, and helped our clients transform the power of the Sun into power for us all. Today we offer a portfolio of solutions that deliver proven power and lasting value over the long term. Whatever your material needs, you can count on quality DuPont Photovoltaic Solutions to deliver the performance, efficiency and value you require, day after day after day…
Understanding PV Module Durability

– Through Analysis of Fielded Modules and Accelerated Sequential Testing

Models for module and component degradation
• What do we see in the field?
• What are we trying to predict in accelerated testing?

Understanding Module Durability Begins in the Field
• Understand both degradation of modules and components
• Global Field Program to assess degradation and aging
• 2017 Analysis and Case Studies
• Analysis of Backsheet Erosion
• Glass / Glass Operating Temperature

Accelerated Tests must Match Field Degradation
• Formalism: Sample / Stress / Measurement
• Sequential Tests Development and Results

Future Directions
Conclusions
DuPont PV Reliability: Global Organization – Broad Capabilities

**Labs**
- Experimental Station, Wilmington, DE
- Chestnut Run, Wilmington DE
- China Technical Center, Shanghai
- KSP Technical Center, Japan

**People**
- US, Europe, India, China, Japan

**Module Reliability**
- Fielded Module Evaluation and Analysis
- Outdoor Field Exposures – Fla, De
- PV module Fabrication and Characterization
- Accelerated Testing and New Test Method Development
- Broad Analytical Capabilities
- Fundamental Material and Polymer Science

Minimodule Fab  Measurement  Accelerated Testing
Model for Module and Component Degradation

1. Overall module performance – power loss
2. Degradation of components – degradation leading to defects seen in the field

IEA International Energy Agency, PVPS report
T13-01:2014

Two distinct regions for P loss
- Baseline degradation ~ 20%
- End of life Failure > 50%

Power Loss in the Field (Mean) ~ 0.5 – 0.8% / year

- Desert = 1.2%
- Tropical = 0.8%
- Temperate = 0.6%

Mean = 0.8%/year
- 25 years = 20%
- 30 year = 24%

Module Component Degradation

1. Overall modules performance – power loss
2. Degradation of components – degradation leading to defects seen in the field

Degradation builds over time until critical point is reached
- Polymer degradation increases – backsheets yellowing, loss of mechanical properties, loss of molecular weight, erosion, acetic acid formation
- Eventually point of degradation is high enough that failure occurs
  - Retained properties < stresses
  - Resulting in visual defects: cracking, delamination, yellowing, loss of thickness

EVA
- Acetic Acid Formation
- Increase in Yellowing
- Loss of Mechanical Properties
- Loss of Polymer Mwt
- Crack Growth and Propagation
Understanding Module Durability Begins in the Field

Use modules from the field to understand both the aging performance and degradation of modules and critical components and materials

- Excellent literature for power performance - NREL
- Few studies on components – especially backsheets

DuPont Field Assessment Program
- Study module and component degradation
  – develop data for backsheets
- Developed Visual inspection protocols
- Statistical analysis of fields and aggregate data
- Analysis and learning from case studies
- Select modules for extensive analytical analysis
- Collaborations with field partners
DuPont Global Field Assessment Program

Multi-step Inspection Protocol
- Documentation of location, age, climate, module, energy production, visual imaging, thermal imaging, IR spectroscopy,
- Defect categorization
- Select modules for further analysis

Defect Analysis and Statistics

Thermal Imaging IR camera identifying hot spots in modules

Backsheet identification and degradation using FTIR spectrometer
Data size more than doubled from 2016 to 1 GW
- All defects 22.3%
- Cell related defects 12%
- Backsheet defects 9.5%

2018 Analysis
1+ GW inspected

- Cell: 77.7%
- Backsheet: 9.5%
- Encapsulant: 12%
- Others: 1.3%
- Others: 0.4%

2018 Field Analysis and Database - Overview

Climate sample sizes 2018

- Temperate
- Tropical
- Hot
- All Climates

<table>
<thead>
<tr>
<th>Category</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installations</td>
<td>286</td>
</tr>
<tr>
<td>Number of panels</td>
<td>4,234,324</td>
</tr>
<tr>
<td>Average age (years)</td>
<td>3.3</td>
</tr>
<tr>
<td>GW</td>
<td>1.047</td>
</tr>
</tbody>
</table>
Cell and Metalization show less or small effect with Climate
Polymer Components (Backsheet and EVA) show stronger trend
• Hot arid > Tropical > Temperate
• Use Defect Rates to determine “harshness” of Climates?
• Dominant factors are likely Temperature and UV

1 Temperate cell defects are dominated by Snail Trails, likely due to sampling
Analysis of Defect Rates for Roof vs Ground Mounted Systems

Overall Higher defect rates for roof vs ground installations
- Backsheet defects are > 2.5X higher on roof systems
- Cell defects are similar for Roof and Ground

Differences are likely due to higher temperatures for roof systems
- Roof Systems are typically 15 °C higher than Ground Mounted
- This trend with temperature is similar to the effect seen in climates

Analysis of Defect Rate vs Backsheet

Backsheet defects increased by 27% vs 2016 Analysis

- Polyamide increased by 18%
- PVDF increased by 51%
- Glass / Glass starting to show up
- Tedlar rate unchanged
Analysis of Backsheet Defects vs Age

- Tedlar® makes up the oldest installations with lowest percentage of defects
  - Defect rate is low and not increasing over time
- PVDF and Polyester defect rate is high and is increasing with time

1. Front side yellowing due to inner layer chemical treatment
2. TPE, Weak inner layer adhesion led to delamination
3, 4, 5. Slight Front side yellowing
6, 7. BS delamination
Field Erosion Rates Results of Backsheet Outer Layers

Polymers degrade and lose thickness over time

Tedlar® PVF-based backsheets erode at a rate of 0.34 µm per year.
- Both 25µm and 38µm thick Tedlar® film layers will last over 30 years.

Other backsheets have erosion rates 3-5 times larger:
- Erosion rates for PVDF and PET are statistically different from PVF rate.
- Variation in rates for PVDF and PET could be due to different film compositions.
- A 25 µm PVDF outer layer is expected to erode below an acceptable protective level in 8 yrs.

Erosion measured by comparing SEMs from “under label” to exposed areas.
Polymer Erosion in Space – Measured Erosion

38 polymer samples loaded on exterior of the US Space Station
Samples faced into the direction of travel
Constant exposure to reactive atomic oxygen, UV, X-Rays for 4 years
PVDF, PET, PA and PMMA eroded significantly
Lowest erosion with white Tedlar® PVF

<table>
<thead>
<tr>
<th>Backsheet Polymers</th>
<th>Erosion Yield (X10^-25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White PVF</td>
<td>1.01</td>
</tr>
<tr>
<td>PVDF</td>
<td>12.9</td>
</tr>
<tr>
<td>PET</td>
<td>30.1</td>
</tr>
<tr>
<td>PA-6</td>
<td>35.1</td>
</tr>
<tr>
<td>PMMA</td>
<td>56.0</td>
</tr>
</tbody>
</table>

Erosion Yield = \( \frac{\text{Mass Loss (g)}}{\text{Area (cm}^2\text{)} \times \text{density (g/cm}^3\text{)} \times \text{fluence (atoms/cm}^2\text{)}} \)

White Tedlar® PVF showed the least erosion
- Similar trend to rate found from PV modules

http://www.asi.it/sites/default/files/attach/evento/de_groh_misse_presentation_italy_5-10-16_30_min.pdf
Backsheet Field Case Studies:

PVDF 5 Years: Cracking and Delamination
  • 69 installations, N America, 1 MW
  • Linked to loss of PVDF Mech Props

PET 9 Years: Cracking, Delamination, P loss
  • Arizona, 35 kW
  • Linked to polymer degradation

Polyamide 6 Years: Cracking, Yellowing
  • China, 22 MW
  • Cracks progressed in severity 1-4 yrs

Glass 10 Years: Cracking, Delamination
  • Arizona, 4 kW
  • Safety hazard

Glass 1 Year: Higher Operating Temp
  • China, 40 MW
  • Lower power output due to higher temp
Reduced Glass-Glass Power Output: Field Case Study in South China

- Initial year of operation: 2016
- Service Time: 13 months
- Location: Xuwen, Guangdong
- Date of inspection: Aug, 31, 2017
- # of modules: 150945
- System size: 40MW (4.8 G/G; 35.2 G/B)
- Mounting configuration: Ground open rack
- Fixed tilt or tracking: Fixed Tilt
- Backsheet: Glass; Polymer Backsheet
- Module Maker: Same for both types
- Technology: Poly-Si
- Surface: Grass/water
- Climatic conditions: Tropical

Summary
- Lower power generation for Glass-Glass modules
- G-G module shows some bending/bow ~10%
- Transparent pinholes found in G-G module with white EVA

Unframed G-G modules with 4 pads parallel to long edge
Analysis of Monthly Cumulative Power Generation Data

Data obtained for

a. Three G-G blocks: block 11, 13, 15
b. Two G-B blocks: block 12, 14

Time Period
Jan 1 to Aug 30, 2017

The standard deviation in power data is too high to show any differences
Comparing Daily Cumulative Power Data

- **Jan-Apr**
  Mean efficiency difference between G-G and G-B modules is **not statistically significant** (p=0.103 > 0.05 in paired t-test; difference of means = -4.7)

- **May-Aug**
  Mean efficiency difference between G-G and G-B modules is **statistically significant** (p=0.000 < 0.05 in paired t-test; difference of means = 65.14)

  - Peak Eff Δ in summer: 2.3%
  - Avg Eff Δ in summer: 0.95%
  - Avg Irradiation Δ: (May-Aug) – (Jan-Apr) = +40%

**Avg Eff Δ of 0.95% → Operating T difference of G-G vs G-B modules: 1.95°C-matches modelling results**

Temperature coefficient of $P_{max}$ for the G/G module* : -0.488%/°C, * Source: SAM, NREL & California Energy Commission
## Connecting and Comparing the Field to Accelerated Tests – Sample / Stress / Measurement

### Stress and Response Formalism – Response for Field and accelerated stressors

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stresses</th>
<th>Response [Measurement]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module</td>
<td>Power loss, IV curve, EL, Visual, Insulation</td>
<td></td>
</tr>
<tr>
<td>Cell</td>
<td>Contact Resistance, SEM, EL Image, Visual</td>
<td></td>
</tr>
<tr>
<td>Backsheet</td>
<td>Mechanical Properties, Adhesion, Color, Molecular Weight Change, Gloss, Visual</td>
<td></td>
</tr>
<tr>
<td>EVA</td>
<td>Color, VA content, Acetic Acid concentration, Visual</td>
<td></td>
</tr>
</tbody>
</table>

#### How can we Assess or Predict the Field Performance of New Materials?

<table>
<thead>
<tr>
<th>Field</th>
<th>Accelerated Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old Materials</td>
<td>X</td>
</tr>
<tr>
<td>New Materials</td>
<td>?</td>
</tr>
</tbody>
</table>

**Develop and validate new tests by correlating to the field Test using old (or as close as possible) materials and structures.**

**Compare performance in accelerated tests of new materials / structures to predict / estimate field performance**
# DuPont Sequential Tests

<table>
<thead>
<tr>
<th>Test 1</th>
<th>UV / DH / 3x (TC / UC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damp Heat</td>
<td><img src="image1.png" alt="Diagram" /></td>
</tr>
<tr>
<td>UVX, 90°C BPT</td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
<tr>
<td>1000 hours</td>
<td>542 hours</td>
</tr>
<tr>
<td>200 cycles</td>
<td>200 cycles</td>
</tr>
<tr>
<td>542 hours</td>
<td>542 hours</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test 2</th>
<th>DH/TC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damp Heat</td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Thermal Cycling</td>
<td><img src="image4.png" alt="Diagram" /></td>
</tr>
<tr>
<td>1000 hours</td>
<td>200 cycles</td>
</tr>
<tr>
<td>200 cycles</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test 3</th>
<th>UVX Water spray</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xenon Weatherometer: ASTM G155 or SAE J1960 protocols</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test 4</th>
<th>UV / DML / TC / HF</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV</td>
<td><img src="image5.png" alt="Diagram" /></td>
</tr>
<tr>
<td>DML 1</td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td>Thermal Cycling</td>
<td><img src="image7.png" alt="Diagram" /></td>
</tr>
<tr>
<td>1000 hours</td>
<td>1000X</td>
</tr>
<tr>
<td>200X</td>
<td></td>
</tr>
<tr>
<td>DML 2</td>
<td>Humidity Freeze</td>
</tr>
<tr>
<td>DML 3</td>
<td>1000X</td>
</tr>
</tbody>
</table>

## Rationale

Our #1 Test. Combines the most important stress factors in the field. Appropriate for component, minimodule, or full-size module testing.

Combines two important stress factors in a shorter test not requiring expensive UV equipment. Appropriate for full-size module testing.

Combines UV and rainfall simulation, common weathering test conditions in commercially available weatherometer.

Combines UV and Temperature cycling with the dynamic stresses of Dynamic Mechanical Load (DML)
Module Accelerated Sequential Test (FAST MAST)

6 months duration

1000 hours

Damp Heat

542 hours 90°C BPT

UVX

Thermal Cycling

200X

542 hours 90°C BPT

UVX

Thermal Cycling

200X

542 hours 90°C BPT

UVX

Thermal Cycling

200X

50 hours 90°C BPT

UVX

Shortened MAST Sequential Test

- Higher intensity UV Xenon exposure
- Higher 90°C BPT with shortened time
- Results are equivalent to original MAST.

1000 Hours in a Humidity Chamber
Amounts to > 25+ years worth of stress

600 Thermal Stress Cycles
Mimics thermal stresses seen in the field

1676 Hours in a UVX Chamber
Amounts to ~20 years desert dose of UVA

Amounts to > 25+ years worth of stress

Mimics thermal stresses seen in the field

Amounts to ~20 years desert dose of UVA
Sequential Test Results Compared to Field Results for Backsheets

Polyamide backsheet
Cracking
Cracked, 5 yrs (Spain)

PVDF backsheet
Cracking
Cracked, 5 yrs (Canada)

PET backsheet
Yellowing
Yellowing, 15 yrs (Japan)

Sequential Test DH/UV + x(UV/TC)

Field

DH 85C/85%RH UVA 1.2W/sqm (340nm), 70C BPT, TC 85°C ↔ -40°C, per IEC 61215
Comparison of Stress Tests to Field Results for Backsheet Degradation

<table>
<thead>
<tr>
<th>Stress</th>
<th>PPE</th>
<th>KPE</th>
<th>PolyAmide</th>
<th>TPT/TPE</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>Cracking Front Side Yellowing</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>Low defects</td>
<td>Effects of simultaneous and sequential stresses</td>
</tr>
<tr>
<td>Damp Heat (1000 hrs)</td>
<td>Slight Yellowing</td>
<td>No Change</td>
<td>Mech Prop Loss</td>
<td>No Change</td>
<td>Misses UV degradation</td>
</tr>
<tr>
<td>UV (4000 hrs)</td>
<td>Yellowing Mech Prop Loss</td>
<td>No Change</td>
<td>Mech Prop Loss</td>
<td>No Change</td>
<td>Misses hydrolysis and moisture</td>
</tr>
<tr>
<td>DH/UV/TC (MAST Sequential Test)</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>Cracking Front Side Yellowing</td>
<td>Yellowing Mech Prop Loss Cracking</td>
<td>No Change</td>
<td>Combines key stresses Gives best correlation</td>
</tr>
</tbody>
</table>

**Sequential Tests correlate better with degradation seen in the field**

- Combine most important stress factors
- Use Stress levels / dosages that match field exposures
- Accelerate with highest temperature **but** do not produce degradation not found in the field
New Accelerated Sequential Dynamic Mechanical Load Test

Designed to better simulate the Field by combining Sequential Testing and with Dynamic Load

**Protocol**
- **UV exposure**: 65kWh/m² on the front
- **DML 1**: 1000 cycles of ±1500 Pa of loading @ 1/6 Hz
- **DML 2**: 1000 cycles of ±1500 Pa of loading @ 1 Hz
- **TC200** = Thermal Cycling, -40°C ↔ 85°C, ramp and hold *per IEC62782*, 200 cycles
- **HF30** = Humidity Freeze, 30 cycles
- **DML 3**: 1000 cycles of ±1000 Pa of loading @ 4 Hz (Optional)

Tests by independent 3rd party testing lab DNV-GL, USA
## Summary of Results

<table>
<thead>
<tr>
<th>G/G modules</th>
<th>G/Backsheet modules</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>UVA</strong></td>
<td>No change</td>
</tr>
<tr>
<td><strong>DML 1</strong></td>
<td>No change</td>
</tr>
<tr>
<td><strong>DML 2</strong></td>
<td>Slight delamination on front</td>
</tr>
<tr>
<td><strong>TC 200</strong></td>
<td>Delamination on front, encapsulant voids on back</td>
</tr>
<tr>
<td><strong>HF 30</strong></td>
<td>Severe delamination on front, multiple encapsulant voids on the back</td>
</tr>
</tbody>
</table>

*DML 3 not performed*

Glass-Glass modules show delamination induced by mechanical load combined with UV exposure, thermal cycling and humidity

- Due to rigidity and non-breathability allowing trapping of degradation products
Future Directions

Field Investigations

- Continue to expand data sets and analysis to understand failures and degradation mechanisms
- Deeper understanding of degradation mechanisms through chemical and physical analysis of fielded modules and comparison to accelerated testing
- Analysis of component / material degradation and power loss

Accelerated Testing

- Continue to use field results to develop new and better accelerated tests
- Develop shorter, more highly accelerated and predictive sequential tests

Materials and Components

- Use field results and accelerated tests to better understand component and module performance and design better backsheets and films
Conclusions

To understand PV Module durability and performance over time

- Consider – module, components, and materials
- All of the components of a module must be durable and perform over time
- Fundamental importance of field results
  - Understand degradation, aging mechanisms, and defects
  - Basis and guide for accelerated test development
- Importance of carefully designed accelerated tests
  - Correlate to the field (not induce new degradation modes)

Combining field results with accelerated tests to evaluate and give insights on how today's new material will perform in the future

Using these tools can result in even better modules, components, and materials that will last and perform longer than those we are studying from the field today.
DuPont PV Reliability R&D Group

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Axel Borne
Tom Felder
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Yushi Heta
Hongjie Hu
Rahul Khatri
Sherly Kurian
Steve MacMaster
Nancy Phillips
Randi Ress
Kaushik Roy Choudhury
Kate Stika
John Trout
Bao Ling Yu
Correlation of Field Performance and Artificially Aged Modules due to IEC 61215 & Qual Plus

PV Reliability Workshop 2018

Cara Libby (EPRI) and Will Hobbs (Southern Company)
February 28, 2018

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0007137.
Objective: Advance the state of the art in terms of module wear-out degradation prediction certainty with an emphasis on correlating field-aged and accelerated-aged module degradation data

Tasks
- Identify host site with spare modules that meet specific technology, age, quality, and availability criteria
- Artificially age 36 modules at the SSRC following the IEC 61215 and Qualification Plus testing standards
- Perform non-destructive evaluation at intermediate steps, followed by on-sun testing
- Destructively test failed modules at Sandia’s PV Systems Reliability Group and Microsystems Science and Technology Center (MESA)
- Use financial modeling to compare LCOE benefits of novel accelerated aging protocols
Project Team

<table>
<thead>
<tr>
<th>Organization</th>
<th>Project Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPRI</td>
<td>Project management and reporting</td>
</tr>
<tr>
<td>Southern Company</td>
<td>Host site funder, field measurements</td>
</tr>
<tr>
<td>Southern Research</td>
<td>Project host, module non-destructive evaluation</td>
</tr>
<tr>
<td>Sandia National Laboratories</td>
<td>Statistical data analysis, module destructive evaluation, economic analysis</td>
</tr>
</tbody>
</table>
Module Characterization

- Spare modules from a commercial plant in the U.S. Southwest were shipped to the SSRC and characterized.

- Sample set observations
  - Multiple power ratings: 285 W and 290 W
  - Defects and unique manufacturing signatures, cracks, dark spots, etc.
  - At least two distinct backsheets identified based on appearance, thickness, etc.
  - Potential variation in encapsulant based on light transmission

Initial screening revealed several non-uniformities.
Accelerated Aging Progress

**IEC 61215**
- 10 of 12 modules completed Oct. 2017
- 2 TCHF modules expected Mar. 2018

**Qual Plus**
- 12 modules (Batch 1) completed in late-Feb.
- 12 modules (Batch 2) expected Jun. 2018
Continuous Monitoring – SSRC Outdoor Test Facility

- 10 IEC 61215 modules are currently on-sun
- Stratasense online IV curve tracers (installed on half of test modules) collect data every 10 minutes

Grid-connected Enphase microinverters

Stratasense IV tracer
Continuous Monitoring – Commercial Host Plant

- Modules were installed in 2012
- 12 online Stratasense IV curve tracers were installed on 6 strings in Oct. 2017
  - Autonomous gateway is solar-powered with battery, cellular modem, irradiance sensor, and micro-computer
  - Zigbee wireless protocol for communication between gateway and individual tracers
  - Curve trace data are collected hourly

- Kipp and Zonen pyranometer collects irradiance data, which are correlated with long-term satellite irradiance data
In-field Imaging – SSRC

- Outdoor EL images were taken after IEC 61215 modules were placed on-sun
  - Images were compared with indoor EL
  - Modules were checked for damage due to handling between lab and field

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crack</td>
</tr>
<tr>
<td>B</td>
<td>Multiple cracks</td>
</tr>
<tr>
<td>C</td>
<td>Broken cell</td>
</tr>
<tr>
<td>D</td>
<td>Dark cell</td>
</tr>
<tr>
<td>E</td>
<td>Busbar defect</td>
</tr>
<tr>
<td>F</td>
<td>Backsheet scratch</td>
</tr>
</tbody>
</table>
### Agreement between lab and in-field image defect counts

Agreement between lab and in-field image defect counts is very good, with only 5 of 40 total defects (12.5%) missed in the in-field images.

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Crack</td>
<td>Multiple cracks</td>
<td>Broken cell</td>
<td>Dark cell</td>
<td>Busbar defect</td>
<td>B.sheet scratch</td>
</tr>
<tr>
<td>Lab Defect Count</td>
<td>24</td>
<td>2</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>In-Field Defect Count</td>
<td>22</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>
In-field EL Imaging – Commercial Host Plant

- In-field EL images taken of 72 sample modules in Year 4 of plant operation
- Imaging repeated in Year 5
- Dark cells and busbar defects were compared between the two years*

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>D (Cells)</th>
<th>D (Modules)</th>
<th>E (Cells)</th>
<th>E (Modules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 4</td>
<td>2</td>
<td>2</td>
<td>37</td>
<td>23</td>
</tr>
<tr>
<td>Year 5</td>
<td>3</td>
<td>3</td>
<td>45</td>
<td>28</td>
</tr>
</tbody>
</table>

*The earlier scans used a ground-mounted tripod, which introduced focus and alignment issues, so other defects could not be compared with high confidence.
In-field EL Imaging – Commercial Host Plant

New defects are present in the Year 5 images. The number of modules affected by busbar defects increased from 32% of modules in Year 4 to 39% in Year 5. Additional investigation is planned.

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Dark cell</td>
</tr>
<tr>
<td>E</td>
<td>Busbar defect</td>
</tr>
</tbody>
</table>

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Data Analysis for IEC 61215 (8 Modules)

Analysis Pathways
- SSRC indoor lab progression of IEC 61215 sequence
- SSRC indoor lab vs. SSRC outdoor testbed
- SSRC outdoor testbed vs. commercial plant modules

Evaluations considered
- Voc
- Isc
- Max power
- Fill factor
- Shunt & series resistance
IEC 61215 Analysis: IV Curve Evaluations (Indoor)

- TC200 and TCHF modules both exhibit:
  - Voc: minimal change
  - Max power: minimal change
  - Isc: decrease of ~1.5%
IEC 61215 Analysis: IV Curve Evaluations

- No significant changes in normalized performance between indoor and outdoor IV measurements
  - Outdoor Isc values match with final indoor Isc values
  - Outdoor Voc results are significantly lower than final indoor Voc results
- Scaling to STC using temperature coefficients may be source of Voc discrepancy
IEC 61215 Analysis: IV Curve Evaluations

- TC50HF10 modules have lower Isc than TC200 modules
- Scaling to STC using temperature coefficients may be affecting Voc

PV plant modules operating in the field for 5 years at the commercial plant show similar, but slightly lower short-circuit current than the IEC 61215 test modules during initial monitoring period.
Next Steps

- Complete aging test sequences for remaining IEC 61215 modules and Qual Plus modules
- Install remaining modules on-sun at SSRC
  - Conduct EL imaging on all modules
  - Install remaining Stratasense IV tracers
- Complete data analysis for all modules, including comparison with plant degradation
- Conduct LCOE analysis
Together…Shaping the Future of Electricity

The information, data, or work presented herein was funded in part by the Office of Energy Efficiency and Renewable Energy (EERE), U.S. Department of Energy, under Award Number DE-EE0007137.

The information, data, or work presented herein was funded in part by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
Appendix: Plan for Correlating Accelerated Aging with Field Aging Data (1)

Step 1: Correlate flash test data from the manufacturer at the time of shipment with flash test data collected on spare modules with further flash data collected throughout the Qual Plus test sequence.

Reasonable correlation of $P_{\text{max}}$, $I_{\text{sc}}$, and $V_{\text{oc}}$ between the factory flash test and our flash test; lowest $I_{\text{sc}}$ module flashed lowest in both the factory test and in our test, and $P_{\text{max}}$ and $V_{\text{oc}}$ were one of the lowest

All spare modules meet manufacturers specifications and tolerances for $P_{\text{max}}$, $I_{\text{sc}}$, and $V_{\text{oc}}$ but $I_{\text{sc}}$ outliers

Color-coded representation of $I_{\text{sc}}$ and $V_{\text{oc}}$ versus $P_{\text{max}}$ indicating modules selected for IEC 61215 testing
Appendix: Plan for Correlating Accelerated Aging with Field Aging Data (2)

Step 2: Correlate individual I-V sweep data from Qual Plus samples with samples still in the field at the commercial plant using real-time I-V curve collection at both sites. Qualitative and quantitative changes of these I-V curves between field-aged and lab-aged modules will then be compared and correlated on a continuous basis, which will give us information to derive degradation rates.
Appendix: Plan for Correlating Accelerated Aging with Field Aging Data (3)

Step 3: Historical power production data (multiple variables) from the commercial plant will be correlated with future power production data from the accelerated aging samples after the Qual and Qual Plus testing are completed to derive degradation rates.

Example variable (inverter combiner currents) for six different combiners (input to just one inverter)
Appendix: In-Field EL Equipment

- Tripod with an articulating center column with ball head and a separate extension mount (Vanguard Alta Pro 263AB 100, Manfrotto 259B)
  - alignment marks made on all adjustment points, and fixed-length pieces of cord tied between two pairs of legs on the tripod
- Camera (Olympus E-PL7, NIR filter removed from sensor)
  - Used inexpensive wireless remote shutter release
- 1000 nm longpass filter and holder (Edmund Optics #84-766, #83-340)
  - allowed for capturing single images without needing to subtract a dark image to remove background light
- Lens (Navitar 12 mm F/1.8 1” 6MP, #1-24420)
  - provided better transmission than consumer lenses that we tested
  - For proper focus, a custom mount was fabricated from a lens mount adapter (Fotodiox C-MFT), which then replaced the original mount plate on the camera
- Camera settings: ISO-800 to ISO-1600, and exposure times of 15-20 seconds. Lens aperture of f/2.8 to f/4.0.
- 60V, 15A benchtop dc power supply (BK Precision 1902B)
- AC power from vehicle inverters or a portable battery + inverter (Bioenno Power BPP-M720)
  - Inverter power limits often limited dc current to 4-6A, despite ratings that should have allowed for higher current

Module being imaged (A); adjacent module (B); camera (C), centered above the module; tripod center column, extension, and ball head (D); cord between bottom legs of tripod with mark that is aligned with gap in modules (E); second cord (F).

Original camera lens mount plate (left) and modified adapter (right). Four 2mm diameter holes (red arrows) drilled in the adapter matching locations of the screw holes in the original mount. Notches (indicated by red dashed lines) cut in the rim of the adapter allow clearance for the screw heads.
Appendix: Example Defects Not Detected in the In-field EL – SSRC

<table>
<thead>
<tr>
<th>Defect Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crack</td>
</tr>
<tr>
<td>B</td>
<td>Multiple cracks</td>
</tr>
<tr>
<td>C</td>
<td>Broken cell</td>
</tr>
<tr>
<td>D</td>
<td>Dark cell</td>
</tr>
<tr>
<td>E</td>
<td>Busbar defect</td>
</tr>
<tr>
<td>F</td>
<td>Backsheet scratch</td>
</tr>
</tbody>
</table>

No defects with partially or fully darkened areas of cells were missed in the in-field images.
Module defect trends from >6GW of operational PV

2018 PV reliability workshop

Rob Andrews
rob.andrews@heliolytics.com
Company Overview

- Heliolytics specializes in aerial infrared audits of PV assets
- Heliolytics has provided inspections of over 6GW of projects globally
- Heliolytics operates on commercial rooftop to large scale utility assets
- Heliolytics uses proprietary manned aircraft sensor systems and analysis software
Aircraft inspection process

Create Digital As-Builts → Aerial Inspection → Data Analysis → Reporting
Data Capture
Data Capture
Data Capture
Data Capture

• Acquired from manned aircraft

• All data capture at irradiance greater than 600 W/m\(^2\)

• Technical attributes compliant to NREL best practices document

• Capture time is optimized for consistent meteorological conditions during inspection
  • 50 MW capture time ~30 min
Machine Vision Analytics
Data Analytics

- Artificial Intelligence (AI) tools provide a powerful methodology for detection of faults
- Provides accurate localization and classification of detected defects
- Converts from an analog dataset into a digital dataset
Aircraft inspection for asset optimization
Helioltyics fault database

- Opt-in database including:
  - Fault occurrences
  - Site age
  - Module Manufacturer
  - Site region
  - Other metadata

- Includes sites from 100kw to 200MW+
Data presented

• **Assumptions**
  • Faults categories are reduced to 4 main categories
  • Thin-film excluded
  • Includes data from troubleshooting and routine maintenance scans
  • The majority of sites are <4 years old

• **Work to be done**
  • Filtering of visible anomaly defects
  • Filtering of troubleshooting vs. routine maintenance
Cumulative Distribution Function - All

More Faults than median

Fewer faults than median

Median

Faults detected on site
Cell Faults

- Cell faults are caused by hot-spots which may be caused by inherent module damage or surface fouling.
- Heliotyics reports include data to discern between the two, however this dataset does not.
- It can be seen that there is a much higher occurrence of hot spots on sites within the full dataset:
  - More damage is caused to modules in closer proximity to people.
  - Cleaning of these sites is more difficult.
Sub-module faults

- Most common fault mode leading to warranty claims
- Has a measurable energy impact
  - Payback for module replacement including labor and module purchase:
    - X years or X% over a 15 year project life
- Can be caused by sub-string damage or diode failure

Rule of thumb fault level where a warranty claim makes financial sense
String faults and energy loss

- “String” faults or faults related to balance of system failures account for the majority of the occurrence of non-functional modules and of energy loss
- The total line includes a combination of all faults found on the site
- The energy loss line is the combination of assumed energy loss due to each fault on the site

Rule of thumb point where the revenues of yearly energy recovery are greater than the costs of aerial inspections
String faults and energy loss

- There is a large difference in string failure rates between the full dataset and the dataset filtered to sites of only 4MW+
  - Note that these statistics treat each site as a single unit, so the faults/MW may be similar
  - String failures do have a crossover, showing that larger failure levels are more common
Conclusions

• Aircraft inspections provide a valuable tool for high-accuracy detection of module faults

• Helioltyics is building a database of system faults to allow industry-wide trends to be analyzed

• This presentation provides an initial view into the results from this database, showing that sites across all classes have a median energy-weighted fault rate of 0.5%
Heliolytics

Dr. Rob Andrews

rob.andrews@heliolytics.com
Outdoor Electroluminescence and Hot Spot Analysis of Crystalline Photovoltaic Modules

Stefan Wendlandt, S. Koch, B. Litzerburger, C. Sobottka, L. Podlowski
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PI Photovoltaik-Institut Berlin AG, Wrangelstraße 100, 10997 Berlin, Germany
Outline

- Why do we need large scale power plant analysis and why are we using electroluminescence (EL) in field measurements?
- What are the EL systems PI-Berlin is using and what are the advantages and disadvantages?
- How operate modules with broken cells and what is influence on their IV-Curve?
- What is influence of permanent high temperatures on electrical insulation protection?
Handling the tasks

Data generation

Data analysis

Data interpretation
Data generation: Tripod

- Flexible
- High resolution
- Easy to transport (airplane)
- Little human resources
- Detail image is possible

- Only a few images per power plant (low statistics)
Data generation:
Two camera system on rails

+ More modules per image
+ Good resolution
  - Redesign for each power plant
  - Bulky transport
  - High human resources

Source: Fladung Solartechnik GmbH
Data generation: Drone based photovoltaic inspection

- Many modules per image
- Flights during rain are in progress
  - Flight time only up to 20 min
  - Flight-licenses are necessary

Source: Fladung Solartechnik GmbH
Data analysis: Supporting steps

Images or videos → Module identification

→ Crop and equalize → Result processing

Failure detection
Data analysis: 100 % EL (rail system) of a 6.5 MW PV power plant

- Single module evaluation
- 25 000 EL images
Data analysis: Image examples

Statistical location of cells with isolated fragments

Frequency

low → high
Data interpretation: Isolated cells #1

- Typically cells break in parallel to the bus bars.
- The isolated cells operate in reverse bias of their IV-characteristic and heats up.
- The effect is comparable to a partly shadowed solar cell.
Data interpretation: Isolated cells #2

- Better blocking behavior in reserve bias
- The cell with lowest current limits the cell string current
Data interpretation: Isolated cells #3

- **Worst case:** one cell is broken! If more cells are broken the power loss depends on the percentage of isolated cell fragments and the number of broken cells.

<table>
<thead>
<tr>
<th>Cell 1: “2”</th>
<th>Cell 1: “2” and cell 2: “2”</th>
<th>Cell 1: “1+2” and cell 2: “2”</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Table 1" /></td>
<td><img src="image2" alt="Table 2" /></td>
<td><img src="image3" alt="Table 3" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>P (W)</th>
<th>V (V)</th>
<th>I (A)</th>
<th>P (W)</th>
<th>V (V)</th>
<th>I (A)</th>
<th>P (W)</th>
<th>V (V)</th>
<th>I (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.962</td>
<td>-0.44</td>
<td>-0.001</td>
<td>-1.851</td>
<td>-0.44</td>
<td>-0.001</td>
<td>-2.790</td>
<td>-0.47</td>
<td>-0.001</td>
</tr>
<tr>
<td>-0.915</td>
<td>11.01</td>
<td>-0.001</td>
<td>-1.887</td>
<td>11.01</td>
<td>-0.001</td>
<td>-2.770</td>
<td>11.01</td>
<td>-0.001</td>
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<tr>
<td>-0.993</td>
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<td>-0.001</td>
<td>-1.817</td>
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<td>-0.001</td>
<td>-2.790</td>
<td>11.01</td>
<td>-0.001</td>
</tr>
</tbody>
</table>

28/02/2018  NREL-Workshop  12
Data interpretation: Isolated cells #4

- Major hot spot’s after mechanical stress at the bus bar area are in IR visible -> higher hot spot risk.
- The broken cell shows a lower parallel resistance -> local short circuits.

reverse IV-characteristic of broken cell

\[ R_p \downarrow \]
Data interpretation: Isolated cells #5

- Cells with a high local current in reverse bias show a higher hot spot temperature compared to cells with homogeneous current in reverse bias.

\[ T_{\text{max}} = 189\,\text{°C} \]
\[ T_{\text{mean}} = 106\,\text{°C} \]
- high local current
- high local temperature

\[ T_{\text{max}} = 122\,\text{°C} \]
\[ T_{\text{mean}} = 114\,\text{°C} \]
- homogeneous current
- homogeneous temperature
The electrical insulation protection of backsheet foils depends on the permanent stress temperature. For ≤ 80°C no risks, for ≤ 120°C it can be a risk and for ≤ 160°C high risk. -> delamination, discoloration, melted foils -> electrical isolation loss.
Data interpretation: Isolated cells #7

- The hot spot temperature at cracked cells depends on the system topography
  - Module inverter reduce the risk at lower isolated cell fragments

percentage of isolated cell fragment 75%

percentage of isolated cell fragment 25%
Summary

- Electroluminescence is a powerful diagnostics tool for (huge) photovoltaic power plants. With-it almost all kinds of defects can be made visible (cell grid interruption, PID, broken cells) and it can be used nearly weather independent.
- Different EL systems are used and adjusted according to the specific project. The drone inspection shows the biggest potential in the future.
- Cells having (broken) isolated parts operate in reverse bias of their IV-characteristic part and heats up. The effect is comparable to a partly shadowed solar cell.
- Typically cells break in parallel to the bus bars. Major hot spot’s after mechanical stress at the bus bar area are visible in IR.
- Permanent high temperature heated backsheet foils can show a loss in their electrical insulation protection.
- The hot spot risk depends on the pv system topography. Micro inverters can limit the hot spot risk.
Thank you for your attention!
Inspection – maintenance of PV-systems

Quality control

In Germany in 2016

- 41.9 GWp installed PV
- 37.5 TWh solar power

- Is this the maximum output?
- Optimal return of investments, optimal supply with renewable solar power
**Inspection – methods**

AIM – inspection of modules in the field = WITHOUT dismounting, transporting, handling the modules

1. **Methods** – quality control of PV-installations – aIR-PV-check, metering, IV-tracer, IR+EL
2. **Selection of module failures** – PID, PV-modules with precracked cells, edge isolation
3. **Degradation study** – cleaning PV-modules
4. **Statistic** – module failures
alR-PV-check

alR-PV-check + EL-imaging of PV-plant
PV-systems - IR-Thermography
alR-PV-check
= inspection of PV-plants with IR-camera from the air

OBSERVATIONS
Case study I – Potential induced degradation - PID

Definition of defect ratio

\[ k = \frac{\text{no. of PID-affected cells in a string}}{\text{no. of cells in a string}} \]

Example:

24 cells in a string PID-affected
1200 cells / string \[ \Rightarrow k = 2\% \]

Power evaluation on string level

\[ P_{\text{string,est}} = n (1 - k) P_{\text{nom}} \]

\[ P_{\text{nom}} = 245 \text{ W} \]
\[ n = \text{number of module in a string} \]
\[ k = \text{defect ratio} \]

Uncertainty:

\[ \Delta P_{\text{string}} = P_{\text{est.string}} - P_{\text{meas.string}} \]
\[ \Delta P_{\text{max.string}} = 20.9\% \]
\[ \Delta P_{\text{string}} = 5.0\% \]

Case study I – Potential induced degradation - PID

Distribution of defect ratio and performance ratio on string level

Performance ratio $PR_{DC}$ - defect ratio $k$

Monitoring data - IR-imaging data

Case study II – Mechanical loading of PV-modules

Cleaning of PV-systems
Case study II –
Mechanical loading of PV-modules
Cleaning of PV-systems

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PV Reliability Workshops, Lakewood, CO, February 27 – March 1, 2018, Buerhop
Case study II – Mechanical loading of PV-modules

Wind and snow loads


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Case study II – Mechanical loading of PV-modules

Testing in the lab

Test facility
- Module mounting system
- Over- and underpressure
- EL-imaging (InGaAs-camera, 100 Hz)
- Strain gauges
- „Mobile flasher“

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Case study II – Mechanical loading of PV-modules

Simulating subsequent „normal“ operating conditions

- $v_{\text{wind}} = 55 \text{ km/h}$
  - $h_{\text{snow}} = 5 \text{ cm (wet snow)}$ to 20 cm (fresh snow)
- $v_{\text{wind}} = 96 \text{ km/h, storm}$
  - $h_{\text{snow}} = 15 \text{ cm (wet snow)}$ to 60 cm (fresh snow)
- $v_{\text{wind}} = 124 \text{ km/h}$

Simulating subsequent “normal” operating conditions $v_{\text{wind}} = 55 \text{ km/h}$, $v_{\text{wind}} = 96 \text{ km/h, storm}$, $v_{\text{wind}} = 124 \text{ km/h}$.

Case study III – Edge effects
Case study III – Edge effects

Humidity ingress at the edges

Summary

Statistical analysis of IR-inspections of PV-systems

140 PV-systems – 180,000 modules – 50 MWp
Grid-connected, open-area, rooftop, and others
Crystalline + thin-film modules, kWp- and MWp-PV-systems
Operation time: 0.5 to 6 years
Germany and Southern Europe

aIR-PV-check:
2% substring-failures + 6% module irregularities
THANK YOU FOR YOUR ATTENTION!

ACKNOWLEDGEMENT
ZAE Bayern gratefully thanks the German Federal Ministry for Economic Affairs and Energy (BMWi) for financial funding of this project.
Renewables Key Performance Indicator (KPI) & Off Taker Tech. Compliance

2018 Photovoltaic Reliability Workshop (PVRW) | Denver, CO | Feb 27 – Mar 1 2018

Pramod Krishnani, Performance Engineering Manager, Asset & Risk Management
Content

1. Definition & Significance of KPI
2. Lifecycle of Solar Asset Investment – Owner’s Perspective
3. Prevailing KPI – Owner’s Perspective
4. Visual Demonstration of Fleet KPI
5. Conclusion
A **Key Performance Indicator (KPI)** is a measurable value that demonstrates how effectively a renewables project is achieving key technical & financial performance excellence.

- Consolidated & assured view of performance for different Internal business groups
- Driving force to measure & improve technical & financial performance gain
- Increases certainty of identifying systematic & irregular issues
- Affirmation to Financial Investors/ off-takers & enables focus on important issues
- Enables perf. & optimization team to capture low hanging fruits & monitor on going issues
Lifecycle of Solar Asset Investment – Owner Perspective

Asset Management (Center of knowledge)

Operation & Maintenance Group

Performance & Optimization Engineering Group

KPI (Key Performance Indicator) (Performance Monitoring)

Technical Off-taker/Investor Compliance Reporting
- PPA Energy Forecasting
- Plant Performance PPA Compliance Guarantee Report
- Investor Portfolio Performance Reports

DCS, Production Log
CMMS

Communication of KPI to optimize monitoring & improve detection

Reporting & Financial Improvement Feedback
Collaboration, feedback & knowledge sharing

O&M Group

Comprehensive Performance Monitoring

Operation Service Delivery

Deterioration and Maintenance

Design/Performance Standards

Procurement

Construction

Commissioning

Engineering & Design

Demand/Load Forecasts

Funding/Economic Modeling

START

End/Restart

Renewal/Replacement

Decommission

Identify Need Objective/Risk

Lifecycle of Solar Asset Investment – Owner Perspective

4

(1) DCS: Distributed Control System; (2) CMMS: Computerized Maintenance Management System; (3) RBI: Risk Based Inspection; (4) RCM: Reliability Centered Maintenance; (5) RCA: Root Cause Analysis

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Prevailing KPI – Owner’s Perspective

Asset Development & Financial Modeling Prediction (Lifetime MWh & Revenue) – P50

Construction, Commissioning, Performance Acceptance Testing, IE approval & hand over to Asset Management

Pre – Asset Management hand over phases

Measured

Actual Revenue Meter Production (MWh)

Baseline IE Benchmark – Prod. (MWh)

Actual Insolation (kWh/m²)

Baseline IE Benchmark – Insolation (kWh/m²)

Actual PV Panel Temp (deg C)

Baseline PV Panel Temp (deg C)

Module Temp Coeff. %/deg C

Improvement in accuracy

Measured

INVESTMENT PERFORMANCE INDEX

IPI

WEATHER PERFORMANCE INDEX

WPI

OPERATIONAL PERFORMANCE INDEX

OPI

S-POWER An AES and AIMCo Company

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Demonstration KPI

WATERFALL DEMO
Conclusion

THANK YOU, QUESTIONS?

CONTACT INFO, PRAMOD KRISHNANI, PERF. ENGG. MGR, SPOWER, PKRISHNANI@SPOWER.COM
Quantifying and mapping PV soiling at scale

Michael G. Deceglie, Leonardo Micheli
Denver West Sheraton, Lakewood (CO), USA
March 1st, 2018

2018 PV Reliability Workshops
Quantifying soiling risk

Our industry has benefited from typical meteorological year (TMY) data

Can we come up with a similar tool for soiling?
Quantifying PV soiling

Michael G. Deceglie
Goal: Use historical PV data to inform planning

- We’re already collecting the data we need, in PV production data
- To unlock the potential:
  - Globally Scalable
  - Statistically rigorous
  - Flexible
Two part calculation

Operational data
Metadata

Model PV System

Performance metric
(example: temperature corrected PR)

Extract soiling

Soiling loss
Confidence interval
Extraction should handle varying detail/quality in data and model
Steps

1. Detect cleaning events
   – This divides data into intervals

2. Fit the slope for each interval
   – Yields a daily soiling derate
   – Also get an uncertainty in each slope and intercepts

3. Use soiling interval slopes/intercepts to probabilistically generate soiling profiles (Monte Carlo)

4. Calculate irradiance-weighted soiling ratio for each Monte Carlo realization

5. Calculate confidence intervals from the Monte Carlo results
Step 1: Detect cleaning events

Example subset

Performance Metric

Step 1: Detect cleaning events

- Apply rolling median
- Detect upward steps
- **No need for precipitation data**
Step 2: Extract slope and intercept for each interval
Step 2: Extract slope and intercept for each interval

- Robust slope estimation needed for anomalous data
Step 2: Extract slope and intercept for each interval

- Robust slope estimation needed for anomalous data
- Solution: Theil-Sen estimator
  - Consider lines between all pairs, take the median slope
Step 2: Extract slope and intercept for each interval

- Robust slope estimation needed for anomalous data
- Solution: Theil-Sen estimator
  - Consider lines between all pairs, take the median slope
Step 2: Extract slope and intercept for each interval

- Robust slope estimation needed for anomalous data
- Solution: Theil-Sen estimator
  - Consider lines between all pairs, take the median slope
- Keep track of slope, uncertainty, and intercept
Step 3: Probabilistic profiles

- Capture uncertainty in slope and cleaning magnitude
Step 4: Irradiance weighted soiling ratio

- Raw insolation
- Derated insolation
- Daily performance
- Soiling derate
Step 5: Confidence interval

95% confidence interval

P50

Insolation-Weighted Soiling Ratio
Validation

- Applied calculations to the clean module in a soiling station
- Bias is likely in the station soiling ratio, due to co-soiling of modules between cleaning
Conclusion: quantification

Validated scalable method for quantifying soiling directly from PV generation
• No need to know soiling rate or have reliable precipitation data
• Flexible and scalable, automatically captures uncertainty

M. G. Deceglie, L. Micheli and M. Muller *IEEE JPV*, 8:2, pp. 547-551 (2018).
doi: 10.1109/JPHOTOV.2017.2784682
Mapping PV soiling

Leonardo Micheli
The map contains data from 83 sites in the USA:
- 41 soiling stations (square markers);
- 42 full-scale PV systems (triangular makers).

Map available at: [www.nrel.gov/pv/soiling.html](http://www.nrel.gov/pv/soiling.html)
## Soiling Stations and PV Systems

<table>
<thead>
<tr>
<th>Soiling Station</th>
<th>PV System</th>
</tr>
</thead>
</table>
| Consists of two cells / modules:  
  • one is cleaned regularly  
  • one is left to soil naturally. | Soiling is extracted from PV performance by comparing:  
  • The **electrical output** of the system  
  • The **expected output**, determined by using the irradiance and atmospheric data from the National Solar Radiation Database (NSRDB) |

Soiling is determined by *comparing the electrical outputs of the two PV devices.*

### Electrical output

| Short-circuit current | Maximum power-point data |

### Filter conditions

| 11 AM to 1 PM, POA > 500 W/m² | NSRDB clear-sky days |
PV Module Soiling Map

Available at: www.nrel.gov/pv/soiling.html
For each site, the map shows:

- Years of operation, and County
- Mean **Soiling Ratio**, and Uncertainty;
- Median **Soiling Rate**, and Soiling Rate range.

Map available at: [www.nrel.gov/pv/soiling.html](http://www.nrel.gov/pv/soiling.html)
Soiling Ratio is reported as insolation-weighted mean of the daily ratios:

- Lower impact if soiling is accumulated in low-insolation period
- High impact if soiling is accumulated in high-insolation period.
Soiling Map: Soiling Rate

Daily rates of change in soiling ratio during dry periods (>14 days), expressed in %/day.

**SRate = 0 %/day**
in clean conditions

**SRate < 0 %/day**
in presence of soiling

- Soiling rate is reported as **median** of the soiling rates occurring on each site.
- Soiling rate range: the **97.5th** and the **2.5th** percentiles of the soiling rate distribution
Sources of Uncertainty

Electrical output:
• Soiling stations use short-circuit current.
• PV systems use maximum power-point data.
  Maximum power-point data are more affected to nonuniform soiling [1].

Time considered:
• Soiling stations data are limited to 11 AM to 2 PM period only.
• PV systems are considered all day.
  Soiling ratio is lower at higher angles of incidence [2].

More uncertainty sources:
• Cleaning schedule of the soiling station is not defined.
• PV systems:
  • May be affected by clipping
  • Irradiance is sourced from satellite-based data
  • Different inverters may behave differently.

Five macro-regions, based on Environmental Protection Agency airborne regions:

- **Hawaii (HI)**
- **Northeast (NE):** Connecticut, New Jersey
- **Southeast (SE):** Florida, Georgia, Maryland, North Carolina
- **Southwest (SW):** Arizona, California (excluding Southern California counties), Colorado, Nevada, New Mexico, Texas
- **Southern California (SC):** Counties: Imperial, Kern, Los Angeles, Orange, Riverside, San Bernardino, San Diego, San Luis Obispo, Santa Barbara, Ventura
Regional Analysis: Results

Southwestern states experience highest level of soiling, Southern California in particular.
Regional Analysis: Results

Previous investigations show good correlations between soiling ratio and particulate matter (PM) concentration (i.e. mean concentration of particles suspended in air). [3]

Regions with higher PM are those that experience most soiling.

Regional Analysis: Results

The average length of the dry period had good correlation with soiling as well.

Regions with the longest dry periods are those with the lowest Soiling Ratios.

Longest dry period ➔ Highest soiling
Conclusions

A soiling map reporting data from > 80 sites has been presented. The map shows soiling ratio and soiling rate data from both soiling stations and PV systems.

Initial regional analysis shows different behaviors among the various regions.

Regional particulate matter and rainfall trends seem to match soiling.

The map will be updated as new national and international data become available.
Thank You

www.nrel.gov

Michael G. Deceglie, michael.deceglie@nrel.gov
Leonardo Micheli, leonardo.micheli@nrel.gov

Soiling Extraction Model:
M. G. Deceglie, L. Micheli and M. Muller IEEE JPV, 8:2, pp. 547-551 (2018).

Soiling Map:
www.nrel.gov/pv/soiling.html
Soiling Modeling and Dust Removal

Bing Guo
Texas A&M University at Qatar

NREL PV Reliability Workshop. March 1\textsuperscript{st}, 2018. Lakewood, CO.
Acknowledgements

- **Co-authors:** Wasim Javed, Ben Figgis, Chang-Yu Wu, Jennifer Chesnutt, Hiroyuki Kawamoto, Klemens Ilse, Ahmed Ennaoui, Remond Yvés, Charles Pett, Jonathan Scheffe
- **Project Collaborators:** Ben Figgis, Chang-Yu Wu, Hiroyuki Kawamoto, Nicoleta Sorloaica-Hickman, Haitham Abu-Rub
- **Funding Agency:** Qatar National Research Fund (UREP15-083-2-030, NPRP7-987-2-372, UREP18-140-2-054)
Presentation Outline

• A few facts about solar PV soiling
• Mechanisms and modeling of natural dust accumulation
• Mitigation technologies with a focus on electrodynamic dust shield (EDS)
• Concluding remarks
Overview of Solar PV Soiling

- Airborne dust (e.g., PM2.5) is the best predictor of PV soiling loss. [Prog. Photovolt.: 25 (2017), 291-307]
- Natural dust accumulation 0.1-0.14 g m\(^{-2}\) d\(^{-1}\), at average airborne dust concentration 0.15 mg m\(^{-3}\). PV output decreases about 0.5%, with every 0.1 g m\(^{-2}\) dust covering a solar panel. [Sol. Energy. 142 (2017), 123-135]
- Soiling loss can be modeled as function of environmental variables. [Sol. Energy. 157 (2017), 397-407]
- We could potentially use electrodynamic dust shield (EDS), “traveling wave” or “standing wave”, to repel dust from solar panels. [J. Electrostatics 73 (2015), 65-70]

**Research Needs:**
- (1) Further understand natural dust accumulation on solar panels
- (2) Further understand performance of soiling mitigation technologies’ performance under realistic field conditions.
PV Soiling without Artificial Mitigation

UNABATED SOILING
Dust Deposition and Accumulation

Deposition: airborne particles falling onto solar panel

Removal: deposited particles being removed by rebound or resuspension

Air Flow with Dust

Accumulation = Deposition – Removal

Solar Panel
Deposition Mechanisms and Modeling

- Deposition Flux = (Airborne Dust Concentration) *(Deposition Velocity)

\[ V_d = u_* \eta_d l + V_g \]

- Total Deposition Velocity
- Deposition Due to Gravity
- Deposition Due to Turbulence

Function of Particle Size
Function of Particle Size & Friction Velocity

Bing Guo. PVRW, 03/01/2018. Lakewood, CO.

ASME Proceedings
doi:10.1115/ES2016-59390
Deposition Model Agrees with Experiment

Experimental deposition velocity and model results for 10-μm dust particles

Removal via Rebound or Resuspension

“Inverse time law” of resuspension

Main factors of removal
- Particle size
- Wind speed
- Relative humidity
- Surface properties
- Tilt angle


Bing Guo. PVRW, 03/01/2018. Lakewood, CO.
Diurnal Variations of Deposition and Resuspension

Diurnal patterns of meteorological conditions and dust deposition/accumulation rates at a Doha test site

IRSEC 2017 Proceedings
Nighttime Processes: Dew Formation and Drying

• Water condensation
  – Partial washing
  – Dust caking and cementation
    • Enhanced adhesion to solar panels
Modeling Objectives and Approaches

• Objectives
  – Long-term prediction of soiling loss (state of the art)
  – Short-term prediction of soiling loss (work in progress)

• Approaches
  – Models
    • Linear regression; Semi-physical models; Artificial neural network models
  – Model input
    • Airborne dust concentration; Wind speed; Air humidity; Air temperature; Gustiness; Exposure time; .......
  – Model temporal resolution
    • 24-hour (state of the art)
    • 1-hour or finer (work in progress)
Example: Long-Term Prediction Application

- Results for a site in inland China ➔
- Prediction of long-term PV soiling loss for a site with meteorological data, using our linear regression model [SGRE2015 Workshop Proceedings]
- Dust concentration data unavailable, assumed to be 0.1 mg/m³
- Cleanness Index (CI) quantifies how clean the solar panel is, CI = 1 for a clean module

Three dry months predicted to be free of dust accumulation.
Short-Term Prediction Accuracy Still Poor

Long-term prediction looks quite good.

Better understanding of resuspension is needed to improve short-term prediction accuracy.

Short-term prediction can be quite inaccurate.
PV Soiling with Technological Intervention

MITIGATED PV SOILING
Mitigation Methods

• Passive methods
  – Surface coating
  – Tilt manipulation

• Active methods
  – Washing, wiping, brushing, etc.
  – Electrodynamic activation
Mitigation increases dust removal rate (compared unabated soiling)

Greater mitigation efficiency → greater economic benefits
Anti-Soiling Coatings

• Working principles: low surface energy, suitable surface morphology
• After-market coatings reported in literature
  – Metal oxide nanoparticles with polymer binder
  – Soiling reduction ranging 2% - 7%
  – Based on field test up to one year
• Factory-built coating (e.g., DSM anti-soiling coating)
  – No efficiency data available
• Other coating technology (e.g., TiO₂)?
Basics of Electrodynamic Dust Shield (EDS)

- Particle repulsion when (repelling) net body force exceeds the net surface adhesion force
- Body forces:
  - Coulomb force
  - Dielectrophoretic force
  - Image force
- Surface adhesion forces
  - Van der Waals force
  - Liquid bridge force (capillary force)
- EDS has both “traveling wave” and “standing wave” options

https://youtu.be/mZ1OZCOTwSU
EDS Dust Removal Efficiency

- Initial studies: high dust loading levels, high EDS efficiency

<table>
<thead>
<tr>
<th>Study</th>
<th>Dust Loading Levels (g m⁻²)</th>
<th>Equivalent Time of Soiling under Severe Conditions (d)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mazumder et al. [4]</td>
<td>6–78</td>
<td>20 – 260</td>
</tr>
</tbody>
</table>
EDS Dust Removal Efficiency

• Initial studies: high dust loading levels, high EDS efficiency
• But at lower dust loading levels, EDS efficiency is significantly lower

Bing Guo. PVRW, 03/01/2018. Lakewood, CO.
EDS Dust Removal Efficiency

- Initial studies: high dust loading levels, high EDS efficiency
- But at lower dust loading levels, EDS efficiency is significantly lower
- In the cyclic mode, EDS efficiency can further decrease significantly
Concluding Remarks

• Meteorological conditions play important role in soiling, with airborne dust being the dominant factor

• Long-term soiling prediction based on dust/meteorology data possible

• Feasibility (cost effectiveness) of soiling mitigation technologies yet to be determined
Thank You!
Waterless Web-monitored Soiling Monitoring Station

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Arizona State University
manit@asu.edu

Project Partners: EPRI & SRP
Funding Supports: SERIIUS/SunShot/DOE, EPRI & SRP
Site Hosts: Duke Energy, SRP & ASU
Motivation

Why waterless, online and redundant soiling station?

- Waterless: No need to replenish water in the tank
  - Lower labor cost and no need to monitor water level
- Online: No need of in-field data downloading
  - Lower labor cost
  - Data available anytime (real-time data)
  - Immediately detect DAS malfunctioning
- Redundancy: Data redundancy using four sensors instead of two
  - No loss of data due to malfunctioning of one of the four sensors
Outline

• Parameter to be Monitored for SLF Determination: Module $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?
• Design and data acquisition of soiling station
• Data collection in the field
• Data analysis
• Summary
Outline

• Parameter to be Monitored for SLF Determination: Cell $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?

• Design and data acquisition of soiling station

• Data collection in the field

• Data analysis

• Summary
Soiling Loss
Isc or Pmax?

Best method?

Parameter to be monitored

Uniform

Best method?

Cell/Module-Isc

Quantitatively accurate (temperature correction not necessary)

Module-Pmax

Semi-quantitatively accurate (temperature correction not necessary but string mismatch not accounted; Pmax temperature coefficient is irradiance level and age dependent; I-V tracer required)

Cell-Isc

Semi-quantitatively accurate (temperature correction necessary and string mismatch not accounted; multiple stations could partially address the string mismatch issue)

Non-uniform

Best method?

Module-Pmax

Semi-quantitatively accurate (temperature correction necessary and string mismatch not accounted; multiple stations could partially address the string mismatch issue)

All Strings-Imax

Quantitatively accurate if coupled with cell-Isc method (String Imax or Pmax from all inverters and no temperature correction necessary)

String mismatch factor to account for non-uniformity

$\text{SLF}_{\text{string } i} = \text{SLF}_{\text{cell-Isc}} \times \left( \frac{I_{\text{max-string } i}}{I_{\text{max-string best}}} \right)$
Outline

• Parameter to be Monitored for SLF Determination: Cell $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?
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Design Evolution @ ASU-PRL

So far, ASU-PRL has developed four different types of outdoor soiling stations:

- **Generation 1 (2010)** - Manual cleaning and data downloading: 18 mini-PV modules with small cells for 9 tilt angles (Demerit: small area cells – bird dropping issue)

- **Generation 2 (2014)** - Manual cleaning and data downloading: 10 large split-cell coupons with large area cells for 10 tilt angles (Demerit: manual data downloading)

- **Generation 3 (2015)** - Automated water-based web-downloading: 2 split-cell coupons with large area cells for 1 tilt angle (Demerit: Water-based cleaning)

- **Generation 4 (2016)** - Automated waterless web-downloading soiling station: 2 split-cell coupons with large area half-cells for 1 tilt angle (Demerit: None yet) – Focus of this presentation
Design Evolution of ASU-PRL Soiling Stations

Generation 1 (2010)

Generation 2 (2014)
Design Evolution of Soiling Stations

- **Generation 3 (2015)**
  - Water Sprayer
  - Water Tank (1.5 years)
  - Soiled split sensors

- **Generation 4 (2016)**
  - Split sensors with glass shutter
  - Split sensors without glass shutter

Note: US patent application filed for the Generation 4 station (licensing available from ASU)
4th Generation Design: Components

A. PV Cells/Sensors

B. Extruded Aluminum Frame and Aluminum Sheets

C. DAS Enclosure

D. Actuator and PLC Control Circuitry Enclosure

E. Battery Located Inside Enclosure: 12V, 12Ah

F. Adjustable Tri-pod Stand

G. 30W PV Module To Keep The Battery Charged
4th Generation Design: Automated Waterless Web-monitored

- Each station has two PV coupons and each coupon contains two half cells
- Left coupon (with glass shutter) “CLEAN”
- Right coupon (without glass shutter) “SOILED”
- A data logger collects and transmits data wirelessly from all four stations at 1 minute interval
- Typically, the glass shutter of the clean sensors opens once a day for about 2 minutes around solar noon at near-zero angle of incidence (Note: the shutter can be opened several times on clear sunny days to obtain loss due to higher angle of incidence)
4th Generation Design

Fixed Tilt

The collected clean and soiled data points of Isc are used to calculate the soiling loss factor and other useful ratios.

Different stages of operation

(Option: flip-opening or slide-opening of glass cover)
4th Generation
1-axis Tracking
Collected Data
No temperature correction is needed because: (i) all sensors are practically at the same temperature (white painted aluminum heat sink); (ii) the temperature coefficient of $I_{sc}$ is practically zero.

Midday shutter opening is recommended to reduce the angle of incidence effect on the soiling loss determination and to obtain the data at a high irradiance condition (> 600 W/m$^2$) which would mitigate the sensitivity limitation of the DAS.
Video of waterless soiling station: Fixed Tilt
Video of waterless soiling station: 1-axis Tracking
Station 2-CA, Pumpjack: Jan 17, 2016

Soiled 1
Soiled 2
Clean 1
Clean 2

Shutter opens/closes
Shutter opens/closes
## Useful Ratios

**6 x 6 Matrix**

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Sensor Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1/C2</td>
</tr>
<tr>
<td>2</td>
<td>S1/S2</td>
</tr>
<tr>
<td>3</td>
<td>S1/C1</td>
</tr>
<tr>
<td>4</td>
<td>S2/C1</td>
</tr>
<tr>
<td>5</td>
<td>S1/C2</td>
</tr>
<tr>
<td>6</td>
<td>S2/C2</td>
</tr>
<tr>
<td>7</td>
<td>CC1/CC2</td>
</tr>
<tr>
<td>8</td>
<td>S1/CC1</td>
</tr>
<tr>
<td>9</td>
<td>S2/CC1</td>
</tr>
<tr>
<td>10</td>
<td>S1/CC2</td>
</tr>
<tr>
<td>11</td>
<td>S2/CC2</td>
</tr>
<tr>
<td>12</td>
<td>CC1b/CC1a</td>
</tr>
<tr>
<td>13</td>
<td>CC2b/CC2a</td>
</tr>
</tbody>
</table>

- **b** = before shutter opening
- **a** = after shutter closing

---

**Shutter Closed**

- S1: Soiled 1
- S2: Soiled 2
- CC1: Clean Covered 1
- CC2: Clean Covered 2

**Shutter Opened**

- C1: Clean 1
- C2: Clean 2

**Useful Ratios**

- Useful Ratios: 1, 2, 3, 4, 5, 6, 7, 8, 9
- Not Useful Ratios: 10, 11, 12, 13
- Other Useful Ratios: 12, 13
### Usefulness of 13 Ratios

13 different useful sensor ratios can be obtained from the four sensors (2 clean & 2 soiled)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Sensor Ratio</th>
<th>Usefulness</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C1/C2</td>
<td>Sensor malfunction</td>
</tr>
<tr>
<td>2</td>
<td>S1/S2</td>
<td>Sensor malfunction</td>
</tr>
<tr>
<td>3</td>
<td>S1/C1</td>
<td>SLF1</td>
</tr>
<tr>
<td>4</td>
<td>S2/C1</td>
<td>SLF2</td>
</tr>
<tr>
<td>5</td>
<td>S1/C2</td>
<td>SLF3</td>
</tr>
<tr>
<td>6</td>
<td>S2/C2</td>
<td>SLF4</td>
</tr>
<tr>
<td>7</td>
<td>CC1/CC2</td>
<td>Sensor malfunction</td>
</tr>
<tr>
<td>8</td>
<td>S1/CC1</td>
<td>AS coating effectiveness*</td>
</tr>
<tr>
<td>9</td>
<td>S2/CC1</td>
<td>AS coating effectiveness*</td>
</tr>
<tr>
<td>10</td>
<td>S1/CC2</td>
<td>AS coating effectiveness*</td>
</tr>
<tr>
<td>11</td>
<td>S2/CC2</td>
<td>AS coating effectiveness*</td>
</tr>
<tr>
<td>12</td>
<td>CC1b/CC1a</td>
<td>Cemented/loose soil ratio#</td>
</tr>
<tr>
<td>13</td>
<td>CC2b/CC2a</td>
<td>Cemented/loose soil ratio#</td>
</tr>
</tbody>
</table>

* If the cover glass is coated with anti-soiling (AS) coating

# Provides cemented/loose soil ratio

b = before shutter opening

a = after shutter closing

Soiling loss factor (SLF) = \([\text{SLF1}+\text{SLF2}+\text{SLF3}+\text{SLF4}]/4\)  
(Daily SLF is the average of eight SLF values if the shutter is opened for about 2 minutes and the data is collected every minute; The average SLF cannot be trusted if ratios 1, 2 and 7 deviate from 1±0.01)

Slide-opening if ratios 12 and 13 are not needed.
Outline

• Parameter to be Monitored for SLF Determination: Cell $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?
• Design and data acquisition of soiling station
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• Data analysis
• Summary
Installed Waterless Soiling Monitoring Stations

- AZ-ASU
- CA-Pumpjack
- TX-San Antonio
- AZ-SRP
Installed Locations

Four soiling loss monitoring stations built at ASU-PRL have all been placed in various test fields:

- Station 1 is located at AZ-SRP - Rogers solar PV plant in Mesa, Arizona – set to 5° tilt.
- Station 2 is located at Duke Energy solar PV plant in Pumpjack/Bakersfield, California – on a single-axis tracker.
- Station 3 remained at ASU-PRL test field in Mesa, Arizona – set to 33° tilt.
- Station 4 is located at Duke Energy solar PV plant in San Antonio, Texas – set to 20° tilt.
Outline

• Parameter to be Monitored for SLF Determination: Cell $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?
• Design and data acquisition of soiling station
• Data collection in the field
• Data analysis
• Summary
Data Filtering

• \( C_1 \geq 0.6 \)
  – irradiance shall be higher than 600 W/m\(^2\)
• \( C_2 \geq 0.6 \)
  – irradiance shall be higher than 600 W/m\(^2\)
• \( \frac{C_1}{C_2} \geq 0.996 \) and \( \frac{C_1}{C_2} \leq 1.004 \)
  – No bird dropping
• \( \frac{S_1}{S_2} \geq 0.996 \) and \( \frac{S_1}{S_2} \leq 1.004 \)
  – No bird dropping
SLF: California

Pumpjack (Bakersfield), California: 1-axis
Jan 27, 2017 - Jan 12, 2018

- Sensors cleaned by cleaning crew
- Data filtered mostly due to cloudy days (<600 W/m²)
- Rain event above 1 mm considered

<table>
<thead>
<tr>
<th>Date</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/27/17</td>
<td>0.84</td>
</tr>
<tr>
<td>2/6/17</td>
<td>0.86</td>
</tr>
<tr>
<td>2/16/17</td>
<td>0.88</td>
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<tr>
<td>2/26/17</td>
<td>0.90</td>
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<td>3/8/17</td>
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</tr>
<tr>
<td>3/18/17</td>
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<td>8/15/17</td>
<td>1.24</td>
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<td>1.42</td>
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<td>12/13/17</td>
<td>1.44</td>
</tr>
<tr>
<td>1/2/18</td>
<td>1.46</td>
</tr>
<tr>
<td>1/12/18</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Average = SLF

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1/C1</td>
<td>3</td>
</tr>
<tr>
<td>S2/C1</td>
<td>4</td>
</tr>
<tr>
<td>S1/C2</td>
<td>5</td>
</tr>
<tr>
<td>S2/C2</td>
<td>6</td>
</tr>
</tbody>
</table>
Rain Gain Calculation

Rain Gain (%/mm) = 
\[
\frac{(((SLF_{ar} - SLF_{br}) / SLF_{br}) \times 100)}{\text{Rainfall}}
\]

Where:

\( SLF_{ar} \) = SLF after rain
\( SLF_{br} \) = SLF before rain
Effectiveness of Rain Cleaning: CA

Effectiveness of Rain Cleaning
Pumpjack/Bakersfield, California: Jan 27, 2017 - Jan 12, 2018

Rain Gain (%/mm)

-0.5
0
0.5
1
1.5
2

Rain Level (mm)

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

True RG potential unknown
Maximum RG potential
True RG potential unknown

Negative RG: Dirtier after rainfall
Rain event: > 1 mm Total rain events: 8

Rain Gain (%/mm) • SLF before rain • SLF after rain
Effectiveness of Rain Cleaning: TX

Effectiveness of Rain Cleaning
San Antonio, Texas: Jun 30, 2017 - Sep 1, 2017

- Maximum RG potential
- Negative RG: Dirtier after rainfall

Rain event: > 1 mm
Total rain events: 3

Rain Gain (%/mm)
- SLF before rain
- SLF after rain
Effectiveness of Rain Cleaning: AZ-SRP

Effectiveness of Rain Cleaning
AZ-SRP, Arizona: Sep 10, 2017 - Jan 16, 2018

- Rain Gain (%/mm)
- Rain Level (mm)

- Maximum RG potential
- True RG potential unknown
- RG negative: Dirtier after rainfall

Rain event: > 1 mm
Total rain events: 3

Rain Gain (%) before rain
SLF after rain

Rain Gain (%) after rain
Effectiveness of Rain Cleaning: AZ-ASU

Effectiveness of Rain Cleaning
AZ-ASU, Arizona: July 26, 2017 - Sep 21, 2017

Rain Gain (%/mm)

True RG potential unknown
Maximum RG potential

Negative RG: Dirtier after rainfall

Rain event: > 1 mm
Total rain events: 3

Rain Gain (%/mm) • SLF before rain • SLF after rain
Effectiveness of Anti-Soiling Coating

Average of Ratios S1/CC1, S2/CC1, S1/CC2 and S2/CC2

- Shutter glass \textit{without} anti-soiling coating
- Shutter glass \textit{with} effective anti-soiling coating (expected)
Outline

• Parameter to be Monitored for SLF Determination: Cell $I_{sc}$, Module $I_{sc}$ or Module $P_{max}$?
• Design and data acquisition of soiling station
• Data collection in the field
• Data analysis
• Summary
Summary

• A waterless web-monitored soiling monitoring station has been designed, developed and demonstrated at different sites
• Thirteen different ratios obtained from this station are useful for different analyses
• Data redundancy (four SLFs instead of just one) reduces data loss
• Rain gain is typically about 1%/mm at lower SLFs (thick soil layer)
• Rain gain is typically less than 0.5%/mm at higher SLFs (thin soil layer)
• Rain gain is typically negative (becomes dirtier) at rainfall below 2 mm (at high SLFs)

At lower SLF values, the rain gain is about 1% per mm

Maximum Rain Gain = 0.75-1.00 %/mm

CA
AZ
TX

Negative Rain Gain if < 2 mm
Questions?

Contact:
Mani G. TamizhMani
manit@asu.edu

https://PVreliability.asu.edu
Experience of PV Soiling in desert conditions of DUBAI

Jim Joseph John, Aaesha Alnuaimi, Ammar Elnosh, Marco Stefancich, Pedro Banda

Research & Development Center
DEWA
TABLE OF CONTENTS

• Why understanding soiling is important for Dubai?
• DEWA Research & Development Center
• Soiling rates on fixed tilt system
  • Methodology
  • Results
• Spectral effect
• Particle size and Chemical Composition
Why understanding soiling is important for Dubai?

Dubai Clean Energy Initiative

The Dubai Clean Energy Initiative aims to provide 7 per cent of Dubai's energy from clean energy sources by 2020. It will increase this target to 25 per cent by 2030 and 75 per cent by 2050.
Why understanding soiling is important for Dubai?

Solar Goal for Dubai

- **4000MW Solar PV**
- **1000MW Solar Thermal**
- **Solar Rooftop Program (Shams Dubai)**

“Solar PV on every roof by 2030”- DEWA
Why understanding soiling is important for Dubai?

MBR Solar Park

4000MW PV and 1000MW CSP in one location
Why understanding soiling is important for Dubai?

MBR Solar Park
DEWA Research and Development Center

Sub Heading

- long-term PV reliability test bed
  - Fixed Tilt
  - Single Axis Tracker
  - Multi Tilt structure
  - BIPV cube
Soiling rate study
Methodology

Soiling rate study

- A common approach is based on short-circuit current of the soiled module compared to clean reference [1] [2].

- MPP power considered to account for non-uniform soiling.

---


Methodology-1
Soiling rate study

12 modules were used for the study (tilted at 25° and orientated to the south):

- Mono c-Si (3)
- Poly c-Si (3)
- BF c-Si (3)
- Flex c-Si (1)
- CdTe (1)
- CIGS (1)
Methodology-2
Soiling rate study

• DC electrical parameters, module temperatures, and POA irradiance measured every 30 seconds.
• Data used in this study was from July 2015 to December 2016.
• The soiling rate extracted using the performance metric method described by Deceglie et al [3]:
  • PM calculated by temperature correcting the power measurements and comparing those to the daily plane-of-array irradiation.
  • Daily PM normalized with 95th percentile of observed values for PM at a given site for the consecutive non-cleaning days.
  • Number of non-cleaning days is calculated by taking each day in the data set between two cleaning events.
  • Theil-Sen estimator [4] is used for calculating the slopes for the non-cleaning day dataset and then taking the median values.
  • Theil-Sen estimator removes any anomalies in the data.

Results

Sub Heading

- The months Mar-16 and Apr-16 are excluded from the study due to the occurrence of a high number of cleaning events.
- Soiling rates have high seasonal dependence.
- Jan-16 and Feb-16 showed significantly less soiling rates than other months, while the rates seem to considerably increase in Oct and Nov 2016.
- Soiling rate in a month can be as low as -0.02% (Feb-16) and as high as -0.66% (Oct-16).
- Soiling rate can be very different for the same month across different years.
- Comparing the different PV module types, soiling rates for c-Si, Bifacial c-Si and mc-Si are very similar.
- However, rates for the Flexible mc-Si, CIGS, and CdTe modules are relatively higher.
• Soiling rates for c-Si, Bifacial c-Si and mc-Si modules were found to be very similar across the study period

• High rates for flexible mc-Si rate can be attributed to textured polymeric film front cover, while for thin-film modules can be attributed to the high bandgap property

<table>
<thead>
<tr>
<th>Type</th>
<th>Avg Soiling Rate</th>
<th>Min Soiling Rate</th>
<th>Max Soiling Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>C-Si</td>
<td>-0.22</td>
<td>-0.05</td>
<td>-0.5</td>
</tr>
<tr>
<td>Mc-Si</td>
<td>-0.21</td>
<td>-0.03</td>
<td>-0.52</td>
</tr>
<tr>
<td>Bifacial c-Si</td>
<td>-0.21</td>
<td>-0.03</td>
<td>-0.47</td>
</tr>
<tr>
<td>Flex mc-Si</td>
<td>-0.29</td>
<td>-0.04</td>
<td>-0.58</td>
</tr>
<tr>
<td>CIGS</td>
<td>-0.29</td>
<td>-0.1</td>
<td>-0.63</td>
</tr>
<tr>
<td>CdTe</td>
<td>-0.29</td>
<td>-0.02</td>
<td>-0.66</td>
</tr>
</tbody>
</table>
Spectral effect of dust on PV panels
Spectral Effect

Methodology

• Study Period: Nov & Dec 2017 (Low soiling season)
• 5 glass slide arrangement, placed parallel to PV panels – south facing and 25 deg tilt
• Location: 5 different locations in different parts of UAE
• the weight of slides with and without dust on the surface was measured using a microbalance
• the transmittance of the glass slides was measured before and after cleaning the slide, using UV-VIS spectrometer
Spectral Effect

Results

Al-Ain, UAE

Jabal Ali, UAE

MBR Solar Park, UAE

Week Number (Nov-Dec 2017)

Reduction of T(%)
Chemical Composition and Particle Coverage
Chemical Composition and Particle Coverage

Methodology

• Particle Coverage study
  • Study done on samples with dust deposited on glass slides
  • Images were taken on microscope
  • Use ImageJ to study the particle coverage

• Chemical Composition study
  • Dust collected from PV module surface
  • Instrument used - XRD
Particle coverage

Sub Heading

Al-Qouz
(Industry area)

Jebel Ali
(Thermal Power station, Port, Industries)

MBR Solar Park
(Desert)
Particle coverage

<table>
<thead>
<tr>
<th>Location</th>
<th>Week 2</th>
<th>Week 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-Qouz (Industry area)</td>
<td><img src="image1" alt="Graph" /></td>
<td><img src="image2" alt="Graph" /></td>
</tr>
<tr>
<td>Jebel Ali (Thermal Power station, Port, Industries)</td>
<td><img src="image3" alt="Graph" /></td>
<td><img src="image4" alt="Graph" /></td>
</tr>
<tr>
<td>MBR Solar Park (Desert)</td>
<td><img src="image5" alt="Graph" /></td>
<td><img src="image6" alt="Graph" /></td>
</tr>
</tbody>
</table>
Chemical Composition

Common Inorganic compounds found in dust samples other than Quartz

<table>
<thead>
<tr>
<th>Composition</th>
<th>Chemical Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>Al₂Si₂O₅(OH)₄</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>KAl₃Si₃O₈</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>NaAlSi₃O₈ – CaAl₂Si₂O₈</td>
</tr>
<tr>
<td>Pyrite</td>
<td>FeS₂</td>
</tr>
<tr>
<td>Dolomite</td>
<td>CaMg(CO₃)₂</td>
</tr>
<tr>
<td>Mullite</td>
<td>Al₆Si₄O₁₄</td>
</tr>
<tr>
<td>Calcium hydroxide</td>
<td>Ca(OH)₂</td>
</tr>
<tr>
<td>Anhydrite</td>
<td>CaSO₄</td>
</tr>
</tbody>
</table>

Jebel Ali (Thermal Power station, Port, Industries)

Al-Qouz (Industry area)
SUMMARY
SUMMARY

Soiling rate study

• The study aimed to start a benchmark for soiling rate estimation in the desert environment of Dubai & UAE

• Method using Theil Sen estimator was found to be the best method to estimate soiling rates reducing anomalies in the data

• 1.5-year data from 12 PV modules from different technologies in DEWA's OTF at MBR Solar Park were used

• Soiling rates based on Theil-Sen estimator applied for the daily normalized Performance Metric (PM) of each module during each non-cleaning period.

• The daily soiling rates for each month of the studied period was reported, and the seasonal dependence of the soiling rate has been shown from the monthly variations.

• Soiling rates can be significantly different for the same month between different years
SUMMARY

Spectral effect

• Study done for short duration – 5 weeks, low soiling season

• Places like AlAin do not show almost no spectral sensitivity whereas places like Jebel Ali, industrial area show high spectral sensitivity at approx. 400-500nm, about 6-7% higher than other wavelength ranges.

Particle coverage area and Chemical Composition

• It has been observed that high concentration of small particles (Clay sediments) are found on PV modules near industrial area and areas with high vehicular movement

• Presence of clay sediments are relatively less in desert regions but they tend to increase with time

• 9 same inorganic compounds were found in all the samples, study of the organic compounds are planned.
THANK YOU
Goal and Activities for PVQAT TG 11 (T, RH, V)

Scope: degradation and failure mechanisms of power conversion electronics.

Industry is asking for better understanding of:
- Failure mechanisms at the materials science level
- Results from field
- Designing appropriate tests for specific mechanisms
- Various test protocols in existence
- Learnings from related products
- Visualizing results
- Design for durability
- Nuisance trips
- How to testing components
- Wear out mechanisms
O&M Service Requests/Interventions

- Inverters highest O&M ticketed item
Actual and supplier-projected cost of ownership for four inverter types
Relative frequency of inverter component failures
Scope: degradation and failure mechanisms of power conversion electronics.

Industry is asking for better understanding of:
- Failure mechanisms at the materials science level
- Wear out mechanisms

FMEA to
- Understand failures we are looking at
- Step to assigning rate equations
# PVQAT TG3: Interaction of stress factors

<table>
<thead>
<tr>
<th>Component</th>
<th>Potential Failure Mode(s)</th>
<th>Potential Failure Mechanisms(s)</th>
<th>Failure Mechanisms Type</th>
<th>Critical Stressors (if applicable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit</td>
<td>Self-heating dielectric breakdown</td>
<td>Overstress</td>
<td>Vc, Ta, dV/dT</td>
<td>Ta, ripple Ic</td>
</tr>
<tr>
<td></td>
<td>Heat contraction of the dielectric leading to connection instability</td>
<td>Overstress</td>
<td></td>
<td>Temperature cycling and vibration Relative Humidity</td>
</tr>
<tr>
<td></td>
<td>Fatigue induced cracks in through hole solder joints</td>
<td>Overstress/Wear out</td>
<td></td>
<td>Ta, ripple Ic</td>
</tr>
<tr>
<td></td>
<td>Reduction in electrode area due to oxidation as a result of moisture absorption</td>
<td>Wear out</td>
<td></td>
<td>Relative Humidity</td>
</tr>
<tr>
<td>Short Circuit</td>
<td>Dielectric breakdown of oxide layer</td>
<td>Overstress</td>
<td>Vc, dV/dT</td>
<td>Ta, ripple Ic</td>
</tr>
<tr>
<td></td>
<td>Self-heating due to overcurrent</td>
<td>Overstress</td>
<td></td>
<td>Relative Humidity</td>
</tr>
<tr>
<td></td>
<td>Moisture absorption by Polymer</td>
<td>Wear out</td>
<td></td>
<td>Ta, ripple Ic</td>
</tr>
<tr>
<td></td>
<td>Rapid increase in leakage current due to the presence of iron particles in the dielectric layer, which originate from iron salt used in polymerization process of the electrolyte</td>
<td>Wear out/early wearout resulting from issues with manufacturing-process control</td>
<td>Vc, ripple Ic, Ta, Humidity</td>
<td>Ta, ripple Ic</td>
</tr>
<tr>
<td>Liquid Electrolytic Caps</td>
<td>Decrease in Capacitance and Increase in ESR</td>
<td>Aging of dielectric material</td>
<td>Wear out</td>
<td>Vc, ripple Ic, Ta, Humidity</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Prolonged use - T and V outside of rated values</td>
</tr>
</tbody>
</table>
PHOTOVOLTAIC SYSTEM POWER CONVERSION EQUIPMENT

DESIGN QUALIFICATION TESTING

82/1328/CD

COMMITTEE DRAFT (CD)

PROJECT NUMBER:
IEC 62093 ED2

DATE OF CIRCULATION:
2017-08-18

CLOSING DATE FOR COMMENTS:
2017-11-10

SUPERSEDES DOCUMENTS:
82/862/RR

IEC TC 82: SOLAR PHOTOVOLTAIC ENERGY SYSTEMS

TITLE:
Power conversion equipment for photovoltaic systems – Design qualification testing
Failed electrolytic capacitor (India)
Failed Aluminum electrolytic capacitor

Flashover

• Arc/discharge between e-cap and chassis observed
• The insulation between e-cap internals and outer layers of capacitor failed
• E-cap appears to have expanded (H₂ is byproduct of degradation process)
• Reducing clearance to the chassis, facilitating arcing
• The e-cap manufacturer, recommends to keep capacitors below 35°C and 75% RH.
• Stated in the spec sheet that e-caps exposed to water, high temperature and high humidity at atmosphere, or condensation, may fail
• Was the humidity recommendation maintained?
• Is this recommendation realistic?
• What is the failure mechanism when humidity goes up in this e-cap type (what is the moisture ingress path)
Dust internal to the inverters observed
Dust internal to the inverters observed

- Rain intrusion test
- Wind driven rain test
- Shipping vibration test
- Shock test
- Salt mist test
- Dust and sand test
- Mixed gas corrosion test
- Ammonia corrosion test
Michael Kempe guest Lecture: humidity ingress

<table>
<thead>
<tr>
<th>D₀ (cm²/s)</th>
<th>Ea₀ (kJ/mol)</th>
<th>S₀ (g/cm³)</th>
<th>Ea₂ (kJ/mol)</th>
<th>Reactive Ca absorption (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.33</td>
<td>47</td>
<td>0.16</td>
<td>5</td>
<td>0.047</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>Modeled K (cm/h³/²)</th>
<th>Modeled 25 y required width (cm)</th>
<th>Modeled 25 y equivalent time at 85°C/85% RH (h)</th>
<th>Modeled 25 y equivalent time at 45°C/85% RH (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denver, Colorado</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00087</td>
<td>0.40</td>
<td>900</td>
<td>1.2</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00103</td>
<td>0.44</td>
<td>1,000</td>
<td>1.4</td>
</tr>
<tr>
<td>Munich, Germany</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00096</td>
<td>0.45</td>
<td>1,100</td>
<td>1.5</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00107</td>
<td>0.47</td>
<td>1,200</td>
<td>1.7</td>
</tr>
<tr>
<td>Riyadh, Saudi Arabia</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00102</td>
<td>0.47</td>
<td>1,200</td>
<td>1.6</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00124</td>
<td>0.51</td>
<td>1,400</td>
<td>1.9</td>
</tr>
<tr>
<td>Phoenix, Arizona</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00128</td>
<td>0.56</td>
<td>1,700</td>
<td>2.4</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00153</td>
<td>0.61</td>
<td>2,000</td>
<td>2.8</td>
</tr>
<tr>
<td>Miami, Florida</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00199</td>
<td>0.84</td>
<td>3,700</td>
<td>5.3</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00225</td>
<td>0.90</td>
<td>4,300</td>
<td>6.1</td>
</tr>
<tr>
<td>Bangkok, Thailand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Open Rack</td>
<td>0.00228</td>
<td>0.96</td>
<td>4,900</td>
<td>6.9</td>
</tr>
<tr>
<td>Insulated Back</td>
<td>0.00258</td>
<td>1.03</td>
<td>5,600</td>
<td>7.9</td>
</tr>
</tbody>
</table>

- Conclusion: Moisture will get in

A sensitivity analysis cave about ±15% on K and Width, and ±30% on 25 yr equivalent time.
How to appropriately test for moisture ingress/corrosion

Failed EMI capacitor (PET PEN Material) - popcorning

Challenge to test for moisture ingress in a timely and realistic way

- Speed vs accuracy
- Discount non-relevant failures

2000 h 85°C/85 %RH DH
Two generation old MLPE device (three tested)

**Unpotted** device – reported to exhibit field failures by moisture ingress/corrosion

IEC 61215 humidity freeze 7 + IEC 60068-2-30 DB-7 damp heat cycle with cyclically pulsed power to drive corrosion, conductive anodic filaments, & simulate cold starts in damp environment

- At approximately 1040 h of stress, one device input open-circuited. Hard failure
- At approximately 1780 h, second device input resistance increases, especially in condensation (low T) part of the cycle. Soft failure (after drying the device, the device appears functional)
- Stress test ended after 12 weeks, detailed measurement of all devices (max power tracking, efficiency) in progress
- To be followed by failure analysis

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ramp 55°C/95% RH 3H</td>
</tr>
<tr>
<td>2</td>
<td>Soak 9 h</td>
</tr>
<tr>
<td>3</td>
<td>Ramp 25°C/95% RH 3H</td>
</tr>
<tr>
<td>4</td>
<td>Soak 9 h</td>
</tr>
<tr>
<td>5</td>
<td>Jump Step 1</td>
</tr>
</tbody>
</table>

Input: open circuit  
FA in progress
1 Generation old MLPE device (three tested)

**Potted device**
IEC 61215 humidity freeze 7 + IEC 60068-2-30 DB-7 damp heat cycle with cyclically pulsed power to drive corrosion, conductive anodic filaments, & simulate cold starts in damp environment

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
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<td>4</td>
<td>Soak 9 h</td>
</tr>
<tr>
<td>5</td>
<td>Jump Step 1</td>
</tr>
</tbody>
</table>

- No degradation through 12 weeks of stress test when viewed at maximum power during the course of stress testing.
- Efficiency testing shows reduced performance at low input power compared to unstressed control
- Work in progress to confirm statistical significance, to be followed by failure analysis attempt

![Irradiance steps used the test-case](image)

![Efficiency η (%)](image)
Thank you to the members of PVQAT TG 11...

Thank you for your attention

Please give me your business card to join PVQAT TG 11

www.nrel.gov

Publication Number
PV Inverter Scorecard
Michael Mills-Price PE
Head of Inverter Testing
PV Inverter Scorecard Presentation Outline

- Introduction to the PV Inverter Scorecard
  - Sample acquisition
  - Approach to testing

- Product Qualification Program (PQP) Overview
  - Inverter Performance Tests
  - Inverter Reliability / Resiliency Tests
  - Inverter Field Tests

- PV Inverter Scorecard Inclusions and Expected Release Date
  - Commentary on importance / relevance of tests
About DNV GL

DNV GL is the world’s largest independent energy & renewable advisory firm.

We have over 2500 energy experts. More than 1000 are focused on renewables.

DNV GL has advised over 5500 solar projects.

DNV GL has extensive lab testing capabilities across the globe to evaluate renewable energy products.

350 OFFICES

100 COUNTRIES

14,000 EMPLOYEES

Energy

Maritime

Oil & Gas

Software

Business Assurance

151 Year History
Information Sharing – The Target of the Inverter Scorecard

▪ What should you look for when selecting inverter products?
  – Performance
  – Resiliency

▪ How do you compare similar products?
  – Datasheet differentiation
  – Feature sets

▪ Project lifecycle and technology evolution
  – Will my inverter product be serviceable
  – Will suitable products be available when necessary

▪ Independent testing and evaluations
  – Reduce project performance risk
  – Improve system operations from onset
Inverter Variability and Need for Comparative Testing

- Manufacturer’s capabilities widely vary
  - Design guidelines / practices
  - Supply chain and component qualification
  - Manufacturing practices and quality processes
  - Equipment capabilities
  - Self certification

- Interconnection Rules and Regulations
  - Utilities requiring increased functionality from inverters
  - More severe operational response challenges (FW vs HW modifications)
  - Increased stress on inverter components and sub assemblies

- Cost Reductions and Market Pressure
  - Longer field operational lifetimes
Inverter Scorecard Inputs

- Device Performance and System Needs
- IEC 62093
- Field Failure Data
- Commercial Bus. Practices

Inverter PQP

Inverter Scorecard
Inverter Product Qualification Program (PQP)

Risk reduction (not elimination)

- **Comparative Testing**
  - Benchmark relative to other manufacturers
  - Important when making supply chain decisions
  - Reducing risk associated with new market entrants / new firmware / new products
- **Qualification Testing**
  - Pass / fail based criteria
  - Important for QA / QC testing
  - Reduction of OOB failures
- **Continuous Testing Process Refinements**
  - Alignment with emerging standards
  - Improvements based on field findings

1. Inform product suppliers of opportunities for product improvements
2. Inform “buy side” of market to product capabilities and performance indicators
Keeping the PQP Relevant to Market Needs

Manufacturers/Equip Providers

Product Submitted and Evaluated

Inverter Product Qualification Program

Product Perf & Rel Analysis

Downstream Partners

Feedback on Product Design and Improvements

Field Failure Data, Product Needs and Use Cases
Inverter Testing and Evaluation Approach

**Performance**
- Will it harvest available energy?
- Does it meet environmental and electrical requirements?
- Will it interoperate with other system components?
- Does it provide adequate interconnection flexibility?
- Do my design practices lead to optimized performance?

**Reliability**
- Testing helps to inform project lifetime projections
- How susceptible is it to environmental conditions (temperature / humidity)?
- How much design margin exists for main power path (Temp, Voltage, Current)?
- Do engineering design choices + manufacturing practices result in a quality product?
- Assists to provide independent data to better inform warranty reserve predictions

Laboratory + Field Testing
PQP -- Performance Testing
PQP Performance Testing Sequence

- Operational Envelope Characterization
- Energy Harvest
- MPPT Efficiency
- CEC Conversion Efficiency
- Multiple Inverter Interaction Testing
- Shading Performance
- DC Loading Ratio
- AFCI Robustness
- Data Accuracy / Integrity / Response Time
- System Start-up / Shutdown

MPPT Window

DC Operational Window

- Operational Envelope Characterization
- Energy Harvest
- MPPT Efficiency
- CEC Conversion Efficiency
- Multiple Inverter Interaction Testing
- Shading Performance
- DC Loading Ratio
- AFCI Robustness
- Data Accuracy / Integrity / Response Time
- System Start-up / Shutdown
Performance Testing -- Overview of Operational Envelopes

Takeaways:

- Inverter does not de-rate as function of AC Voltage (bottom left)
- Inverter does de-rate as function of input voltage (bottom right)
- Important for field energy harvest, design and stringing configurations
Performance Testing -- Direct Comparison of MPPT Efficiencies

Low to Moderate Irradiance Ramps

Moderate to High Irradiance Ramp Rates

PR EN 50530 MPPT Efficiency
Performance Testing -- Energy Harvest

- Conversion Efficiency * MPPT Efficiency
- Repeatable System response
- Total Energy Harvest
Performance Testing -- DC Loading Ratio

- System sizing default testing to 1.4
- Reliability impacts and warranty support
- Energy yield
- Transitions in and out of MPP tracking
## Performance Testing -- Data Accuracy / Integrity / Response Time

- **Coordinated Control**
  - IEC 61850-90-7 object models
  - Defined functions
  - Interconnection defined settings
- **Set-Point handling**
- **Accuracy Validation**
- **Response Time of System**
- **Interface Testing**
  - Tool to input data
  - Fidelity of data channel
  - Polling features
PQP -- Reliability Testing
PQP -- Reliability and Robustness Testing and Evaluations

- IEC 62093 Influences on Testing Approach
  - Module Level Power Electronics (MLPE)
  - String Level Power Electronics (SLPE)
  - Centralized Power Electronics

- Field Failure Data
  - AFCI False Trip

- Emerging Interconnection Needs
PQP -- Inverter Reliability / Robustness Testing

- Passive Environmental
  - Water ingress
  - Corrosion
  - Thermo-mechanical cycle fatigue
  - Electrolyte evaporation
- Powered Environmental
  - Stress testing
  - Full power cycling across stated temperature range
  - Health monitoring (DC ripple, THD, Saturation, etc.)
- Component and Sub-Assembly Design Margin
  - Thermal, Voltage, Power
  - Out of box failures
  - Early component wear out
Resiliency Testing -- Passive Environmental

- Damp Heat (85°C / 85 RH)
  - Identifies corrosion related mechanisms
- Temperature Cycle (TC--200)
  - Identifies weaknesses related to thermo-mechanical fatigue (solder joints, etc.)
- Humidity Freeze (85°C 85% RH → -40°C)
  - Identifies weaknesses in environmental protection

- All Samples are pre and post characterized to determine if exposure has resulted in component / system failure
Resiliency Testing -- Powered HTOL / LTOL

- Main Power Path Component Temps
- Inverter Power Response
- THD, DC Ripple, AC Waveform
- Inverter De-rating in AC power
- Component Temperatures
- Critical Insights into Operations
Resiliency Testing -- Powered Environmental Testing

- Comprehensive Mapping of Inverter Operational Landscape
  - DC voltage
  - AC voltage
  - Real and reactive power

- High / Low Temperature Operating Bias
  - Identifies thermally activated mechanisms including electrolyte evaporation.

- Electrical “Health Monitoring”
  - THD
  - DC ripple characteristics
  - Mis-operation

- Thermal Monitoring
  - Main power path components
  - De-rate verification

![AC Power and Temperature Graph](image-url)
Resiliency Testing -- Powered Thermal Cycling

Component Temperatures and Power (-40°C to +60°C)

- Temp. Setpoint [°C]
- DC Inductor Core [°C]
- DC Bus Capacitor [°C]
- AC Relay at PCB [°C]
- AC Inductor Core [°C]
- Output CM Choke Core [°C]
- Aux PS Xmir Winding [°C]
- Logic board Processor [°C]
- Ambient [°C]
- AC Power (W)
Powered Thermal Cycling -- Single Cycle Analysis

Power and voltages during Powered TC

- Power (W)
- Voltage (V)

Time (S)

AC Power

AC Voltage (V)

DC Voltage (V)
PQP -- Field Testing and Verification
Field Testing and Evaluations – PV USA

- Installation / Sun Time
- AFCI Response
- Ground Fault Testing
- Start, Operation, Energy Harvest
- Common Mode Noise / Harmonics
Field Testing Results and Findings

- Broad Spectrum of Field Testing Results
  - Energy Harvest
  - Power Quality
- Installation and Runtime Characteristics
  - Monitoring System Integration
  - Validation of Inverter Provided Data
Field Tests – Ground and Arc Fault

![Diagram of PV System with Test Locations and 15 Module PV Array]

### Figure 2: Ground Fault Test Matrix

<table>
<thead>
<tr>
<th>Test Resistance (Ohms)</th>
<th>Test Location in Array</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>550 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>500 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>450 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>400 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>350 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>300 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>250 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>200 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>150 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>100 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
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</tr>
<tr>
<td>50 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>10 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>5 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
</tr>
<tr>
<td>0 kOhms</td>
<td>Detected - Ground Fault Reported</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Unable to Detect</td>
<td>Detected - Ground Fault Reported</td>
<td></td>
</tr>
</tbody>
</table>
Testing – Analysis – Results

- Not all inverters are the same regarding design, workmanship, operation, and resiliency.

- Thorough product testing and analysis, combined with knowing your product and capabilities can greatly improve project performance and return on investment.

- DNV GL’s **PV Inverter Scorecard** is a tool designed to help you make more informed inverter product decisions.
Conclusions -- PV Inverter Scorecard

▪ Comprehensive evaluation of PV inverter products
  – > 30 products included
  – > 15 manufacturers

▪ Scorecard as a tool to aid in product decisions
  – Operations
  – Warranty reserve
  – Purchasing

▪ Expected Initial Release ‘Q2’ 2018
  – Subsequent releases every 18-24 months
Thank You

Michael Mills-Price PE
Head of Inverter Testing
Michael.Mills-Price@dnvgl.com

www.dnvgl.com

SAFER, SMARTER, GREENER
PV Component Reliability Distributions – Database and Insights

2018 PV Reliability Workshop

Geoffrey T. Klise, Olga Lavrova, Renee Gooding
Sandia National Laboratories

Janine Freeman, Andy Walker
National Renewable Energy Laboratory

March 1, 2018
Outline

- What kind of data are we collecting?
- Summary of reliability database
- Portfolio A (utility-scale)
- Portfolio B (DG)
  - Failure and Repair Distributions – insights into events and maintenance response
- Where the data can be used
  - SAM PV-RPM feature
  - O&M Cost Model
## PV System Data – DG and Utility Scale

<table>
<thead>
<tr>
<th>Maintenance Data</th>
<th>Performance Data</th>
<th>System Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Component</td>
<td>Energy production</td>
<td>Engineering and one-line diagrams</td>
</tr>
<tr>
<td>Fault or failure timestamp</td>
<td>Energy loss</td>
<td>Commissioning date</td>
</tr>
<tr>
<td>Repair timestamp</td>
<td>Performance model estimates</td>
<td>Component manufacturer and model/make detail</td>
</tr>
<tr>
<td>Equipment replaced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Repair under warranty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fault Code (inverter)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Narrative description</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(relationship to other components or external events)</td>
<td></td>
</tr>
<tr>
<td>Quarterly maintenance reports</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Reliability Database

Data compiled and analyzed up through December 2017

<table>
<thead>
<tr>
<th>Portfolio</th>
<th>Commissioning year</th>
<th>Data collection range</th>
<th>Number of PV systems</th>
<th>MW&lt;sub&gt;DC&lt;/sub&gt;</th>
<th>% of DG systems</th>
<th>% of utility scale systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2003</td>
<td>2003-2008</td>
<td>1</td>
<td>3.5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>B</td>
<td>2008-2009</td>
<td>2012-2014</td>
<td>2</td>
<td>1.75</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>C</td>
<td>2008-2016</td>
<td>2015-2016</td>
<td>180</td>
<td>578</td>
<td>3.4</td>
<td>96</td>
</tr>
<tr>
<td>D</td>
<td>2010-2017</td>
<td>2013-2017</td>
<td>61</td>
<td>25.6</td>
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<td>61</td>
<td>25.6</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Portfolio C

All Inverter Downtime - Frequency and Trend

Distribution of Downtime Events - Red colors represent peak production months

All Downtime Events - Symbol size and color a function of kWh production loss

Production Loss (kWh)
0 - 532,560

Downtime Start

Downtime (hours)

Count of Downtime


Downtime Hours (bin)
## Reliability Database

Data compiled and analyzed up through December 2017

<table>
<thead>
<tr>
<th>Portfolio</th>
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<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Portfolio</th>
<th>Unique module mfrs.</th>
<th>Unique module models</th>
<th>Total number of modules</th>
<th>Unique inverter mfrs.</th>
<th>Unique inverter models</th>
<th>Total number of inverters</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>11</td>
<td>25</td>
<td>83,891</td>
<td>8</td>
<td>29</td>
<td>129</td>
</tr>
</tbody>
</table>

Portfolio D – Event Summary

- Inverter
- Grid
- Combiner
- PM Events
- Weather Events
- AC Meter
- Weather Station Events
- String
- AC Disconnect
Portfolio D –

Breakdown of Events that Tripped Inverters

- Offline due to unknown fault
- Offline due to PM
- Inverter not communicating
- Offline due to arc detection fault
- Offline due to fuse failure
- Offline due to hardware fault
- Offline due to hardware malfunction
- Offline due to water intrusion
- Offline due to fuse failure
- Offline due to AC breaker trip fault
- Offline due to AUX supply fault
- Offline due to current fault
- Offline due to ground fault
- Offline due to power supply failure
- Offline due to software fault
- Offline due to voltage fault
- Underperforming due to core fault
- Offline due to ground fault
- Offline due to AC disconnect fuse failure
- Offline due to AC slow voltage fault
- Offline due to contactor fault
- Offline due to core fault
- Offline due to hardware failure
- Offline due to loose connector
- Offline due to overheating reactor
- Underperforming due to fan failure
- Underperforming due to unknown reason

Failures: 9%
PM events: 17%
Comms: 14%
Faults: 60%
**Portfolio D**

- Fuse failure at inverter
- DC side arc fault – Trips inverter
- Recloser trip – grid event

<table>
<thead>
<tr>
<th>Example</th>
<th>Component &amp; Location</th>
<th>Failure Type</th>
<th>Fault/Failure Distribution</th>
<th>Repair Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Type</td>
<td>Shape / Mean</td>
</tr>
<tr>
<td>1</td>
<td>One Inverter at a site in the Eastern U.S.</td>
<td>Fuse failures</td>
<td>Weibull-2</td>
<td>13.03</td>
</tr>
<tr>
<td>2</td>
<td>One Inverter at a site in the Eastern U.S.</td>
<td>Tripping and resetting due to arc faults</td>
<td>Normal</td>
<td>256.979</td>
</tr>
<tr>
<td>3</td>
<td>One Site in the Eastern U.S.</td>
<td>Recloser tripping on grid side</td>
<td>Weibull-2</td>
<td>1.36296</td>
</tr>
</tbody>
</table>
Fuse failure at inverter – failure and repair distribution

- Highest probability of fuse failure at 700 days
- Highest probability fuse will be replaced around 1.5 days. Only 20% chance the repair will happen three days after the event
DC side arc fault – inverter fault and repair distribution

- Highest probability of arc fault event tripping the inverter at 300 days
- Highest probability inverter will reset at 0.15 days (~4 hours). Repairs happening later suggest manual restart
Recloser trip – grid event

- Highest probability of recloser shutting down all inverters (entire system) at 125 days
- Operator can remotely reset the recloser. The highest probability of repair is around 1 hour after the event
Evaluating failure or ‘trip’ rate for reclosers

What does the MCF say about the failure, is it becoming more or less frequent?

1134 failures per 1M hours. MTBF ~ 34.56, if failure rate is constant

Shape factor less than 1 indicates failure rate decreasing. 0.8 for this event, so failures occurring less frequently. Failure rate and MTBF are more appropriate for constant failure rates.
PV-RPM in SAM

- System Design Window
  Same as any other SAM model

Components that can be simulated with probability distributions:

- Modules
- AC Disconnects
- Strings
- Transformers
- DC Combiners
- Grid Impacts
- Inverters
- Trackers

Output File:
- Power & Energy loss,
- costs,
- labor hours,
- LCOE,
- failures per component.
- Time series and annual results, per realization

Recorded demonstration webinar

https://sam.nrel.gov/node/75555
Evaluates whether service cost is less than expected energy loss based on probability of failure. Ties PM to potential failure event.

If cost of service is below the maximum likelihood estimation of the energy lost, then it may be a good business decision to perform the specific PM event.
Thank You

gklise@sandia.gov
PV Inverters and Harmonics

Not widely recognized, but significant technical risk.
PV Inverters and MVT Harmonics; Who Cares?

This not widely recognized operation and failure mode can represent important technical risk and negatively impact the financial performance of PV assets.
The Role of Harmonics in Inverter/MVT Interaction

• Established standards such as UL1741 and IEEE1547 are helpful
• The role of guidelines such as IEEE C57.159-2016

* Representative Photo of Typical PV Inverter Skid
Why are Harmonics Created?

In creating the AC sine wave from the DC inputs to the inverter, IGBT switching creates harmonics which need to be filtered.
What Happens When You Have Harmonics?

- Heat
- Resonance – high voltages
- Breakdown of coils
- Breakdown of coils to ground (tank) within the MVT
- Fuse opening & damage
Actual Occurrence

• Damage to conductors
• Damage to insulation & electrostatic shield
• Solution was small adjustment to inverter switching frequency --- but it took a lot of time, investigation, experimentation and money to figure that out.
Design and Certifications
IEEE C57.159-2016

IEEE Guide on Transformers for Application in Distributed Photovoltaic (DPV) Power Generation Systems

IEEE Power and Energy Society

Sponsored by the Transformers Committee

IEEE 3 Park Avenue
New York, NY 10016-5997
USA
Design Recommendation

The main advantage is that the electrostatic ground shield transfers the high frequency harmonic energy to ground and minimizes possible transfer of the high voltage impulses.
Field Measurement Recommendations

Monitor skids in operation over a couple of weeks looking at voltages and power factors on the MV side of MVT and harmonics in real life at a full range of operating conditions (10%, 50% and 100% power).
Confirm Inverter/MV Transformer harmonic compatibility on **ONE SKID**.

**Option 1:** Factory Acceptance Test (FAT) of with PV Energy Simulator using generation profiles expected in field.

**Option 2:** Site commissioning using a “Golden Skid” after completion of the first sub-array, prior to export to the grid.

**Option 3:** Site commissioning using when energy export to grid is allowed and feasible.
Objective

Problem

• **Reference modules** used for soiling & irradiance measurement
• Module **temperature** needed
• Back-of-module temperature sensors inconvenient, add cost $

Solution

• Determine module temperature from \( V_{oc} \)
• Use **equivalent cell temperature** method, modified from IEC 60904-5
• Use I-V sweeps in **soiling & irradiance** monitoring system
• **Lowers system cost**
Soiling System with Reference Module

- **Clean Reference Cell**
  - Measure irradiance

- **Soiled Reference Module**
  - Sense soiling power loss

- **Cell Wash System**
  - (Reservoir, Pump, Level/Flow Sensors, Heaters)

- **Measurement & Control Electronics**
  - (Module IV Sweep, Cell Irradiance Measurement, Data Analysis, Wash Control)

- **Daily Automatic Washing**
Back of Module Temperature Sensor

SolarPro, May/June 2015
Modified** Equations Based on IEC 60904-5 (2011):

\[ T = 25 \, ^\circ\text{C} + \frac{1}{\beta} \left[ \frac{V_{oc}}{V_{oc,STC}} - 1 - a \cdot \ln\left( \frac{I_{sc}}{I_{sc,STC}} \right) \right] \]

\[ a = \frac{V_{oc,NOCT}}{V_{oc,STC}} - 1 - \beta \cdot (T_{NOCT} - 25 \, ^\circ\text{C}) \]

**Equations modified to use module datasheet parameters for two known irradiance/temperature combinations, STC & NOCT:

\[ \beta \ (V_{oc \ temp \ co.}), \ V_{oc,STC}, \ I_{sc,STC}, \ V_{oc,NOCT}, \ I_{sc,NOCT} \]

Assumes datasheet parameters are accurate. But can also be field-calibrated by customers / users.
Datasheet

**THE Utility Module TSM-PD14**

### ELECTRICAL DATA (STC)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>200</th>
<th>205</th>
<th>210</th>
<th>215</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Power Watts (Wp)</td>
<td>200</td>
<td>205</td>
<td>210</td>
<td>215</td>
</tr>
<tr>
<td>Power Output Tolerance (%)</td>
<td>0</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum Power Voltage (V)</td>
<td>35.2</td>
<td>36.5</td>
<td>37.0</td>
<td>37.1</td>
</tr>
<tr>
<td>Maximum Power Current (A)</td>
<td>2.88</td>
<td>2.93</td>
<td>2.98</td>
<td>3.01</td>
</tr>
<tr>
<td>Open Circuit Voltage (V)</td>
<td>45.4</td>
<td>45.3</td>
<td>45.3</td>
<td>45.0</td>
</tr>
<tr>
<td>Short Circuit Current (A)</td>
<td>0.77</td>
<td>0.79</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Module Efficiency (η)</td>
<td>15.6</td>
<td>16.7</td>
<td>16.0</td>
<td>16.2</td>
</tr>
</tbody>
</table>

**Note:** STC: Irradiance 1000 W/m², Cell Temperature 25°C, Air Mass AM1.5 according to EN 60904-3, typical efficiency reduction of 4.3% at 200 W/m² according to EN 60904-1.

### ELECTRICAL DATA (NOCCT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>220</th>
<th>227</th>
<th>231</th>
<th>239</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Power (W)</td>
<td>220</td>
<td>227</td>
<td>231</td>
<td>239</td>
</tr>
<tr>
<td>Maximum Power Voltage (V)</td>
<td>33.6</td>
<td>33.8</td>
<td>34.1</td>
<td>34.1</td>
</tr>
<tr>
<td>Maximum Power Current (A)</td>
<td>6.16</td>
<td>6.72</td>
<td>6.77</td>
<td>6.88</td>
</tr>
<tr>
<td>Open Circuit Voltage (V)</td>
<td>42.1</td>
<td>42.2</td>
<td>42.2</td>
<td>42.5</td>
</tr>
<tr>
<td>Short Circuit Current (A)</td>
<td>7.63</td>
<td>7.31</td>
<td>7.15</td>
<td>7.27</td>
</tr>
</tbody>
</table>

**Note:** NOCT: Irradiance of 800 W/m², Ambient Temperature 30°C, Wind Speed 1 m/s.

### MECHANICAL DATA

- Solar cells: Multicrystalline 156 x 156 mm (6 inches)
- Cell orientation: 72 cells (6 x 12)
- Module dimensions: 1566 x 992 x 40 mm (77.7 x 39.0 x 1.6 inches)
- Weight: 37.6 kg (83.4 lbs)
- Glass: 4.8 mm High Transmission AR Coated Tempered Glass
- Backsheet: White
- Frame: Silver Anodized Aluminum Alloy
- J-Box: IP 65 or IP 67 rated
- Cables: Photovoltaic Technology cable 4.0mm² (0.060 inches), 1200 mm (47.2 inches)
- Connector: MC4 or MC4 Compatible

### TEMPERATURE RATING

- Nominal Operating Cell Temperature (NOCT): +45°C (113°F)
- Temperature Coefficient of Power: -0.41%/°C
- Temperature Coefficient of Voltage: -0.32%/°C
- Temperature Coefficient of I_sc: 0.56%/°C

### MAXIMUM RATINGS

- Operational Temperature: -40°C to +85°C
- Maximum System Voltage: 1500VDC (IEC) 1000 VDC (UL)
- Max Series Fuse Rating: 15A

### WARRANTY

- 10 year Product Workmanship Warranty
- 25 year Linear Power Warranty

*(Please refer to product warranty for details)*
Example Results

Data filtered to irradiance >100 W/m²
Temperature Difference vs. Irradiance

\[ y = 0.0036x + 0.3095 \]
Reasons for Temperature Differences

• Accuracy of datasheet values
• Irradiance
  – Cell is hotter than back surface
• Wind speed
  – Cell is hotter than back surface
• Temperature non-uniformity
  – Back surface RTD measures one point only
• RTD thermal mass
  – RTD temperature changes more slowly than cell temp. RTD can be higher/lower depending on cloud movement.
Conclusions

- Voc temperature method can be used to eliminate module temperature sensors
- Atonometrics formulation uses datasheet values
- Advantageous for reference modules:
  - More convenient
  - Lower cost
- Potentially more accurate
  - Irradiance, wind, time lag, and temperature non-uniformities all contribute to back-surface RTD error
- May require an in-field calibration procedure to fine-tune datasheet values
Variability of xenon arc weathering exposures: A comparison of optical filters and their effect on spectral irradiance using two common irradiance control points

Sean Fowler
Weathering & Corrosion Technical Director
Q-Lab Corporation
Abstract

IEC 62788-7-2 was published in 2017 as the results of round robin testing revealed variability of test results on module backsheet materials. Method A of the standard references a very narrow definition of the spectral irradiance in the UV light region, originally defined in ASTM D7869. Xenon arc chambers require optical filters to remove unnatural short-wavelength UV light, and international weathering standards provide broad definitions of three types of optical filters: Extended UV, which pass shorter wavelengths than experienced at the Earth’s surface, Daylight, which are designed to provide a nominal match to mid-day summer sunlight, and Window, which simulate sunlight filtered through common window glass types. However, the spectral irradiance requirements of D7869 and IEC 62788-7-2 cannot be met by xenon arc systems using most common Daylight filters. The specific optical filter defined in ASTM D7869 was developed during prior work by Ford Motor in order to replicate more accurately the photo-oxidation caused by natural exposures in south Florida compared to the common optical filters used in the automotive industry.

Although the primary rationale for inclusion of this spectral irradiance requirement in 62788-7-2 was its accurate replication of sunlight in the UV, a separate reason was promotion of the most reproducible spectral irradiance across commercially available xenon arc chambers. This work will provide detailed spectral irradiance measurements of two xenon arc chamber types with the 62788-7-2 optical filter and compare them to other Daylight filters to highlight the differences. Additionally, the effect on irradiance resulting from the control sensors in these devices will also be examined.
Experimental design

Spectral power distributions were taken over a period of several years in multiple xenon arc weathering chambers. The measurements were made on chambers with optical filters and lamps at approximately the mid-point of their recommended life. The spectroradiometer used was a Gooch & Housego (Optronics) OL-750 equipped with double grating monochromator.

In some cases, the spectral power distribution shown was normalized from the original measured irradiance.

Sunlight spectra represented are taken from ASTM G177, representing AM1 sunlight.
Figure 1: Irradiance control with 340 nm sensors in a xenon arc exposure.
Wide-Band Control
300-400 nm “TUV”

Figure 2: Irradiance control with 300-400 nm sensors in a xenon arc exposure
Figure 3: Irradiance values of the same exposure at three different control points: 340 nm, 420 nm, and 300-400 nm.

- 81 W/m² @ 300-400 nm
- 1.36 W/m²/nm @ 420 nm
- 0.80 W/m²/nm @ 340 nm
Irradiance in most xenon arc tests is controlled with one of two sensor types: 340 nm or 300-400 nm. U.S. standards most commonly use the 340 nm control point, and European standards most commonly use 300-400 nm control points.

Although it is possible to convert between set point types, the conversion factors are not universal.
Figure 4: Spectral Power Distribution, IEC 62788-7-2, Method A

Very little spectral mismatch

0.80 W/m²/nm @ 340 nm
Comparison of two xenon arc chambers properly configured for IEC 62788-7-2. This filter is specified in ASTM D7869. One reason it was chosen by IEC is that the two filters from different chamber manufacturers provide a nearly identical UV spectrum.

However, we will see that not all “Daylight” filters for xenon arc chambers are the same.
Figure 5a: Comparison of proper 62788-7-2 optical filter and a common (historical) “Daylight” filter type.
Figure 5b: Comparison of proper 62788-7-2 optical filter and a common “Daylight” filter type.
Due to spectral mismatch errors between the optical filter types, two problems occur:
1) photochemically-effective irradiance can be significantly different between exposures
2) Irradiance conversions between control points can be incorrect
Why the SPD Is Critical

“Photochemically-effective irradiance” is area under curve

Spectral Sensitivity of material: $s(\lambda)$

SPDs of Light Source: $E(\lambda)$

$s(\lambda) * E(\lambda)$
# Irradiance Conversion Errors

<table>
<thead>
<tr>
<th>Xenon Arc Optical Filter</th>
<th>Measured Irradiance at 340 nm (set to 0.80 W/m²/nm)</th>
<th>Measured irradiance 300-400 nm (W/m²) (set to 0.80 W/m²/nm at 340nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q-Lab (Q-SUN) Daylight-F</td>
<td>0.80</td>
<td>81</td>
</tr>
<tr>
<td>Atlas Right Light®</td>
<td>0.80</td>
<td>83</td>
</tr>
<tr>
<td>Q-Lab (Q-SUN) Daylight-B/B</td>
<td>0.80</td>
<td>87</td>
</tr>
<tr>
<td>Atlas Boro Type S/ Boro Type S</td>
<td>0.80</td>
<td>93</td>
</tr>
<tr>
<td>Q-Lab (Q-SUN) Daylight-Q</td>
<td>0.80</td>
<td>88</td>
</tr>
</tbody>
</table>

Table 1: Comparison of irradiance values at 340 nm (narrow band) to 300-400 nm (wide band).
Conclusions

• IEC 62788-7-2 specifies a very specific UV spectrum, which requires a certain type of optical filter.
• Using a different “Daylight” filter produces significant spectral mismatch error
  – Different photochemical degradation possible
  – Irradiance set point conversion errors
Summary of survey of IEC TC82 WG2: standardizing data collection from extended-stress testing

Sarah Kurtz*, NREL; Nancy Phillips, Dupont; Tony Sample, JRC

Feb. 27, 2018
PV Reliability Workshop, Lakewood, Colorado

* Moved to University of California Merced
Demand is there: Responding to customer requests, multiple extended-stress test protocols have been created.

Purpose is not to be ‘right’: There is not a single right way to gather accelerated-stress test data, so it’s not obvious that it should be standardized.

Case for a standard: An international standard could avoid some redundant testing and enable comparison of data.

Case against a standard: The standard could be misused and creating another test would just motivate more (and...).

Motivation for this poster: Communicate survey results exploring sentiments about a standard for collecting data from extended-stress testing.
In spring 2017, IEC TC82 WG2 discussed extended-stress testing and voted to conduct a survey. During summer and fall much discussion analyzed the situation and multiple survey drafts were considered. Based on the discussions, a draft New Work Item Proposal was developed and a survey written to obtain additional feedback on that draft. 17 individuals completed the survey.

This poster summarizes the survey responses and proposed next steps.
Proposed NWIP Scope:

This Technical Specification describes a consistent data collection methodology to identify photovoltaic module strengths and weaknesses by applying stresses and characterizing changes caused by those stresses. For some specific tests, coupons or minimodules may be most appropriate.

This Technical Specification describes data collection rather than defining pass-fail criteria for issuance of a certificate. The data are designed for two primary purposes:

- Documentation of results of qualification testing such as those defined in IEC 61215 and IEC 61730 as a basis for evaluating adequate design qualification and type approval of terrestrial photovoltaic (PV) modules suitable for long-term operation in general open-air climates.
- Identifying variability in a module’s response to long-term stress in order to assess the risk associated with variability of manufacturing or design.

Achievement of these two primary purposes would be useful toward:

- Identifying whether a design or bill-of-materials modification may change (either favorably or unfavorably) a module’s response to stress.
- Identifying whether variability in manufacturing may affect a module’s response to stress.
- Gathering statistics to assess and track the variability in manufacturing.
- Identifying whether one module design differs in a measurable way from another.
- Providing data for analysis of risk of failure for the intended use conditions by applying stresses that are prolonged enough to identify the majority of problems observed after long-term field deployment in the harshest use conditions.
- Identifying possible corrective actions that may be taken to mitigate or address any potential weaknesses that are observed.

This technical specification:

1. Is not intended to be used as a pass-fail test.
2. Is not intended to be used in isolation. Without comparing the stresses in the intended use environment with the stresses that cause degradation of the module, differences between test results may be irrelevant for the intended use environment.
3. Is not intended to create data for superficial analysis: the data are designed to be analysed to determine the most probable causes of module failure and what situations are most likely to lead to those types of failure so as to be able to evaluate the relevance of the test results to the intended use environment.
4. Does not define the sampling methodology. The data are intended to be evaluated in the context of the sampling methodology, just as the data are intended to be evaluated in the context of the intended use environment.
When defining the data elements in the attached NWIP, what elements should be included?

<table>
<thead>
<tr>
<th>Option</th>
<th>Yes</th>
<th>Maybe</th>
<th>No</th>
<th>Unsure</th>
<th># resp</th>
</tr>
</thead>
<tbody>
<tr>
<td>New combined or sequential stress tests</td>
<td>44%</td>
<td>25%</td>
<td>31%</td>
<td>0%</td>
<td>16</td>
</tr>
<tr>
<td>Repeated application of existing IEC tests (e.g. thermal cycling to 600 cycles or humidity freeze sequence three times over or PID)</td>
<td>59%</td>
<td>24%</td>
<td>12%</td>
<td>12%</td>
<td>17</td>
</tr>
<tr>
<td>Sequential application of existing IEC tests (e.g. damp heat alternate with 200 thermal cycles or damp heat followed by PID)</td>
<td>29%</td>
<td>41%</td>
<td>24%</td>
<td>6%</td>
<td>17</td>
</tr>
<tr>
<td>UV stress longer than IEC 61215/61730, probably coupled with other stresses</td>
<td>53%</td>
<td>18%</td>
<td>24%</td>
<td>12%</td>
<td>17</td>
</tr>
</tbody>
</table>
At Swiss RE we are now conducting all these tests to determine insurability of the PV modules.

I support including above tests, however, added tests should be carefully selected and total number of them should be limited to small.

Biggest gap in current testing lies in degradation modes which come from sequential stresses. Some long duration testing will be more effective on mini-modules or test coupons rather than full-size modules. UV must be included in the sequences, along with humidity and TC.

Sequences should remain unchanged. Testing time shall be extended but not based on e.g. usage different climates.

It is probably a good idea to base a Quality Assurance standard on existing tests defined by existing standards. The QA standard can be a portfolio of tests defined by other IEC standards and Technical Specifications. This avoids a lot of redundant work. There will always be a tension between updating test methods and having consistency with historical tests. A module QA test need to be able to be performed in a reasonable period of time. So, for that reason very long term component testing should be separate.

3 times Damp Heat to DH 3000 3 times TC 200 to TC 600 3 times HF 10 to HF 30 All repeated not sequential

Before starting work on a new standard the existing data from existing similar testing plans should be analysed and scientifically evaluated. (RETC Tresher Test, TÜV Supertest, PI Berlin, CSA, etc.) It does not bring any benefit to publish not scientifically based specs. It rather contains a high risk that the document is used in a way which has not been intended. Instead of this, the interested parties in the committee should start a research project.

Maybe some new tests, but most likely different sequence with existing ones

A distinction between tests designed to duplicate field failures and those designed to find bad materials should be made. e.g. damp heat should not be combined with other tests or extended beyond 1000 h. It does not duplicate field failures.

Developing a new combined or sequential test to identify new failure modes should be left as a separate exercise, and such new tests should be considered only after corresponding TSs are published.
The scope of work could include extended testing with data collection:
A. To assess variability in manufacturing (compare modules produced on different manufacturing lines, or different dates of manufacture)
B. To compare different module designs (compare different BOMs)

<table>
<thead>
<tr>
<th>Option</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Assess variability in manufacturing</td>
<td>13%</td>
</tr>
<tr>
<td>B. Assess difference in module designs</td>
<td>19%</td>
</tr>
<tr>
<td>A. and B. Assess both</td>
<td>69%</td>
</tr>
</tbody>
</table>
Survey question #2 comments

- Yes, this is critical as what we're looking for is the reliability of millions of modules coming off the production line each year.
- BOM comparisons are critical as different BOMs will have different degradation and durability characteristics. Mfg variability has been proven to be an issue in the industry as the source of many serial defects (different line, or same line on a "bad" week)...
- We believe differences between module designs and component types is much larger than manufacturing variability at this time, and should be addressed first. Different test sets may be relevant for the two different issues.
- QA testing is comparative in nature, comparing new modules or BOMS against known good modules or BOMS or new manufacturing lines against known good manufacturing lines.
  - A. Different manufacturing lines not different dates of manufacturing
  - B. No
- Does anybody has data in which magnitude data are scattering for the different tests? In statistical relevant sample sizes?
  - B is a higher priority than A
- This methodology could determine "differences" but this is likely to be misinterpreted as determining higher or lower quality. More time on a bad test will not accurately say one design is better than another.
Testing of smaller samples (e.g. mini-modules) can aid in comparison of different module designs/BOMs. This allows for longer UV or other combined stresses, and can make some testing easier or more informative (e.g. adhesion testing). Information from these tests could supplement the module testing.

### Survey question #3

<table>
<thead>
<tr>
<th>Option</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>I support consideration of testing of smaller sample sizes for comparing different module designs/BOMs</td>
<td>53%</td>
</tr>
<tr>
<td>I am interested; would need to hear more details</td>
<td>18%</td>
</tr>
<tr>
<td>I am opposed to consideration of smaller sample sizes</td>
<td>29%</td>
</tr>
</tbody>
</table>
If IEC TC82 were to agree to a Technical Specification along the lines of what is described here, would your organization or you individually find this useful?

<table>
<thead>
<tr>
<th>Option</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes, this would be valuable for my organization</td>
<td>71%</td>
</tr>
<tr>
<td>It doesn't much matter</td>
<td>0%</td>
</tr>
<tr>
<td>This is a mistake</td>
<td>18%</td>
</tr>
<tr>
<td>Unsure</td>
<td>12%</td>
</tr>
</tbody>
</table>
What would you want to include or exclude in order for this TS to be most useful to your organization?

- Intermediate characterizations, extra component test for critical failure modes, and "look ahead" components.
- Desired: Full transparency on all test data and results, not just a "pass/fail".
- Sequential testing including UV exposure. Coupon or mini-module testing in combination with module tests.
- The TS must be written in such a way that results can be used also for the Basic 61215/61730 qualification. Means intermediate measurements after e.g TC 200 to grant the Basic qualification, even if the module would fail after TC 600.
- Test method reliability & durability
- Limiting the scope to just a test protocol is the most efficient way forward. Different labs or CBs will add additional layers to the protocol - sampling requirements, BOM specifications, pass/fail (possibly). Those issues are difficult to resolve and probably are best left out of the test specification.
- Representative Samples and 3X DH 1000, TC 600 and HF 30
- For example, a clear definition of key components
- Taking known stresses to wear out limits like 600 thermal cycles. Make sure we do not overstress and cause failures that are not seen in the field.
- No DH longer than 1000 hrs
- No extended damp heat. Should include instructions on how to determine through scientific study, if differences actually indicate one design is better than another.
- Maybe a TRF
- Combining and sequencing of tests is done for 10 years now. To my understanding no real world correlations were able to be made from such tests. Before we standardize those long and expensive tests it should be clear what the purpose is.
What other comments do you have?

• We believe this will be a very valuable initiative to take on by IEC.
• The industry seems to continue to try to make a universal module that will perform in many very different environments (desert, tropics...). If we do this correctly, the industry may be able to start focusing their BOMs on environment-specific sales. Separately, understanding how different modules from different manufacturers degrade over time will enable more informed buying decisions, and also may enable module manufacturers to differentiate their products and thus escape the terrible "modules are a commodity" syndrome.
• In general such a TS would be critical because the industry will argue why the extended testing is not already included in 61215/61730 if it is important/reasonable.
• This type of testing is widespread in the industry and it would be good to have a baseline standard.
• Consider alternate sets for different climates. Particularly need to include tests for higher temperature (roof top) applications.
• Regarding #3, (1) Allowing smaller samples may lead to 62788 material tests being pulled into this document, going beyond the scope of "Photovoltaic Modules". (2) Smaller samples tend to be produced in non-standard production facilities, thereby inevitably introducing a variability in production. UV weathering-related adhesion tests are probably best left to an effort related to 62788.
• The laminate itself is just one piece of the module. More attention is need for the other components like J-Box, cables and connectors.
• Based on our discussions, we propose to add descriptions of the anticipated end uses to the NWIP:

• End use #1: Large investors, EPCs and insurers already require extended-stress testing as a basis for risk assessment for large investments. These (and the manufacturers making the tests) would like an international standard.

• End use #2: Many manufacturers use multiple suppliers and would like to understand the effects of using different BOMs. Analyzing changes after extended-stress testing can help to assess whether all BOMs are equivalent.
Summary and conclusions:
1. The majority of responses indicated support, but a few individuals are hesitant or negative
2. The inputs give some guidance, but also show a variety of opinions.

Next steps:
1. Circulate this document to WG2 with request to form a committee to discuss in more depth
2. Submit the draft NWIP to IEC Central Office for processing
3. Initiate committee discussions to sort through the differences

If you are interested in joining the discussion: email skurtz@ucmerced.edu and/or join dinner discussion: Meet outside the meeting room Tuesday, Feb. 27 at 18:00
INFLUENCE OF LID EFFECTS IN MULTI/MONO-CRYSTALLINE MODULES ON DURABILITY TESTING AND QUALIFICATION STANDARDS

Max B. Koentopp, E. Herzog, F. Kersten, F. Fertig
Hanwha Q Cells GmbH, OT Thalheim, Sonnenallee 17-21, 06766 Bitterfeld-Wolfen, www.q-cells.com, m.koentopp@q-cells.com, phone +491743383870

MOTIVATION
LID effects have the most direct impact on the performance of a pv system, they translate 1:1 into energy losses. In crystalline silicon modules light induced degradation mechanisms of different origins and time scales are present:
- BO complex: mainly p-Cz, up to ~ 6%
- FeH/FeI: Cz and mc, up to ~2%
- LID: mainly mc PERC, up to ~13%
but also Cz PERC
Current qualification standards (IEC 61215 and IEC 61730) do not address all of these effects, especially in the case of PERC type modules. A modification of procedures is unavoidable to obtain reliable qualification results.

CHARACTERISTICS OF LETID IN mc-SI

Fig. 1: LETID test setup (top) and LETID module characteristic curve (bottom).

OUTDOOR RESULTS CYPRUS VS LAB

Fig. 2: (left) Relative annual yield loss over time in years for LETID sensitive (black) and QUANTUM modules (blue) at Cyprus, i.e. Southern Mediterranean, test site. (right) Comparison between relative module power loss due to LETID for sensitive (black) and QUANTUM (blue) as measured in lab setup (upper legend) versus outdoor results from Cyprus (black, blue) and Germany (red) test sites. Several years are needed to reach maximum degradation in field.

LONG TERM STABILITY

Fig. 4: Degradation over time for the proposed test conditions.

IMPLICATIONS ON QUALIFICATION TESTING

Proposition for LETID stabilization for future editions:
- Use current induced instead of light for LETID module in order to maximize test and injection level comparable to maximum power point conditions.
- Deliberate omission in degradation curve.
- Harmless results of current stress with minimum risk.
- Use a degradation that allows tests in reasonable time without risking to miss any degradation.

CONCLUSION
- LID effects can have very significant effect on energy yield production of PERC modules.
- LETID occurs in multi- as well as mono-crystalline PERC modules.
- QUANTUM permanently suppresses LID and LETID.
- LETID testing can be done more efficiently using current induced degradation.
- Test conditions proposed are 75°C at mpp injection level.
- Module Qualification should include testing for LETID for both multi- and monocrystalline modules.

References
1. B. Hartnäck et al., Proc. 27th EU PVSEC 2012, Frankfurt, Germany, pp 2031-2034
2. F. Fertig et al., Proc. 27th EU PVSEC 2012, Frankfurt, Germany, pp 53-56
5. M. Koentopp et al., NREL PV Reliability Workshop 2017
6. F. Fertig et al., Energy Procedia, 2013 (42), pp 338-345
7. F. Fertig et al., Proc. 20th EU PVSEC 2013, Valencia, Spain, pp 821-826
8. F. Kersten et al., Proc. 22nd EU PVSEC 2017, Amsterdam, Netherlands, pp 822-825

IMPLICATIONS ON QUALIFICATION TESTING

Current version of IEC 61215 and IEC 61730:
- Initial stabilization misses LETID, as process is slow at 50°C and stability criterion fulfilled before LETID maximum is reached
- Allows for alternative stabilization method to be qualified

LETID EFFECTS IN Cz-PERC

Fig. 5: BO (@25°C) and LETID (@75°C) degradation over time in days for BO-stabilized mono-PERC cells.

- LETID also occurs in p-type Cz PERC
- LETID cannot be avoided by BO stabilization

Fig. 6: LID in Cz PERC: BO-LID @25°C (left), LETID @75°C (center), and avoidance in QUANTUM (right).

Fig. 7: BO degradation monitoring for Cz QUANTUM (Q PEAK) in volume production for 2017.

Implications for qualification testing
- BO-LID and LETID both can be present in Cz and mc modules

Fig. 3: relative module power degradation through current induced degradation over time for the proposed test conditions.
A DIGITAL PV PLANT FOR DEGRADATION RATE IDENTIFICATION
A benchmark for machine learning methods

CONTEXT
With the fast technological changes in the PV community, the knowledge of real Degradation Rate (DR) of PV panels is critical for stakeholders (project developer, farm owner, PV manufacturer...). Unfortunately, since we don’t know the true degradation rate (DR) of any plant without panel testing, the statistical methods currently used can’t be proven accurately. A wide range of value for DR can thus be found in the literature. The additional effect of soiling, sensor uncertainty or weather events is also difficult to assess. We present a “digital PV power Plant” where we model the degradation, the measurement errors and the weather, based on classical PV system modelling. It allowed us to generate datasets on which we tried classical and new machine learning (ML) algorithms to estimate degradation rate.

DEVELOPMENT OF A DIGITAL POWER PLANT FOR DATASET GENERATION
The Digital PV power Plant (DPP) is a Dymola/Modelica® model for a PV plant, developed at EDF R&D. With this tool, we can model the operation of a complete field of PV modules, including inverters, against historical plant, developed at EDF R&D. With this tool, we can model the degradation, the measurement errors and the weather, based on classical PV system modelling. It allowed us to generate datasets on which we tried classical and new machine learning (ML) algorithms to estimate degradation rate.

The Digital Power Plant is a comprehensive and useful tool to experiment statistical and Machine learning methods for degradation analysis. The results are coherent with real data analysis. Algorithms such as YoY regression or Arima. However, they do offer a consistent bias overestimating the degradation, around one percent more than modelled degradation. The origin of this bias hasn’t been diagnosed yet. ML methods such as GAMs doesn’t improve the results over simpler algorithms such as YoY regression or Arima. However, they do offer a reliable alternative.

RESULTS
First questions we tried to answer was to compare the influence of two choices: do we measure power on Dc or AC side ? Which performance index gives better results ? We found that the inverter presence adds some uncertainty but doesn’t change the degradation rate. We also found that PVUSA isn’t reliable when the weather is not stable (e.g. continental weather). Temperature corrected performance ratio presents the lesser uncertainty.

Another important finding is that all performance indicators show a consistent bias overestimating the degradation, around one percent more than modelled degradation. The origin of this bias hasn’t been diagnosed yet. ML methods such as GAMs doesn’t improve the results over simpler algorithms such as YoY regression or Arima. However, they do offer a reliable alternative.

CONCLUSION AND NEXT STEPS
- The Digital Power Plant is a comprehensive and useful tool to experiment statistical and Machine Learning methods for degradation analysis.
- The results are coherent with real data analysis.
- A system bias has been found that need to be addressed in the next iteration of the model.

PERFORMANCE INDEXES
Degradation rates have always been measured by performance indexes. The most common are presented in the standard IEC 61724.

The first used is the Performance Ratio, defined as: 
\[ PR = \frac{\text{Sum}}{\Delta t} \frac{G_{DC}}{P_{TRC}} \]

Other indicators are the Pressure Ratio: 
\[ \text{PR} = \frac{P_{\text{ref}}}{P_{\text{ref}}} \]

With: \( P_{\text{ref}} = \frac{G_{\text{ref}} + (T_{\text{amb}} - T_{\text{ref}}) \cdot \text{G}_{\text{ref}} \cdot \text{G}_{\text{ref}}}{G_{\text{ref}}} \)

and PVUSA rating: 
\[ \text{PVUSA} = f(G, G_{\text{ref}} G_{\text{ref}} + W_{\text{ref}}) \]

Index = \[ \text{PVUSA/PRC} \]

Table 1: Annual variation of electrical parameters of PV modules (%/year)

<table>
<thead>
<tr>
<th>Station</th>
<th>Normal</th>
<th>Cold</th>
<th>Mediterranean</th>
<th>Humid Desert</th>
<th>Hot</th>
<th>Sonny</th>
<th>Desert</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp</td>
<td>0.04</td>
<td>1.00</td>
<td>-1.65</td>
<td>-1.75</td>
<td>1.55</td>
<td>-2.75</td>
<td>-2.25</td>
</tr>
<tr>
<td>RH</td>
<td>2.5</td>
<td>1.5</td>
<td>1.75</td>
<td>2</td>
<td>1.5</td>
<td>2.75</td>
<td>2.25</td>
</tr>
<tr>
<td>Temperatures</td>
<td>-3</td>
<td>-2</td>
<td>-1.75</td>
<td>-2</td>
<td>-1.5</td>
<td>0.75</td>
<td>-0.25</td>
</tr>
<tr>
<td>Dew Point</td>
<td>1.29</td>
<td>1.8</td>
<td>2.25</td>
<td>1.75</td>
<td>1.75</td>
<td>2.75</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Figure 1: Soiling and Cleaning effect on front glass transmittance

Figure 2: Results for Athens / Rennes (Mediterranean / oceanic weather)

Red line = modelled DR; boxplot : DR and 95% confidence interval.

right: choice of regression
left: choice of performance index, PVUSA is unstable for Athens.
Potential Induced Degradation (PID) test is performed by exposing Photovoltaic (PV) modules to warm and humid climate in an environmental chamber along with applying positive/negative potential between the cells and frame according to IEC TS 62804-1 (PV modules- Test methods for the degradation of potential-induc ed degradation- Part 1: crystalline silicon).

However, the PID test does not incorporate an important environmental factor of real outdoor condition and light. Industrial p–PERC modules can be affected by positive (+) PID. When the p–PERC module which suffers from the positive PID degradation is tested with light, it barely suffers from PID degradation, regardless of the light intensity. It is assumed that the mechanism of the positive PID degradation is polarization, which is reversible.

Building up of charges which induces polarization seems to be prevented under light irradiation condition and the effect of polarization is eliminated. This suggests that the IEC TS 62804 standard needs to be revised so that it reflects the real outdoor phenomena more correctly.
Degradation analysis of hundreds of systems enabled with open-source software

Michael G. Deceglie, Dirk C. Jordan, Ambarish Nag, Adam Shinn, & Chris Deline
National Renewable Energy Laboratory
kWh Analytics

Introduction

We analyzed PV performance time series data from 340 residential and 119 commercial systems in the United States. We used RdTools to accomplish this analysis. RdTools is an open-source Python library for robust and scalable analysis of PV degradation (and perhaps more types of PV data analysis in the future). RdTools can be used in both large-scale analysis to understand performance at scale (as in this study) or for detailed studies of individual systems.

Further reading

Differences between residential and commercial systems

We observed a significantly faster degradation rate among residential systems (median: −1.5%/year) compared to commercial systems (median: −0.5%/year). Differences in cell technology do not appear to explain the difference.

In this large-scale analysis, the uncertainty of any single system's degradation rate can be large due to scatter and uncertainty. However, when considering the entire dataset of hundreds of systems, significant trends can still be observed.

Factors associated with higher degradation in residential systems

Given the presence of thermally-activated degradation mechanisms, it is generally expected that modules running hotter may degrade more rapidly. This is borne out in the present analysis. Systems with a lower average cell temperature tend to show a slower degradation rate than hotter systems. (Systems are divided according to whether their average temperature was above or below the median for all the systems.)

Systems with more shade tend to show more rapid degradation than those with no or low shade. This could be explained by shade-induced hot spots causing degradation, but also by foliage growth over time, which would appear as a reduction in energy yield.
**UV Light and Ionizing Radiation**

- Earth surface UV radiation beginning in the UV-B band is categorized as “Ionizing Radiation” and has enough energy to break chemical bonds.
- The most significant effect on materials from light energy is caused by UV radiation breaking chemical bonds.
- Visible and IR radiation are categorized as “Non-Ionizing Radiation” and which have somewhat minimal photochemical and heating effects on materials.

**Metal Halide Weathering Chamber**

- The metal halide weathering chamber created UV irradiation combined with weathering conditions that negatively impacted PV cell IV performance.
- The very intense UV energy produced by the metal halide weathering chamber allowed for a simulation of 4.8 years of Florida exposure in 10.4 days.

**Summary**

- Additional exposure time combined with frequent performance measurements, or a comparison with outdoor weathered PV cells, would provide additional insight into chamber capabilities.
- Many international and North American companies are using metal halide tools for strategic R & D.
- ASTM Committee G03 on Weathering and Durability, of which EYE Applied Optix is a member, is developing a test standard for metal halide weathering chambers.

---

**Results – Appearance**

The entire face of both exposed PV cells show change. Both exposed PV cells also show yellowing of the encapsulant or adhesive.

---

**Results – IV Performance**

<table>
<thead>
<tr>
<th>Project</th>
<th>Performance Ratio</th>
<th>Actual Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference Cell</td>
<td>Exposed Cell 1</td>
</tr>
<tr>
<td></td>
<td>Before/After Ratio: 500 hr/0 hr (%)</td>
<td>0 hr</td>
</tr>
<tr>
<td>Pm(W)</td>
<td>99.6</td>
<td>98.8</td>
</tr>
<tr>
<td>Isc(A)</td>
<td>99.1</td>
<td>97.0</td>
</tr>
<tr>
<td>Voc(V)</td>
<td>100.2</td>
<td>100.7</td>
</tr>
<tr>
<td>Vpm(V)</td>
<td>99.9</td>
<td>102.0</td>
</tr>
<tr>
<td>Ipmax(A)</td>
<td>99.7</td>
<td>96.8</td>
</tr>
<tr>
<td>FF</td>
<td>100.3</td>
<td>101.1</td>
</tr>
</tbody>
</table>

---

**PV Cell IV Degradation from UV Exposure**

**BACKGROUND**

- (3) KEI Model GT1633-TF PV Cells
- Expose (2) cells to high irradiance UV energy
- (1) cell to be used for reference and remain unexposed

**EVALUATION**

- IV performance of PV cells to be evaluated using Iwasaki XLP-24 xenon long pulse simulator along with IV curve tracing equipment
- IV data collected twice for each PV cell at beginning and ending of test

**WEATHERING TEST CHAMBER TOOL:** Iwasaki SUV-W261 Metal Halide Chamber

- Irradiance: 1500 W/m² (295nm – 450nm)
- Cycle: 4 hours Irradiation; 4 hours Dew/Dark
- BPT 63 C; RH 50%
- Total Time: 500 hours

**PROCEDURE**

1. Perform IV trace measurements at beginning point of experiment.
2. Retain (1) cell for reference.
3. (2) cells placed into weathering test chamber for UV exposure.
4. Remove UV exposed PV cells after 500 hours.
5. Evaluate all PV cells for visible signs of degradation along with IV performance dropoff.

---

**Abstract**

PV component manufacturers continuously strive to improve product durability and reliability through recommended tests, and proprietary in-house testing to further accelerate the simulation of outdoor exposure. Metal halide tools are relatively new, and the amount correlation data is somewhat limited, but users have found that the benefit of rapidly accelerated testing is of strategic importance with regard to product development and testing.

A simple test will be conducted to demonstrate the accelerated effect of high intensity UV exposure on PV cell IV performance through the use of a metal halide lamp base UV weathering chamber.

---

**Results – IV Performance**

<table>
<thead>
<tr>
<th>Project</th>
<th>Performance Ratio</th>
<th>Actual Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference Cell</td>
<td>Exposed Cell 1</td>
</tr>
<tr>
<td></td>
<td>Before/After Ratio: 500 hr/0 hr (%)</td>
<td>0 hr</td>
</tr>
<tr>
<td>Pm(W)</td>
<td>Max Output</td>
<td>99.6</td>
</tr>
<tr>
<td>Isc(A)</td>
<td>Max Output</td>
<td>99.1</td>
</tr>
<tr>
<td>Voc(V)</td>
<td>Max Output</td>
<td>100.2</td>
</tr>
<tr>
<td>Vpm(V)</td>
<td>Max Output</td>
<td>99.9</td>
</tr>
<tr>
<td>Ipmax(A)</td>
<td>Max Output</td>
<td>99.7</td>
</tr>
<tr>
<td>FF</td>
<td>Curve Factor</td>
<td>100.3</td>
</tr>
</tbody>
</table>

---

**Metal Halide Weathering Chamber**

- The metal halide weathering chamber created UV irradiation combined with weathering conditions that negatively impacted PV cell IV performance.
- The very intense UV energy produced by the metal halide weathering chamber allowed for a simulation of 4.8 years of Florida exposure in 10.4 days.

---

**Summary**

- The metal halide weathering chamber created UV irradiation combined with weathering conditions that negatively impacted PV cell IV performance.
- The very intense UV energy produced by the metal halide weathering chamber allowed for a simulation of 4.8 years of Florida exposure in 10.4 days.
Localization and Characterization of Degraded Site in the Crystalline Silicon Photovoltaic Cells Exposed to Acetic Acid Vapor

Tadanori Tanahashi, Norihiko Sakamoto, Hajime Shibata, and Atsushi Masuda
National Institute of Advanced Industrial Science and Technology (AIST), Japan

Experimental Procedures & Background

Experimental

- (HAc = Acetic Acid)

Background I

Evolution of AC Impedance / I-V Parameters

Background II

Evolution of Gap at Ag-Si Interface (SEM / EPMA Images)

Summary

In this study, we electrically identified the degradation site in c-Si PV cells exposed to HAc vapor as the interface between the front electrodes and the Si emitter by the reconstitution of the divided capacitances beneath the front electrodes (Panels 1-4). This finding fully coincides with those reported by morphological analyses (Background II). It was also revealed that the interface under the busbars is degraded to a similar extent, as well as that beneath the grid fingers (Panel 4).

The isotropic corrosion (with HAc vapor) observed in these PV cells emphasizes the distinguishing characteristics in this interface. That is, the linear dependency of the capacitance ($C_3$) on the applied bias voltage at any temperature is not detected (Panel 8), although typical linear Mott-Schottky plots can be acquired for the capacitance ($C_2$) derived from the p-n junction of the PV cell (Panel 6). Furthermore, the resistance ($R_3$) does not exhibit any temperature dependency, unlike that observed in the series resistance ($R_1$) (Panel 7).

We have not yet sufficiently identified the precise roles of these characteristics on power loss in PV cells/modules that are deteriorating by acidic corrosion. However, since the evolution of these signals is also confirmed by a conventional acceleration test (Panels 9-12), the cause(s) of these peculiar features should be addressed.

Results

Panel 1 Strategy to Identify the C Origin

Panel 2 Strategy to Identify the C Origin

Panel 3 “Surgical” Preparation of Sample

Panel 4 We confirmed that the origin of $C_3$ is the Ag-Si interface underneath the front electrodes.

Panel 5 Temperature Dependency

Panel 6 Temperature Dependency [$R_3$]

Panel 7 Temperature Dependency [$R_1$]

Panel 8 Temperature Dependency [$C_3$]

Panel 9 in also PV Module under DH Test

Panel 10 Consistent C Properties

Panel 11 Evolution of $C_3$ during DH Test

Panel 12 Evolution of “Coefficient A”

This work was supported by the New Energy and Industrial Technology Development Organization, Japan. This poster does not contain any proprietary or confidential information.
What is Bankability?

Novel products are considered ‘financeable’ or ‘bankable’ by the renewable energy industry once they have demonstrated their capabilities sufficiently so that financiers no longer assign additional risk compared to existing products in the market. Consistency and certainty in the performance of a product is key to its bankability, most notably its energy yield, reliability, degradation rate, and predictability of its useful life, all of which are used by the financiers to prepare the financial model for the project. Initial energy yield estimates are used by financiers to set the baseline revenues expected from a project. Reliability is a key metric for the overall bankability of a product as it predicts the number of unplanned outages the facility might experience between planned maintenance intervals. Predictability in the degradation rate is another key aspect of bankability in that unforeseen or unpredictable degradation rates creates uncertainty in the revenues later in the project. Finally, the useful life of a product is a key issue for financiers in that the life of the facility must meet or exceed the term of the debt, but has recently become a major topic of concern for owners who intend to generate revenues with the asset for a decade or more beyond the term of the debt.

Why is it challenging for novel products?

How to address issues of reliability, degradation rate, and useful life can be especially challenging for new products as they do not have the field history of existing proven products. These products must rely on the experience of the design team, accelerated testing and similarity to conventional products to make a case for financeability.

PERC Solar Cells and Modules

The photovoltaic industry has been dominated by one primary solar cell and module technology for more than ten years (Alumina Back Surface Field (“Al-BSF’’)). However, Al-BSF technology is near its practical limit and further gains in efficiency are unlikely. The search for continued efficiency improvements has led the industry to adopt Passivated Emitter and Rear Contact (“PERC”) solar cells. As of 2016, PERC cells had captured 14% of the total global market share and there were 23 manufacturers with PERC modules in production. This share is expected to grow to more than 40% by 2021 and could replace almost all Al-BSF production by 2027.

Bankability Concerns

The PERC cell is different from a conventional Al-BSF solar cell in that there is an additional passivation layer added to the rear surface of the silicon substrate. This is an incremental and cost effective improvement in the cell design, but can create additional risk associated with the new materials and manufacturing processes involved.

New Materials

Though AlOx is a new material used in PERC manufacturing, it is usually protected by a SiN capping layer that mitigates any additional risk. SiN has been used for front side passivation in Al-BSF cells for more than a decade and has been shown to be capable of surviving the rigors of field deployment.

Additional Manufacturing Steps

The manufacturing processes utilized for rear side passivation and rear contact openings are generally PERC and laser ablation respectively. Both are mature manufacturing processes that have been used in industrial settings for more than a decade. As such, the additional risk associated with them is minimal.

Traditional Degradation Mechanisms

PID and annual degradation are generally linked to module design rather than cell technology. As such, the risk of additional degradation in PERC modules associated with these mechanisms is minimal. Historically, PERC modules have shown higher levels of LID than conventional modules. However, in recent years, manufacturers have found ways to mitigate this mechanism in PERC modules such that they behave comparably to conventional modules.

Light and Elevated Temperature Induced Degradation

Recent research groups have shown that both multi-crystalline and mono-crystalline PERC modules can degrade severely (up to 15%) when exposed to both light and temperatures above 50°C. This is a significant bankability gap for PERC modules because:

- the exact degradation mechanism is unknown;
- there is no standardized lab test to determine if modules are susceptible to this mechanism; and
- there is no way to estimate the degree of the degradation likely to be observed in the field.

Until the uncertainty associated with LIDTID can be addressed, or enough field data becomes available, financiers are likely to continue assigning additional risk to PERC modules.

Bifacial Solar Cells and Modules

As the cost of solar modules starts to plateau and they become a smaller fraction of the total project cost, module manufacturers are looking for new concepts to improve the energy harvest from the same modules. One such concept is called “bifacial,” a generic term for a photovoltaic device that can absorb sunlight from both the front and rear surface. While a conventional solar panel has limited light absorbed from the front surface, a bifacial panel can also absorb diffuse light that is reflected onto the rear surface. The electrical power output increase due to this extra light can vary from 5% to 35% depending on the type of solar cell technology utilized and the fraction of light reflected onto the rear surface.

Bankability Concerns

The rear side of a conventional Al-BSF solar cell is typically an aluminum layer that does not allow for the transmission of light. In a bifacial cell, the rear surface is changed to a transparent material coupled with a metallic grid. At the module level, the conventional backsheets are replaced with a sheet of glass.

There are a number of different cell technologies that can enable bifacial modules (p-PERC, n-PERT, HJT etc.). Each has its own challenges associated with it as compared with conventional Al-BSF cells. As such, we will limit our discussion to the bankability concerns related only to the changes required at the module level.

New Materials

There is minimal risk associated with the transition from a conventional backsheet to a transparent backsheet or rear glass. Module manufacturers have been using glass as the front surface of solar modules for decades and are aware of any related manufacturing and reliability challenges. Backsheet manufacturers are confident that their transparent backsheets will perform as reliable as their conventional backsheets.

Additional Manufacturing Steps

Typically, no additional manufacturing steps are required for bifacial modules. The stringing step must be optimized and that introduces some additional risk. However, off-the-shelf solutions for bifacial stringing are available from most leading equipment vendors.

Module Measurement

The standard for flash tester measurement of bifacial modules is still under development. As such, manufacturers are testing modules using different approaches, and power ratings on the datasheet cannot necessarily be compared directly between manufacturers. Furthermore, it is unclear how the manufacturers’ measurement methodology should be translated into field performance.

System Level Simulation

Conventional solar system simulation tools like PVsyst or SAM are designed for monofacial modules. They have been used for multiple gigawatts of solar projects and their energy generation estimates have been correlated with the historical performance of projects. As such, the uncertainty associated with their simulations is well understood and can be accounted for in the financiers’ revenue forecasts.

Simulation of bifacial systems is significantly more complicated than conventional systems. Multiple components of the system design like module tilt, height, row to row spacing, module to module spacing, rear side shading from the racking system, the reflective surface of the ground and many others can affect the light incident on the rear side of the module. It has been shown that the albedo of different surfaces can vary from less than 10% to more than 90% and the resulting bifacial gain of modules can vary from 5% to 35%. At this time, bifacial simulation tools may not have the field correlation history required to be considered bankable, without a high level of scrutiny and/or possible adjustments to the finace terms. Ongoing efforts to improve the accuracy of bifacial modeling and associated uncertainties will be critical to improve the financeability of bifacial modules.
Evaluating Module Performance and Reliability Utilizing Multi-Irradiance I-V Measurements

Eric J. Schneller and Kristopher O. Davis
Material Science and Engineering Department, University of Central Florida, Orlando, FL USA

Abstract

Long-term reliability of photovoltaic modules is essential for large scale deployment of photovoltaic energy systems to take place. To ensure reliability, module aging studies must include root-cause degradation analysis. For most studies, conventional 1-sun current-voltage measurements and the resulting performance parameters have been established as the standard metric for evaluating performance. In this work we explore the use of multi-irradiance current-voltage measurements as part of a more comprehensive performance evaluation for PV modules. This work presents several case-studies, including long-term outdoor exposure and accelerated aging, to evaluate how multi-irradiance testing can be used to identify degradation mechanisms and quantify their impact on performance. Understanding performance across the full range of incident irradiance is also critical to quantify the impact of specific degradation mechanisms have on long term energy yield of PV systems.

Evaluating Module Technologies

- Evaluations at 1 sun conditions do not capture the entire picture of module performance
- Particularly for novel technologies, the performance parameters plotted vs. the illumination intensity can be quite unexpected and may result in lower than anticipated field performance.

Case Studies: Effect of Degradation Type on Performance vs. Illumination Intensity

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Illumination Intensity</th>
<th>Performance Parameter</th>
<th>Degradation Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1: 10-Year Deployment in Florida</td>
<td></td>
<td></td>
<td>Deformation of cell interconnects</td>
</tr>
<tr>
<td>Case 2: Potential Induced Degradation</td>
<td></td>
<td></td>
<td>Formation of shunt paths</td>
</tr>
<tr>
<td>Case 3: Soiling</td>
<td></td>
<td></td>
<td>Reduction in incident radiation</td>
</tr>
<tr>
<td>Case 4: Light Induced Degradation</td>
<td></td>
<td></td>
<td>Decrease in minority carrier lifetime</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Degradation Modes</th>
<th>Affect Performance Parameter</th>
<th>Comparison of Performance Low vs. High Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deformation of cell interconnects</td>
<td>Increase in series resistance</td>
<td>Significantly lower loss in performance at 0.2 Suns compared to 1 Sun</td>
</tr>
<tr>
<td>Formation of shunt paths</td>
<td>Reduction in shunt resistance</td>
<td>Significantly higher loss in performance at 0.2 Suns compared to 1 Sun</td>
</tr>
<tr>
<td>Reduction in incident radiation</td>
<td>Loss in short-circuit current</td>
<td>Consistent loss in performance across all intensities (in percentage terms)</td>
</tr>
<tr>
<td>Decrease in minority carrier lifetime</td>
<td>Loss in open-circuit voltage</td>
<td>Slightly lower loss in performance at 0.2 Suns compared to 1 Sun</td>
</tr>
</tbody>
</table>

Suns-\(V_{oc}\) Analysis

Case Study: Long-Term Field Exposure

- High efficiency silicon modules were deployed in Florida for just over 7 years.
- The total observed power degradation was approximately 3% with negligible reduction in short-circuit current. All power loss was due to a reduction in \(V_{oc}\) and fill factor.
- Suns-\(V_{oc}\) analysis was used to identify and decouple resistive losses and recombination losses.

Conclusions

- Multi-irradiance measurement provide unique insights into module performance that have significant impacts on total energy production.
- Both multi-irradiance I-V as well as sun-\(V_{oc}\) can be used to identify and quantify the impact of specific degradation modes.
- When used in conjunction with other imaging based analysis techniques this can form a comprehensive loss analysis
Investigating effect of current injection into PV modules during environmental stress testing

Jiang Zhu, Michael Owen-Bellini, Thomas R. Betts, Ralph Gottschalg
Centre for Renewable Energy Systems Technology (CREST), Wolfson School of Mechanical, Electrical, and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK, J.Zhu@lboro.ac.uk

1. Introduction
- PV modules power loss due to FF reduction and I_{ph} loss.
- Three potential driving factors cause FF loss.

2. Experiment
- Mini-module sample
- Test plan and measurements

3. TC
- V_{oc} almost unchanged and I_{sc} saw minor variations.
- FF led P_{mpp} degradation for both injected and non-injected samples.

4. DH
- V_{oc} almost unchanged.
- FF and I_{ph} led P_{mpp} degradation for both injected and non-injected samples.

5. EL & Raman
- PMPP loss of 14% after TC1100 for S1, and after TC1400 for S3
- PMPP loss of 23% after 3500h for S5, and after 5000h for S9

6. Estimation of each driving factor’s contribution to power loss
- Fitting I-V curves to obtain R_{sh}, R_{s}, n, I_{0}, I_{ph}
- IV Roundness related to diode n/I_{0}

7. Driving factor contribution to power loss during TC
- I_{ph} and R_{s} minor contributions.
- R_{s} increase and IV roundness change contributed to power loss.

8. Driving factor contribution to power loss during DH
- R_{s} small contribution to FF loss.

9. Conclusions
- At the same levels of power loss, current injection tends to cause severer localised heat spots during TC, thus more power loss contribution by IV roundness.
- Change of dominant loss occurred during DH.
- Effect of current injection during DH depends on type of EVA.
On-line failure diagnosis of grid-connected photovoltaic (PV) systems

Andreas Livera*, Marios Theristis, George Makrides and George E. Georghiou
PV Technology Laboratory, FOSS Research Centre for Sustainable Energy, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia, 1678, Cyprus
(*corresponding author email: livera.andreas@ucy.ac.cy)

Introduction

• The accurate identification of failures in grid-connected photovoltaic (PV) systems is crucial for their further penetration in the energy mix.
• System malfunctions and failures occur during the operational lifetime of PV systems and decrease the output power of the system.
• The implementation of failure diagnostic tools is nowadays necessary to ensure the reliability and optimal performance of PV systems.
• In this work, failure detection routines (FDRs) have been developed in order to diagnose (detect and classify) failures in monitored PV systems.

Emulation of faults

Figure 1: Grid-connected PV system used for the emulation of failures in Nicosia, Cyprus

Figure 2: Fault introduction – Inverter Shutdown

Figure 3: Fault introduction – Partial shading

Methodology

Data acquisition
- Acquire meteorological and PV operational data

Simulate electrical characteristics
- Parametric and non parametric models

Comparative algorithm
- Compare measured with simulated measurements

Stage 1: Failure detection
- Apply outliers detection rules for failure verification

Stage 2: Failure Classification
- Apply data-driven algorithms and fuzzy logic inference to analyse the failure pattern and classify the detected fault

Detection of fault

Figure 4: FDRs procedural flow chart

Figure 5: a) Measured DC power production and set normal operation limits during an open-circuit fault and b) Power-irradiance diagnostic plot for outliers detection.

Conclusions

• Advanced PV monitoring systems encompassing FDRs can provide a clear indication whether the system is performing as expected and therefore safeguard the optimal performance and reliability
• The obtained results clearly demonstrated that the developed FDRs are capable of detecting and quantifying failures (partial shading, inverter shutdown, failure on bypass diode, open- and short-circuit faults) in PV systems
• In order to enable the generalization of this methodology for diagnosing failures, the developed FDRs will also be tested on acquired data-sets of larger scale PV plants

Acknowledgements

This work was funded through the IPERMON project (KOINA/SOLAR-ERA.NET/1214/08) which was co-financed by the European Regional Development Fund and the Republic of Cyprus through the Cyprus Research Promotion Foundation (DESMI 2009-2010).
A REVIEW OF POTENTIAL INDUCED DEGRADATION IN 3 THIN-FILM PLANTS
Classifying and Quantifying Defects of Solar Modules at Acceptable Cost and Time Frame in Field and Laboratory

Introduction
Thin Film (TF) plants show a different failure pattern in comparison to silicon solar plants. The here investigated plants suffered from quality issues like underperformance and poor module quality. As major defect PID can be identified.

In the recent years, results of PID affected PV plants were reviewed. Three plants are investigated (CIGS, CdTe and µc-Si). The here investigated plants suffered from quality issues like underperformance and poor module quality. As major defect PID can be identified.

Table 1: Investigated TF-PV Plants

<table>
<thead>
<tr>
<th>Plant</th>
<th>Technology</th>
<th>Mod. Power (W)</th>
<th>Type</th>
<th>Impedance</th>
<th>Open Circuit Voltage</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>CIGS</td>
<td>67.5</td>
<td>1</td>
<td>21</td>
<td>0.53</td>
<td>16.5%</td>
</tr>
<tr>
<td>II</td>
<td>CdTe</td>
<td>128</td>
<td>2</td>
<td>2.3</td>
<td>0.54</td>
<td>16.5%</td>
</tr>
<tr>
<td>III</td>
<td>µc-Si</td>
<td>105 &amp; 110</td>
<td>3</td>
<td>2.0</td>
<td>0.55</td>
<td>17.0%</td>
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Methodology (Field & Laboratory)

Field vs. Laboratory Measurements

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Field</th>
<th>Laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
<td>Low</td>
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<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Assumptions</td>
<td>Stable</td>
<td>Low</td>
</tr>
</tbody>
</table>

Laboratory tests enable to classify and quantify defects with high accuracy for TF modules. Field services are providing higher sample numbers at lower costs compared to the laboratory. Therefore, a combination of both gives a reasonable statistical evaluation at an affordable cost and time frame. Return to sustainable profitability can be achieved in affected plants by module replacement and applying state of the art quality control.
EU COST Action PEARL-PV: Performance and Reliability of Photovoltaic Systems; Evaluations of Large-Scale Monitoring Data

WG5: PV in grids

Introduction The EU COST Action PEARL-PV was initiated at the end of 2017. PEARL-PV is the abbreviation for “Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data”. The Action entails the formation of an inclusive network of PV researchers/experts and the largest-ever agglomeration of PV systems performance data in Europe that will be analyzed in order to include more-nuanced evidence-based reliability of PV system evaluation methods, simulation and design tools. To execute the research proposed, 5 Working Groups have been set up that will conduct research using a shared data bank, simulation tools and models in order to analyze and compare these data. The 5 Working Groups are focused on (WG1) PV monitoring, (WG2) PV simulation, (WG3) Reliability and durability of PV, (WG4) PV in the built environment and (WG5) PV in grids.

WG Objectives
- Improve PV grid integration
- Enhance PV performance
- Understand the behaviour
- Use information from WG1 - WG4

Task 1: PV power forecasting
- Short- and long-term forecasting of PV power generation
- Numerical weather predictions, satellite and sky images
- Machine learning techniques
- Application to different climates

Task 2: PV power fluctuations for grid operators
- Feeding distributed PV power into grids under variable conditions
- Impact of PV power fluctuations
- Correlation of PV fluctuations between neighbouring installations

Task 3: PV power quality in the grid
- Power quality indicators
- Harmonics, frequency, voltage, current intensity, power factors

Task 4: PV energy storage and management
- Matching electricity demand with supply
- Electric vehicles and other storage solutions

Task 5: PV performance and fault detection
- Failure detection and classification techniques
- Micro- to macro-scale failure detection
- Machine learning techniques
- Peer-to-peer approach
- Bulk data handling of real applications installed in EU

Acknowledgements
We would like to thank all 23 participants of PEARL-PV WG5 for their enthusiasm and efforts.

This poster is based upon work from COST Action PEARL-PV CA16235, which is supported by COST (European Cooperation in Science and Technology).

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation; see www.cost.eu.

Contact
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www.pearlpv.eu and www.cost.eu/COST_Actions/cA16235
EU COST Action PEARL-PV: Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data

Angélique Reinders*, David Moser†, Wilfried Van Sark†, Gemot Oreski‡, Nicola Peasall∥, Alessandra Scognamiglio§, Jonathan Leolux∥, Marios Theristis∥

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Introduction The EU COST Action PEARL-PV was initiated at the end of 2017. The 4-year research and work plan is presented with the aim to create exposure, receive feedback from various stakeholders and involve new participants to this research network. PEARL-PV is the abbreviation for "Performance and Reliability of Photovoltaic Systems: Evaluations of Large-Scale Monitoring Data". The Action entails the formation of an inclusive network of PV researchers/experts and the largest-ever agglomeration of PV systems performance data in Europe that will be analyzed in order to include more nuanced evidence-based reliability of PV system evaluation methods, simulation and design tools.

Aims PEARL-PV aims to increase performance and hence, lower costs of electricity produced by PV solar electricity systems in Europe via:

(i) obtaining higher energy yields,
(ii) achieving longer operational life time (beyond the 20 years usually guaranteed by manufacturers) and
(iii) lowering the perceived investment risk in PV projects.

Data These objectives will be achieved by a cooperative European COST Action partnership, see Figure 1, collating and analyzing a very large aggregated set of long-term PV performance data with a focus on understanding defects and failures of PV systems installed across Europe. These will fall in the context of PV grid integration where the impact of regional climate characteristics on the generation of PV energy will also be investigated.

Data analysis The data will be used to determine quantitatively the absolute influences of: (i) components’ rated performance, (ii) system design, (iii) installation type, (iv) operation and maintenance practice, (v) interaction with the grid, (vi) geographic location and (vii) weather and climate conditions on the (a) performance degradation over time and (b) failure modes as they affect (1) economic viability, (2) securing project investment, (3) environmental sustainability, (4) security and predictability of electricity supply and (5) diversity and distribution of electricity supply in order to (i) improve the electrical design of PV systems, (ii) achieve optimal sizing via the use of simulation models, (iii) enhance system efficiency, (iv) ease of maintenance, (v) achieve high reliability and (vi) demonstrate excellent durability.

Method To execute the research proposed, 5 Working Groups have been set up that will conduct research using a shared data bank, simulation tools and models in order to analyze and compare these data. The 5 Working Groups are focused on (WG1) PV monitoring, (WG2) PV simulation, (WG3) Reliability and durability of PV, (WG4) PV in the built environment and (WG5) PV in grids, see Figure 2.

Summary Whilst the highest efficiencies for small PV cells in laboratory contexts are near 32%, commercial PV modules have a maximum rated efficiency of close to 22%. In operational PV installations these efficiencies decline further to be in the range of 13 to 17%, because a PV system is exposed to variable solar irradiation intensity and spectra, and because of various system losses. Key factors determining the optimal performance of a PV system are shown in Figure 3.

Acknowledgements We would like to thank all 130 participants of PEARL-PV for their enthusiasm and efforts.

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www.pearlpv.cost.eu and
www.cost.eu/COST_Actions/CA16235

Figure 1: 26 countries take part in this COST Action PEARL-PV by 20 February 2018.

Figure 2: The 5 Working Groups of COST Action PEARL-PV in relation to a shared data bank and simulation tools.

Figure 3: Key factors that determine the optimal performance of PV systems.
Activation Energy Determination for Photovoltaic Encapsulant Discoloration by Indoor Accelerated UV Testing

Archana Sinha1, Deepak Kumar1, Kshitiz Dolia1, Michael Kempe2, Dirk Jordan2, GovindaSamy TamizhMani1
1ARIZONA STATE UNIVERSITY – PHOTOVOLTAIC RELIABILITY LABORATORY (ASU-PRL), MESA, ARIZONA, USA
2NATIONAL RENEWABLE ENERGY LABORATORY (NREL), GOLDEN, COLORADO, USA

Results and Discussion

• The initial measured Isc of the cells under test ranged from 180 – 200 mA.
• Average temperature of mini-modules varied from 77 °C to 123 °C depending on insulation thickness.
• Ea for encapsulant discoloration was determined by fitting a linear regression model to Isc degradation rate in UV stress testing vs module temperature plot.

Visual photograph of a mini-module at 123 °C (a) before stressing, (b) after stressing for two weeks, and (c) after stressing for four weeks along with corresponding IV curve

Objectives:

Determine the activation energy (Ea) using Arrhenius model by considering Isc loss at different module temperatures.

Activation energy is the minimum amount of energy required to initiate the failure mechanism.

Experimental Setup

• Tested eight MSX-05 mini-modules with glass/EVA/cell/EVA/backsheet construction
  o Thermocouple attached to the center cell of each module
• Cell Isc gives more confidence in the results compared to module Isc

• Accelerated UV stress testing performed in Xenon-arc-lamp equipped Atlas CI4000 Weathering chamber.
  o irradiance of 1 W/m² at 340 nm
  o 65% relative humidity (RH)
  o chamber temperature of 20°C
• Different module temperatures were maintained in weathering chamber by using different thickness of insulation on the backsheet.
• Xenon light source closely simulates solar spectrum.
• Effective in maintaining humidity and irradiance.

• Illuminated IV characterization tests were done by a solar simulator at STC condition.

Conclusions

• The activation energy for encapsulant discoloration determined from indoor accelerated UV stress testing lies in the range 0.27-0.46 eV.
• Achieving multiple test temperatures to determine activation energy in a single UV weathering chamber using solar gain has been demonstrated.
• The cell Isc degradation data provide more accurate and statistically reliable estimation compared to module Isc degradation.
• This accelerated UV testing approach can be easily replicated to the commercial size modules, and consumes less time and resources.

References

Acceleration Factor Modeling for Degradation Rate Prediction of Photovoltaic Encapsulant Discoloration

Archana Sinha, Shantanu Pore, Arun Balasubramaniam, and GovindaSamy TamizhMani
Arizona State University – Photovoltaic Reliability Laboratory (ASU-PRL), Mesa, Arizona, USA

Introduction

- Fielded PV modules experience various degradation modes depending on the climatic conditions, electrical configurations and manufacturing quality. Encapsulant discoloration is one of the two most commonly observed degradation modes in EVA encapsulated modules.
- It is important to accelerate the critical degradation modes so the field degradation rates can be predicted to improve reliability and service lifetime of PV modules.

Environmental factors:
- UV irradiance: 5% of the plane of array (POA) irradiance
- Module temperature: Calculated using Sandia model
  \[ T_{\text{min}} = E \cdot e^{\frac{a}{W} (hW)} + T_{\text{amb}} \]
- Hourly weather data are obtained from the Typical Meteorological Year (TMY) database
- Only the daytime (POA ≥ 40 W/m²) weather data is considered for our analysis

Three different climatic regions for encapsulant discoloration study:
1. Hot and Dry: Arizona (AZ)
2. Cold and Dry: New York (NY)
3. Temperate: Colorado (CO)

Objective: Development of rate dependency model to determine the acceleration factor for UV stress testing and the degradation rate for PV encapsulant discoloration in climate-specific fields.

Methodology

- Acceleration Factor Modeling for Degradation Rate Prediction of Photovoltaic Encapsulant Discoloration

For Arizona climate (Hot-Dry):

- Predicted Isc degradation rate in Arizona (AZ) is 0.37%/year, which falls within 14% of the field measured value (0.43%/year)

For New York climate (Cold-Dry):

- Predicted Isc degradation rate in New York (NY): 0.29%/year

Conclusions

- The physical modeling approach developed is able to accurately predict the degradation rate in glass/backsheet specific modules deployed in any outdoor field, and can be extended to other construction, manufacturer and climate-type.
- This work will be instrumental in designing the accelerated stress testing to study the long-term reliability issues associated with polymeric encapsulant and hence evaluating the fielded module’s electrical performance and service lifetime.

References


Acknowledgments: This material is based upon work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) under Solar Energy Technologies Office (SETO) award number DE-EE0007138 (PREDICTS 2).
Evaluation of Technology-Dependent MPP Current and Voltage Degradation in a Temperate Climate

Sascha Lindig¹,², Philip Ingenhoven¹, Giorgio Belluardo¹, David Moser¹
¹EURAC Research – Institute for Renewable Energy
²University of Ljubljana – Faculty of Electrical Engineering

INTRODUCTION

Photovoltaic system degradation and the improvement of degradation models receives an increasing amount of attention in the last years. The majority of publications focuses on values such as maximum power or performance ratio. Although it is convenient to relate performance losses to these values, the results fail to provide information about the root-causes of PV-system degradation. The study of the correlations between current and irradiation as well as voltage and temperature over time might help to better detect the occurrence, and to evaluate the severity, of specific degradation modes. In this work the impact of the exposure of PV systems of 8 different technologies in operation for more than 7 years under a temperate climate (Bolzano/Italy) is evaluated based on the normalized I_{REF} and V_{MPP} trends.

PV INSTALLATION

Climate (Köppen-Geiger):
- temperate climate
Mounting position:
- free standing
Installation type:
- Rack
Azimuth:
- 188.5° (SSW)
Installation slope:
- 30°
Mountainous surroundings

USED FORMULAS NORMALIZED VALUES

\[ I_{\text{NORMALIZED}} [\%] = \frac{I_{G,T_{\text{corr}}}}{I_{\text{STC}} \cdot n_{\text{modules\_parallel}}} \]
\[ V_{\text{NORMALIZED}} [\%] = \frac{V_{G,T_{\text{corr}}}}{V_{\text{STC}} \cdot n_{\text{modules\_series}}} \]
\[ P_{\text{NORMALIZED}} [\%] = \frac{P_{\text{STC}} \cdot n_{\text{modules\_series}} \cdot n_{\text{modules\_parallel}}}{I_{G,T_{\text{corr}}} \cdot V_{G,T_{\text{corr}}}} \]

\[ T_{\text{amb}} + (T_{\text{NOCT}} - T_{\text{NOCT}}) \cdot \frac{G}{G_{\text{STC}}} \]
\[ P_{\text{MPP,corr}} = \frac{P_{\text{MEAS}}}{G_{\text{STC}}} \times \frac{1}{(1 + G \times (T_{\text{corr}} - T_{\text{NOCT}}))} \]
\[ V_{\text{MPP,corr}} = \frac{V_{\text{MEAS}}}{\left[1 + G \times (T_{\text{corr}} - T_{\text{NOCT}})\right]} \]

PERFORMANCE LOSS CALCULATION

Applying Seasonal-Trend Decomposition using LOESS on normalized data set
Extract trend line: trend = seasonal + noise
Linear regression (trend - seasonal data - n of days) \( y = \text{Slope}_{\text{corr}} \times x + \text{Intercept} \)

Performance loss = 365.25 * Slope_loss

Uncertainty = Standard deviation \* 365.25 (Conf. interval 68%)

OVERVIEW PERFORMANCE LOSSES

<table>
<thead>
<tr>
<th>Technology</th>
<th>I_{\text{REF}}</th>
<th>V_{\text{REF}}</th>
<th>P_{\text{REF}}</th>
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</thead>
<tbody>
<tr>
<td>mc-Si</td>
<td>-0.82%/a +0.01</td>
<td>0.09%/a +0.002</td>
<td>-0.76%/a +0.01</td>
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<td>pc-Si</td>
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<td>-0.03%/a +0.003</td>
<td>-1.02%/a +0.01</td>
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<tr>
<td>micromorph</td>
<td>-1.64%/a +0.02</td>
<td>-0.17%/a +0.004</td>
<td>-1.52%/a +0.01</td>
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<td>1j-a-Si</td>
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<td>-1.16%/a +0.02</td>
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<td>HIT</td>
<td>-1.30%/a +0.01</td>
<td>-0.13%/a +0.003</td>
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<td>CdTe</td>
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<td>-0.78%/a +0.005</td>
<td>-2.30%/a +0.02</td>
</tr>
</tbody>
</table>

PLOTS CURRENT / VOLTAGE

CONCLUSIONS

It is visible that a degradation throughout all technologies takes place. For all systems under observation, a decreasing current is the main driver for the performance loss, with current loss rate values between 0.7% and 1.9% per year. The main drivers for the decrease in MPP current and a resulting reduced power output are most probably a degradation in the short circuit current combined with a lowered fill factor.

While analyzing the voltage behavior, a smaller decrease, compared to the current, is visible for most technologies, crystalline silicon systems being an exception.

Further studies including the evaluation of I_sc, V_oc and FF might lead to a better understanding of the degradation mechanisms taking place.

REFERENCES


ACKNOWLEDGMENT

The research has received funding from the European Union’s Horizon 2020 programme under GA. No. 721452 – H2020-MSCA-ITN-2016.
Novel Accelerated UV Testing of Field Aged Modules: Correlating EL and UV Fluorescence Images with Current Drop

Hamsini Gopalakrishna, Archana Sinha, Jaewon Oh, Kshitiz Dolia, Sai Tatapudi, and GovindaSamy TamizhMani
Arizona State University Photovoltaic Reliability Laboratory (ASU-PRL), Mesa, Arizona, USA

Introduction
Accelerated UV exposure testing

- Accelerated UV exposure tests can be time and resource intensive especially when data at multiple temperatures are required
- A novel method of reducing the test duration and resources involved is presented

UV fluorescence (UVF) imaging

- Encapsulant browning detection is generally done by visual inspection
- UV fluorescence (UVF) imaging can accurately show the extent and intensity of encapsulant browning

Experimental Setup

Accelerated UV exposure testing

- Four modules were placed in a walk-in UV chamber; 3 field-aged and 1 fresh
- Backsheet of aged modules were covered in aluminum foil to prevent oxygen photo-bleaching
- UV exposure of 450 kWh/m², double the Qualification Plus standard
- Insulation of varying thicknesses were placed behind the modules
- Solar gain from UV lights combined with insulation enabled maintaining three temperatures

UVF imaging set-up

- 30 UV light sources (385 nm – 395 nm) were mounted equidistant on a rack
- Angled at 45° towards the module to minimize reflection

Results and Discussion

Accelerated UV exposure testing

- 450 kWh/m² dosage over 100 days at 187 W/m²
- UV dosage corresponds to 3.8 years in Arizona
- Average day-time module temperature is 40°C in Arizona
- Temperatures of 60°C, 67°C, 77°C, and 85°C were maintained for non-insulated, fresh, thin, and thick insulated modules, respectively

When temperature effects are considered in the Arrhenius equation, the UV exposure test at 60°C corresponds to 15.2 years, at 67°C to 24.7 years, at 77°C to 49.4 years, and at 85°C to 85.9 years

UV fluorescence imaging

- The extent of browning increases as the module temperature increases
- Large modules can be illuminated with the proposed set-up

<table>
<thead>
<tr>
<th>Module</th>
<th>Fresh Module</th>
<th>Non-insulated</th>
<th>Thin insulation</th>
<th>Thick insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>67°C</td>
<td>60°C</td>
<td>77°C</td>
<td>85°C</td>
</tr>
<tr>
<td>Isc drop (%)</td>
<td>0.85</td>
<td>0.55</td>
<td>1.66</td>
<td>2.76</td>
</tr>
<tr>
<td>Pre-UV exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-UV exposure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- The streak pattern and width remained same implying no further oxygen bleaching occurred
- The encapsulant browned over the cracks implying the new browning occurred uniformly

Conclusions

- Resource and time saving method of obtaining three temperature was presented
- Higher acceleration factors and data at multiple temperatures
- Steady module temperatures of 60°C, 67°C, 77°C, and 85°C were achieved
- Higher temperatures correspond to higher current drops
- UVF imaging set-up uniformly illuminates modules
- Can be applied to power plants as a fast, non-contact technique of encapsulant browning detection

Acknowledgments: This material is based upon work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) under SolarEnergy Technologies Office (SETO) award number DE-EE0007138 (PREDICTS 2).
Mechanisms of Potential Induced Degradation and the Influence of Encapsulant Properties
Brian Habersberger, Lisa Madenjian

**PID-s: Sodium diffusion from glass to cell**

Glass  \(\Delta V\)  EVA  Cell  \(\text{Na}^+\) transport

**PID-p: Charge accumulation in passivation layer**

What is the relationship between these mechanisms and encapsulant properties?
- The use of encapsulants such as polyolefin (POE) and ionomer has been shown to mitigate or prevent PID
- POE and ionomer have higher electrical resistivity than EVA
- The PV technical community has thus assumed that high encapsulant resistivity is associated with PID prevention

IEC 62788-1-2 Measurement of volume resistivity of photovoltaic encapsulants and other polymeric materials

Method A: “For characterization with regard to PID resistance”
Resistivity calculated based on 4 red data points

What is the mechanistic relationship between resistivity and PID-s or PID-p?

**PID-s: Sodium diffusion from glass to cell**
- Known to be caused by \(\text{Na}^+\) specifically
- Replacing \(\text{Na}^+\) with \(\text{K}^+\) prevents PID-s, for example
- Resistivity testing is conducted in the absence of \(\text{Na}^+\)
- Resistivity testing measures mobility of ions natively present in the encapsulant
- Resistivity has no predictive power with respect to PID-s

**PID-p: Charge accumulation in passivation layer**
- Potentially caused by any charge transport
- Has been shown to occur in as little as 2 min of PID testing
- Initial charge transport rate in resistivity testing is often 10-100x relative to longer times
- Accumulated charge (Q) should be the mechanistically relevant parameter
- Critical time frame for fielded module PID-p susceptibility is unknown
Training the Next Generation of PV Reliability Experts – New Marie Sklodowska-Curie (MSCA) Project SOLAR-TRAIN

INTRODUCTION

- SOLAR-TRAIN is a Marie Sklodowska-Curie (MSCA) Innovative Training Network (ITN)
- It brings together 14 international, multi-disciplinary early stage researchers (ESR) to work towards the common goal of «Photovoltaic Life Time Forecast and Evaluation»
- ESRs are hosted by a consortium of eight research institutions, universities and companies with the support of 10 partner organizations in Austria, France, Germany, Italy, Spain, Slovenia and the UK

PV MODULE LIFE TIME FORECAST AND EVALUATION

Motivation

- Enhance quality assurance in the photovoltaic industry by underpinning science and trained personnel
- Gain a profound understanding of degradation factors and their implication on energy yield over life time
- Reduce costs of energy

Objectives

- Develop novel and validated models for service life time and energy prediction of PV modules and systems.
- Enable a scientific assessment of the triangle quality, durability and costs.

14 INDIVIDUAL RESEARCH PROJECTS

Cross-sectoral, multi-disciplinary research

- SOLAR-TRAIN’s research evolves in 14 research projects with individual areas of focus
  - (a) climatic degradation factors,
  - (b) system analytics,
  - (c) material (polymer) parameters,
  - (d) service life & energy models,
  - (e) linking production to performance and
  - (f) performance enhancement by improved O&M.

Knowledge beyond mere academia

- ESRs exchange between industry and research institutes, getting to know the requirements of fundamental and applied research as well as the economic implications of their work.
- For a most effective cross-sectoral training, beneficiaries and partners represent the entire value chain, from materials developers / manufacturers through to operators and insurance companies.

PRESENTATION ESR’S

<table>
<thead>
<tr>
<th>ESR</th>
<th>Name</th>
<th>Institute</th>
</tr>
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<tr>
<td>1</td>
<td>Amantin Panos Mehilli</td>
<td>Fraunhofer ISE/Germany</td>
</tr>
<tr>
<td>2</td>
<td>Djamel Eddine Mansour</td>
<td>Fraunhofer ISE/Germany</td>
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<td>3</td>
<td>Ismail Kaaya</td>
<td>Fraunhofer ISE/Germany</td>
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<td>4</td>
<td>Ashenafi Gebregiorgis</td>
<td>Loughborough Univ./UK</td>
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<tr>
<td>5</td>
<td>Nikola Kyranaki</td>
<td>Loughborough Univ./UK</td>
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<td>6</td>
<td>Francesco Mariottini</td>
<td>Loughborough Univ./UK</td>
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<td>7</td>
<td>Stefan Mitterhofer</td>
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<td>8</td>
<td>Julián Ascencio Vásquez</td>
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<td>Aziz Nairi</td>
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<td>Luis Castillon</td>
<td>PCCL/Austria</td>
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<tr>
<td>14</td>
<td>Guillermo Oviedo Hernández</td>
<td>BayWa r.e./Italy</td>
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</table>

INNOVATIVE TRAINING SCHEME

Eight basic elements to foster ESR’S technological knowledge and the necessary soft skills for their PhD projects and professional careers in an intercultural and interdisciplinary environment

1) Basic Training
2) Beginners’ Week
3) Three Summer Schools
4) Online Seminars
5) Individual Training Modules
6) Action Centered Learning
7) Mentoring
8) Intersectoral Secondments

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 721452.
Camera Calibration and Image Correction to Enabling Quantitative EL Analysis (QELA)

Karl G. Bédřich1, Jing Chai1, Yan Wang1, Armin G. Aberle1, Yong Sheng Khoo1

1Solar Energy Research Institute of Singapore, National University of Singapore, Singapore; www.seris.sg
Contact: karl.bedrich@nus.edu.sg

Introduction

- **Situation:** For quantitative analysis, EL images have to be corrected for camera and perspective distortion. However, camera calibration is time consuming, need to be conducted by qualified personnel and calibration quality is generally not analysed.

- **Problem:** Often, extensive camera calibration is NOT performed and image correction is limited to background subtraction, manual image cropping and possibly a homebrew vignetting correction. Neither camera calibration, nor image correction are sufficient for quantitative analysis.

- **Solution:** Generate camera calibration exclusively from EL images (Fig 1). User interaction is not necessary.

Image Correction

- **Removal of camera and perspective distortion.** Normalisation of image intensity (using ISO, exposure time, f-number and current applied).

- **Calculation of uncertainty map (using SNR, sharpness maps, signal deviation).**

- **Removal of imaging artefacts** (single time effects, hot pixels) and image enhancement (noise reduction, sharpening).

> Corrected images are imaging setup independent. Temporal changes can be visualized by pixel difference.

Workflow

- Raw EL images are imported via drag and drop. A click on the 'Submit' button initialises processing.

- A GPU-accelerated server conducts camera calibration, images correction and analysis (uncertainty, compliance with IEC TS 60904-13, crack distribution, electrical connectivity, power loss estimation)

- For every module, one PDF report is generated (Fig 2). Report and supporting documents (EL/uncertainty images, cell averages) are send to client.

Interactive Image Analysis

- Once processed images are available, individual image comparison and measurement can be conducted using the freely available software ‘dataArtist’ (Fig 3).

Dates

- May 2018 (SNEC): Live presentation of QELA cloud.

- Sept 2018 (EU PVSEC): Comparison of image similarity: manual vs automated camera calibration using results from 1st international Round Robin on EL.
Developing PV Preventative Maintenance (PM): Application of Equipment Reliability framework

Background / Purpose:
The Equipment Reliability framework is broadly used across industries, including at traditional electricity generating plants. It integrates and coordinates a broad range of activities into one process to:
1) Establish the optimum preventive maintenance tasks
2) Monitor and communicate the performance and health of critical equipment
3) Develop and implement long-term equipment health plans
4) Continuously improve maintenance strategies based on operating experience

Hypothesis:
Lessons learned from other generation assets can benefit the solar industry by:
1) Guiding how existing operational experience and data can be turned into action
2) Providing toolset to optimize maintenance activities

Conduct Experiment:
The inverter is “critical” for PV plants and warrants preventative maintenance (PM). Development of PM bases requires:
1) Understanding of the Equipment Reliability framework (workshop on Mar. 2, after PVRW)
2) Expert elicitation for Failure Modes and Effects Analysis (FMEA) to create maintenance template (to happen Q3 ‘18)
Non-critical equipment should use reactive maintenance, a.k.a., “break-fix.”

Observe and Record:
EPRI intends to implement and trial approach in matched power blocks of PV plant(s).

Attend PV Inverter Roundtable meeting on Mar. 2, after PVRW!
Email mbolen@epri.com and pgordon@epri.com to RSVP
Experimental Details

The outdoor EL setup consists of a DC power supply unit (PSU) and a PV module connected to a modulation box. This system synchronizes the image acquisition with an electrical forward bias applied by the DC power supply. The camera synchronization was performed via radio communication with the logic controller.

Results

The critical information regarding the state of the active area of the PV modules was preserved in the processed outdoor EL images, when compared with the indoor EL images, acquired with a high resolution camera.

Conclusions

We have demonstrated the experiment and image processing steps (entire pixel displacement) for the acquisition of EL images outdoors during the day under movement. A 1 m/s movement speed in an automated drone system opens the possibility of performing EL on 1 to 2 modules per second, depending on the installation configuration, corresponding to 1 MW inspected per hour.

Image Processing

To match several images from a non-stationary EL acquisition during the day, several image-processing steps are required. The automation of this process is ongoing. The steps for processing the EL and BG images will include:

- Detection and segmentation
- EL / BG images separation
- Perspective correction
- Motion correction
- Denoise by averaging
- BG subtraction
- Quality control

Introduction

Electroluminescence (EL) imaging can be used to quickly and accurately detect a large range of major and minor faults in PV modules. For EL inspections at PV power plants, the fastest scenario will include a drone based image acquisition in continuous movement.

With this motivation, in this work we investigate the quality of EL images acquired under different movement speeds and frame rate scenarios.

Furthermore, we describe the image processing required for denoising by averaging and background (BG) subtraction, essential for daylight EL imaging.

Outlook

In future work we will perform the same movement experiment on c-Si modules that have significant cell cracks from mechanical load testing. Additionally, we will quantify the image signal to noise ratio per the IEC 60904-13 draft standard as a function of movement speed and exposure time.

Movement experiments with higher speeds and under high sun irradiance will begin in few weeks.

Acknowledgements

The project is funded by Innovation Fund Denmark by project 6154-00012B DronEL – Fast and accurate inspection of large photovoltaic plants using aerial drone imaging.

Partners

Gisele A. dos Reis Benatto1, Nicholas Riedel1, Adrian Antamaria Lancia1, Sune Thorsteinsson1, Peter B. Poulsen1, Anders Thorseth1, Carsten Dam-Hansen1, Claire Mantel1, Søren Forchhammer1, Kenn H. B. Frederiksen2, Jan Vedde3, Michael Larsen3, Henrik Voss3, Harsh Parikh6, Sergiu Spataru6 and Dezso Sera6

1Department of Photonics Engineering, Technical University of Denmark, Frederiksbergvej 399, 4000 Roskilde, Denmark; 2Kenergy, Tobaksgråden 3, 8700 Horsens, Denmark; 3SiCon Silicon & PV consulting, J N Vinthersvej 5, 3460 Birkedal, Denmark; 4Skive Kommune, Torvegade 10, 7800 Skive, Denmark; 5Sky-Watch A/S, Østre Alle 6, 9530 Støvring, Denmark; 6Department of Energy Technology, Aalborg University, Fredrik Bajers Vej 5, 9220 Aalborg, Denmark.
Locating problems in series-connected strings of PV modules can be time consuming. JV monitoring can alert operators of problems at the string level, while IR imaging is unable to see issues with cabling behind the modules. We are developing Spread Spectrum Time Domain Reflectivity (SSTDR), a commercialized technique in other industries, to electrically find changes in impedance along such strings.

Here we present the model framework and some preliminary results. The solar cell's AC impedance is treated as a function of illumination, voltage, temperature, and material properties while conductors are characterized by passive RLGC transmission line elements. The combined model will predict the time domain response of the system and allow interpretation of field-measured data.

**SSTDR Technique**

- Conceptually, SSTDR sends signals through the system and “listens” to the “echoes”. Because of the multitude of impedance discontinuities in a string, the signal is very rich, but complex to interpret at first glance. We are thus developing modelling of the conductors and modules to help to interpret the signals.

- Time delay is measured from time correlation of the sent digital pseudo-noise code with the reflected waveform is converted to physical distance by a propagation velocity.

**Model of the System**

- The full model will incorporate the internal structure of the module, bypass diodes, cables, and MC4 connectors. The string will be assembled from these units (Top).

- (Top left) Cole-Cole plots of cell impedance (Zcell) vs frequency for different cell operating voltages. Forward bias lowers the cell impedance exponentially, allowing low loss propagation over many modules (the plot for 0.5 V is shown in the inset).

- Frequency increases anti-clockwise on this plot.

- Bottom left figure, total cell impedance and the characteristic impedance of the transmission line are plotted together. RLGC model of transmission line has been used.
Photovoltaic Array Foundation Test Program

Ernie U and Aamir Abidi

Failed Foundations in Ontario

What is Frost Heaving?

Water sources can include:
- groundwater and;
- pore water

Freezing air temperatures drive advancement of frost. The speed of advancement is affected by factors like severity of cold, snow cover, etc.

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Grain Size</th>
<th>Permeability (m/s)</th>
<th>Capillary Rise (inches)</th>
<th>Frost Susceptibility Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt</td>
<td>0.002 – 0.07</td>
<td>12 – 475</td>
<td>12 – 150</td>
<td>1 – Highest</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;0.002</td>
<td>&gt;400</td>
<td>&gt;10-9</td>
<td>2</td>
</tr>
<tr>
<td>Sand</td>
<td>0.007 to 2</td>
<td>1 – 20</td>
<td>10-4 – 10-6</td>
<td>3</td>
</tr>
<tr>
<td>Gravel</td>
<td>&lt;2</td>
<td>&lt;1</td>
<td>10-3 – 10-4</td>
<td>Lowest</td>
</tr>
</tbody>
</table>

Heave begins with a hard freeze, which creates a frost front that penetrates the soil. The front causes freezing of pore water. As ice forms this can generate a volumetric expansion of approximately 10%.

The heavy lifting begins when the frost front reaches a penetration limit. Fed by water from saturated ground below, an ice lens forms which will push upward and displace soil.

The heavy lifting begins when the frost front reaches a penetration limit. Fed by water from saturated ground below, an ice lens forms which will push upward and displace soil.

The lens stops growing when its water supply runs out, at which point the frost front continues downward until it reaches saturated soil again and forms another ice lens. This process can continue repeatedly during the course of a winter.

Step-by-Step Process

Conclusions

Ensure cost-effective helical pile design that will resist frost heaving forces at the Nanticoke Solar site

Reduce the overall geotechnical risk of the project

Credits

- Neely, S.D, (P.E.), Terracon – Principal Geotechnical Services, Tempe, AZ, USA
- Olar, A. (P.Eng), Tulloch Engineering – Structural Lead, Sault Ste. Marie, ON, Canada
- Ritzmann, K., ALLTRADE Industrial – Construction Manager, Cambridge, ON, Canada

Typical Pile Test Results

<table>
<thead>
<tr>
<th>Pile Type</th>
<th>Pile Size</th>
<th>Test Load</th>
<th>Displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven Pile</td>
<td>300 mm diameter</td>
<td>200 kN</td>
<td>20 mm</td>
</tr>
<tr>
<td>Screw Pile</td>
<td>250 mm diameter</td>
<td>150 kN</td>
<td>15 mm</td>
</tr>
<tr>
<td>Helical Pile</td>
<td>200 mm diameter</td>
<td>100 kN</td>
<td>10 mm</td>
</tr>
</tbody>
</table>

Managing Frost Heave Risks

Approach | Measures
--- | ---
Modification | Replace frost susceptible soil with non-frost susceptible material
Prevent freezing/thawing | Ground heating or cooling systems
Drainage | Improving site drainage can reduce formation of ice lenses
Accept frost action | Design foundations to resist heave forces or be accepting of potential movements.

Nanticoke Site Soil Condition

Geotechnical report concluded:
- Water
- Temperature
- Frost susceptible soil

Frost heaving risk is high

Field Test Approach/Procedure

Based on an in-situ foundation test program to design a frost heaving resistance foundation system to reduce geotechnical risks

Results

- Measured the displacements for various piles under tension and lateral loadings
- Observed actual in-situ installation time for various piles
- Discovered various geotechnical anomalies in the project site
- Established the relationship between torque vs. apply loading for helical piles
- Recommended suitability the use of galvanized and non-galvanized material

Nanticoke Solar – Project Overview

- Project Location: Nanticoke, Ontario, Canada
- Project Site Area: 350 acres; former coal yard (34 acres) and agricultural land (316 acres)
- Capacity: 44MW ac; 66 MW dc
- Connection: Transmission connected (230 kV)
- Solar Panel: 72 Cells, 330 – 340W, 1,500V, approx. 200,000 panels
- Racking: Fixed Tilt, Landscape 4 x 9 table, approx. 5,600 tables, 23,000 piles
- COD: Q1 2019
- Project Website: www.nanticokesolar.com

Credits

- Neely, S.D, (P.E.), Terracon – Principal Geotechnical Services, Tempe, AZ, USA
- Olar, A. (P.Eng), Tulloch Engineering – Structural Lead, Sault Ste. Marie, ON, Canada
- Ritzmann, K., ALLTRADE Industrial – Construction Manager, Cambridge, ON, Canada
Correlating Field and Chamber Leakage Current Rates for PID Testing of Thin Film Modules

Darshan Schmitz1, Hiroshi Tomita1, Shuji Tokuda1, Keiichiro Sakurai2, Kinichiro Ogawa2, Hajime Shibata2 and Atsushi Masuda1

1. Solar Frontier, 123-1 Shimo-kawarai, Atsugi, Kanagawa 243-0206, Japan
2. National Institute of Advanced Industrial Science and Technology (AIST), Central#2, 1-1-1 Umeonzo, Tsukuba, Ibaraki 305-8568, Japan

February 27, 2018. NREL / SNL / BNL PV Reliability Workshops

Summary

Data sources

Table 1: Overview of data sources used for comparative analysis.

<table>
<thead>
<tr>
<th>Source</th>
<th>Data</th>
<th>Cell</th>
<th>Module</th>
<th>Mount</th>
<th>Test Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIST</td>
<td>field data</td>
<td>CIGS</td>
<td>Framed glass/glass</td>
<td>Insulated clamps</td>
<td>Outdoor measurement in Tosu-shi, Japan, +1000 V (worst case grounded) based on 4 months of data (Aug-Nov).</td>
</tr>
<tr>
<td>Solar Frontier</td>
<td>chamber data</td>
<td>CIGS</td>
<td>Framed glass/glass</td>
<td>Chamber rack</td>
<td>PID96 h @ 85/85, +1200 V (worst case grounded)</td>
</tr>
<tr>
<td>ZSW</td>
<td>field + chamber data</td>
<td>CIGS</td>
<td>Frameless glass/glass, Framed glass/glass</td>
<td>Standard vs. high resistivity (HR) clips</td>
<td>Outdoor measurement in Widderstall, Germany, -1000 V &amp; -500 V recalculated to -400 V (worst case floating) based on 1 year of data.</td>
</tr>
</tbody>
</table>

Test configurations

AIST field data, SF chamber data

Table 2: Transferred charge shown for each case in coulombs / module over a given time period. For comparison with c-Si PID test conditions, the field data quantity highlighted in yellow has been calculated to estimate coulombs transferred after 5 yrs in field under normal outdoor conditions.

<table>
<thead>
<tr>
<th>AIST field data</th>
<th>Tosu-shi, Japan, +1000V</th>
<th>Time: 8/4-9/30, 10/24-11/30</th>
<th>PID</th>
<th>Framed CIGS Modules Transferred charge (C/Module)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module 1</td>
<td>Daytime</td>
<td>0.16</td>
<td>38 days (10/24 - 11/30)</td>
<td>5 yrs</td>
</tr>
<tr>
<td>SF chamber data</td>
<td>85° C / 85% RH, +1000V</td>
<td>Dwelling: 96 hrs</td>
<td>Module A</td>
<td>Module B</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.92</td>
<td>4.87</td>
</tr>
</tbody>
</table>

ZSW field and chamber data

Table 3: For comparison with c-Si PID test conditions, the IEC test time estimates highlighted in yellow have been recalculated to show equivalence to 5 years of field exposure. *Framed module estimates provided by P. Lechner via email. Based on 6 months field data (Jan – July) at same Germany location, also adjusted to assume -400V system voltage.

<table>
<thead>
<tr>
<th>CIGS Modules</th>
<th>Frameless</th>
<th>Framed*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Condition</td>
<td>Standard clips</td>
</tr>
<tr>
<td>1 year outdoor field</td>
<td>Germany, -400 V</td>
<td>0.60 C/yr</td>
</tr>
<tr>
<td>1000h IEC test</td>
<td>85° C/85% RH, -1000 V</td>
<td>26.9 C</td>
</tr>
<tr>
<td>IEC test duration to cover 25 yrs field</td>
<td>550 h</td>
<td>9400 h</td>
</tr>
<tr>
<td>IEC test duration to cover 5 yrs field</td>
<td>113 h</td>
<td>1880 h</td>
</tr>
</tbody>
</table>

Conclusion

While further investigation of the impact of site location is necessary, our initial observation is that 96 h is relatively equivalent to 5 yrs of field exposure for framed CIGS modules mounted in standard configurations.

After adjusting for the impact of electric potential, frameless CIGS modules mounted in standard configurations may require a slightly longer chamber duration. However, the impact of electric potential appears to be significantly less than the impact of mounting.

References


Contact

Correspondence should be addressed to Darshan Schmitz, Solar Frontier. Mail: darshan.schmitz@solar-frontier.com TEL: +81-46-245-7202 FAX: +81-46-245-8761
OBJECTIVES
This project intends to increase understanding of DC arc-flashes, their hazards in PV system, and codify results in IEEE 1584 by:

• Performing dc arc-flash experiments on mock-up and actual PV equipment in the lab;
• Developing detailed physics-based arc-flash models that corroborate lab tests and can aid equipment design; and
• Publishing an easy-to-use, publically-available incident energy calculator to ensure appropriate personal protective equipment (PPE) for field workers in utility-scale PV plants.

APPROACH
• Create, refine, and utilize arc-flash modeling capabilities at Sandia National Laboratories
• Physical testing of arc-flashes up to 1500 V_{dc} in high-power PV equipment to measure incident energy (IE) at Sandia National Laboratories
• Disseminate findings via publications serving as a call-to-arms, which include a public white paper published by EPRI, conference proceedings, and peer-review journal article(s)
• Drive consensus among stakeholders and subject matter experts to codify DC incident energy (IE) methodology and associated calculations for creating IEEE standard

MOTIVATION FOR THE WORK

Incident energy spans multiple PPE categories depending on the calculation model used.

INITIAL FIELD TEST RESULTS

Current and voltage response during purposefully initiated arc-flash in an inverter (within a 1MW_{dc} array).

We are seeking string inverters for arc-flash experiments. Non-functioning units ok!
Optical Spectroscopic Probes of Degradation and Metastability in Cu(In,Ga)Se₂ and (Ag,Cu)(In,Ga)Se₂

Andrew Ferguson¹, Pat Dippo¹, Darius Kuciauskas¹, Rouin Farshchi², Jeff Bailey², Geordie Zapalac², and Dmitry Poplavsky²
¹ National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA
² MiaSolé Hi-Tech Corp., Santa Clara, CA 95051, USA

Objective
Develop rapid, accurate, contactless, non-destructive optical spectroscopic probes of:
- defect properties & reliability physics
- defect-mediated metastability
- stress-induced degradation

Methodology
- Lany-Zunger model predicts conversion of V_{Ag}⁻ into Na⁺/K⁺ divancy complex from shallow donor to deep recombination center
- Employ tunable time-resolved PL excitation wavelength to measure spectra and depth resolve metastable defects
- Defect Spectra in CIGS and ACIGS

Electronic Properties of MiaSolé ACIGS
Potential fluctuations, defined by (σ/γ), are temperature independent:
- device V_{oc} increases when E_{b} increases
- carrier mobility

Degradation of MiaSolé ACIGS PV Devices
Dark-degradation (DH1000) treatment: 2x reduction in doping concentration; little impact on EQE response
- Light-soaking: 10x increase in doping concentration; reduced EQE response in near-IR
- light-soak effect more pronounced for low Se samples

Light Soaking
Light exposure results in a reduction in TRPL lifetime
- sub-bandgap pulsed laser excitation induces similar effect
- light exposure results in a reduction in TRPL lifetime
- light exposure results in a reduction in TRPL lifetime

Conclusions
- optical spectroscopic techniques:
  - are sensitive probes of electronic disorder and defects in CIGS & ACIGS absorbers
  - can distinguish between defects located in different regions of the absorber
  - unravel defect-mediated reliability physics associated with dark-heating treatment and/or light-soaking
  - can be used for rapid "simulation" of the degradation effects of 1-Sun light soaking

Ag Alloying for Improved PV Devices
Alloying with Ag increases bandgap, E_{g}, without affecting recombination and disorder
- V_{oc} increase is determined by E_{g} increase
- MiaSolé PV device efficiencies 17-18%

Material library provided by MiaSolé provides control over:
- composition
- impact of Ag alloying
- pre-growth treatments
- post-growth stress
- defect-mediated metastability
- stress-induced degradation

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with Alliance for Sustainable Energy, LLC, the Manager and Operator of the National Renewable Energy Laboratory. Funding provided by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office, under Award Number 83006.
CONSIDERATION OF TERRAIN EFFECTS FOR DESIGN AND MODELING OF GROUND MOUNTED PV SYSTEMS USING SINGLE-AXIS TRACKERS

Liam Norris, Brandon Liang, and Itai Suez, PhD

Utility Scale Solar Trackers

- Horizontal Single-Axis Trackers (HSAT) most commonly used in utility-scale PV systems
- Racks oriented North/South
- Tracker rotates East/West moving with the solar azimuth angle

Acquiring Reliable Topographical/Elevation Data

- Sample from 100MW+ PV array design on non-flat terrain

Challenges in Modeling Solar Trackers: Row Heights

- Eastern & Western Slopes – “The Elephant in the Room”

Tracker Tilt Angle: Distribution Analysis

- No software currently exists to model an entire complex solar tracker PV array system in 3D
- Must determine “effective” tracker tilt angle through use of weighted averages

Performance Impacts vs. N/S Tracker Tilt Angles

- Row height challenges in modeling solar trackers

Incident Angle Modifier (IAM) Sensitivity

- Southern latitude: East/West orientation can have significant impact

Key Takeaways/Summary

- North-South tracker tilt angle has a non-linear effect on energy production
- This effect on energy production is amplified at higher latitudes and under more “clear sky” conditions
- Both cosine Losses (CSL/θ) and incident angle modifier (IAM) losses are behind the non-linearity
- Losses due to CSL/θ are the primary contributing factor to the non-linear effect on energy production with IAM losses being secondary
- Modelling these effects requires an “effective” tracker tilt angle determined by taking an average of each tracker’s tilt angle after being weighted for both CSL/θ and IAM losses
- Simulating energy production with different neighboring tracker heights or tilt angles is not yet possible.
Effects of Mechanical Damage and Temperature on the Electrical Performance of CIGS Thin Film Solar Cells

Hansung Kim, Benjamin G. Wojkovich
Department of Mechanical and Civil Engineering
Purdue University Northwest
Hammond, IN USA

Introduction

- CIGS thin films for solar cells
  - Widely used for flexible solar cells
  - Bendable and reliable
  - Temperature effect and mechanical effect should be investigated

Experimental Equipment

- Equipment for Solar cell test
  - Universal test machine
  - Temp controlled environmental chamber
  - Solar cell analyzer
  - Crack detecting Infrared camera
  - Atomic Force Microscopy

Influencing Factors on Solar Cells

- Mechanical damage
  - Caused by external load (Impact, bending, rolling)
- Temperature

Research Motivation

- We concurrently evaluate the effect of temperature and mechanical damage on CIGS solar cells to answer the critical questions below.
  - Does the mechanical damage (crack) alter the temperature effect on solar cells?
    - For example, does an undamaged solar cell at 20 °C have the same open circuit voltage as a 20% damaged cell at 20 °C? How the damage effect be quantified?
  - Does temperature alter the mechanical damage effect on solar cells?
    - For example, does a solar cell with 10% damage at 10 °C, have the same open circuit voltage as a solar cell with 10% damage at 70 °C? How can this be quantified?

Experimental Procedure

- Systematically investigated the effect of temperature and mechanical damage simultaneously
  - Temperature variation
    - 10, 20, 50, 70 °C
  - Mechanical damage (at each temperature)
    - 0, 30, 60, 80 % damage
- FG-SM12-11: 7.7 Watt (6V) Solar Submodule
  - By Global Solar Coompany
  - CIGS Thin films
- I-V curve was generated at each design point

Experimental Results

- Light Generated Current vs Damage
- Saturation Current vs Damage
- Short Resistance vs Damage
- Series Resistance vs Damage

Simulation Results

- Diode is a semiconductor device
- Most basic circuit in solar cell modeling
- Simple equations

Single Diode Circuit Model

\[ I = I_L - I_S \left( \frac{V + IR_S}{nF} \right) = I_S \left( \frac{V + IR_S}{nF} \right) \]

light generation current (I_L), saturation current (I_S), shunt resistance (R_S), series resistance (R_S)

Conclusion

- Effect of temperature and mechanical damage was investigated for CIGS solar cells
- Electrical performances were found as a function of temperature and mechanical damage
  - Open circuit voltage (Voc)
  - Short circuit current (Isc)
  - Efficiency
- Parameters of a single diode circuit model was obtained as a function of temperature and mechanical damage
  - light generation current (I_L)
  - saturation current (I_S)
  - shunt resistance (R_S)
  - series resistance (R_S)
Wind Stow Frequency for Tracking PV Plants
Chris W. Wolfrum, Sara M. MacAlpine, Owen W. Westbrook • juwi Inc., Boulder, CO 80301

Abstract
Trackers collect substantially more solar irradiance than fixed-tilt systems on an annual basis, and their cost-effectiveness and reliability has led to their widespread use in large-scale solar photovoltaic power plants. To prevent damage from high wind events, tracking rack manufacturers develop wind stow strategies that ensure that static and dynamic loads remain within design tolerances up to the maximum expected site wind speed. These stow strategies move the arrays to a safe position for the duration of a high wind event and hold that orientation until high winds have subsided for a defined period. While this method is effective at protecting the tracker’s structural integrity, nearly all events result in suboptimal module orientations with respect to the solar resource, leading to lost energy generation.

Data & Methods
- We modeled tracker wind stow frequency at ten sites provided by the Measurement and Instrumentation Data Center (MIDC) using one-minute, daytime peak wind data (3-sec gust) across multiple years.
- Using a power law, the wind speeds were adjusted from their measured height to a control height of 10 feet.

\[ v_w(h) = v_{ref} \left( \frac{h}{h_{ref}} \right)^a \]

- \( v_w \): adjusted wind speed
- \( v_{ref} \): measured wind speed
- \( h \): control height, 10 feet
- \( h_{ref} \): height where wind speed was measured
- \( a \):Hellman exponent, 1/7 in neutral flow

- We modeled six stow wind speed thresholds with four wait periods.
- The stow wind speed threshold is the wind speed that initializes a stow.
- The wait period is the time elapsed after the wind speed drops below the stow threshold before the tracker resumes tracking.
- Duration, S, indicates the total time that the tracker would spend in wind stow based upon varying stow wind speed thresholds and varying wait periods. Higher percentages indicate increased stow time and decreased production.

Summary & Conclusion
- Wind stow effects, though not explicitly accounted for in commercially-available modeling tools, should be assessed when predicting energy generation and establishing performance guarantees for tracking PV systems.
- We performed an analysis of multiple years of one-minute wind data from ten geographically diverse sites, examining the percentage of daylight hours impacted by wind stow as a function of the stow wind speed threshold and wait time.
- Results ranged from 0% to 16% of daylight hours in wind stow, depending on the site and chosen wind stow strategy. No sites experienced more than 1% of daylight hours in wind stow when the stow threshold was set to 40 mph or higher.
- Performance impacts of wind stow can be significant, but modeling those impacts requires a site and design-specific analysis because the time spent in wind stow is highly sensitive to local wind patterns and the details of the tracker stow strategy.

Results

<table>
<thead>
<tr>
<th>Site</th>
<th>Threshold [MPH]</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Las Vegas, Nevada</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Los Angeles, California</td>
<td></td>
<td></td>
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Acknowledgments
The authors would like to thank the National Renewable Energy Laboratory for the data that made this study possible.
SHADING AND HOT SPOT RISK SCENARIOS FOR SHINGLED CELL ARRAY MODULES

Stefan Wendlandt, Bernd Litzenburger, Lars Podowski, Ian Gregory1, Marco Gallazzo2
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SolarBuyer, LLC (a PI subsidiary), e-mail: igregory@solarbuyer.com
2 Baccini Cell Systems, Applied Materials, e-mail: marco_galiazzo@amat.com

Introduction

Common PV modules consist of 60 or 72 6-inch c-Si cells connected in series. To prevent cell and module encapsulation materials from lifetime-limiting overheating or damage resulting from hot spots created by (partial) shading, usually 20 or 24 series cells are parallel connected to a bypass-diode.

To increase module efficiency, new module design concepts have been presented: these so-called “shingled cell arrays" consists of cut cell strips (here: 1/5 strips of 6-inch cells), which are connected in parallel to a bypass-diode. The layout (right) shows the basic circuit design realized in this work.

Approach: Simulation Calculations & Hot Spot Performance Test Setup

In this presentation, we report on IV curve simulation calculations as well as results of hot spot performance tests on specific (worst case) shading scenarios of shingled module concepts. We will present results taking into account different real operating conditions – for example operating shaded modules at the global MPP, respectively (T > 100°C).

Scenario A: One cell per parallel string shaded

- An increasing number of parallel shaded cells result in higher power losses and operating cell temperatures, respectively (T > 100°C).
- String lengths (e.g. of more than 24 cells in series) should be adapted to reverse breakdown voltages of used cells.
- Parallelization of serial cell strings will not help to avoid too high power losses and cell temperatures under shading conditions.
- Operating a module with shaded cells at the global MPP (usual operating condition) of a module string has a higher risk of thermal runaway for shaded cells than operating a module in its own (local) MPP (Module MPP-tracking).

Scenario B: One string completely shaded

- Modules with shaded cells at the MPP of the module string have a higher risk of thermal runaway for shaded cells than operating a module in its own (local) MPP (Module MPP-tracking).

Conclusions

- Power loss vs. string length for one shaded cell per string. More than 30 cells per string result in an inactive bypass-diode and a max. power loss for the shaded cell.
Establishing a Moisture-induced Degradation Model of Flexible PV Modules for Field Life Estimation
Authors: Bill J.J. Liu and Venkata Bheemreddy

Introduction

- Accelerated reliability testing has been widely used as an efficient strategy for assessing the field life of PV modules. Developing a reliability model for correlating accelerated test performance to field life performance is critical as it enables selection of proper barrier material to meet product specific reliability requirements.
- In this work, we have developed a reliability model for assessing the field life of CIGS based flexible PV modules using accelerated damp heat tests conducted at different temperature and humidity conditions.

Degradation Model Establishment

- A time exponent term is introduced into a modified Hallberg-Peck model to represent degradation rate for moisture ingress.

\[
\text{Degradation Rate } (P_d) \propto \tau^\alpha RH^n \exp\left(-\frac{E_a}{k_bT}\right)
\]

\(\tau: \text{Exposure time, } RH: \text{relative humidity}
\)

\(E_a: \text{Activation energy, } K_b: \text{Boltzmann constant,}
\)

\(T: \text{PV module temperature.}
\)

- Degradation at time \(t\) can be calculated as:

\[
\Delta P = A \int_0^t \tau^\alpha RH(t)^n \exp\left(-\frac{E_a}{k_bT(t)}\right) d\tau
\]

Model Parameters and Validation

- Good agreement achieved between measurement and model forecast.

Model parameters fitted by experiment data:

<table>
<thead>
<tr>
<th>Exponents</th>
<th>(\alpha + 1)</th>
<th>(n)</th>
<th>(E_a (\text{eV}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrier-1</td>
<td>0.8</td>
<td>0.03</td>
<td>0.65</td>
</tr>
<tr>
<td>Barrier-2</td>
<td>1.2</td>
<td>2.7</td>
<td>0.70</td>
</tr>
</tbody>
</table>

Degradation Pattern under DH

- Typical module degradation rate under damp heat condition is time dependent.

Experimental

- Modules with two types of barriers (type I – currently used in products, type 2- experimental) are subjected to temperature/humidity matrices to determine model parameters.

Module Temperature Model

- Location specific Module Temperature can be estimated using Sandia Model and TMY Data

Field Life Estimation – Barrier Comparison

- A reliability model with time dependent degradation rate is proposed to forecast module degradation under environmental stress.

- Barrier-1 (WVTR of 5E-4 g/m²/d) is suitable for a 25 year lifetime product and Barrier-2 (WVTR of 1E-3 g/m²/d) for 3-10 years consumer electronics products.

Conclusions

References


Daily soiling rates correlated with air quality in Oakland CA
Jessica Forbess
Sunshine Analytics

Introduction
Analysis of an eight month data set of clean and unwashed daily energy totals from a PV array on a rooftop in light industrial neighborhood in Oakland, California. Air quality was collected starting after four months, but no correlation was found in the current dataset. A seasonal difference in daily soiling rate was detected, but there is still insufficient data to identify the cause. Potential contributors are increased adhesion after wildfire soot or increased energy impact due to low solar inclination angle, despite similar accumulation of soil.

Objectives
• Capture soiling data for light industrial urban neighborhood
• Calculate daily soiling loss rate
• Test correlation of soiling and air quality data from low cost sensor
• Test correlations with other meteo data

Methods
• Microinverter based rooftop PV array
• 10° tilt, SW az, landscape 280 poly-Si
• Identified two pairs of unshaded modules
• Cleaned one of each pair weekly
• Calculated Soiling Ratio based on daily energy
• Collected daily PM 10 and 2.5 averages with Purple Air sensor

Results

Conclusions and Future Work
• There is a seasonal pattern to daily soiling loss rates for the sub-annual dataset under analysis
• Sub-daily energy comparisons should be made to confirm IA impact on soiling ratios
• Air quality captured does not have a strong correlation, and is unlikely to signal particularly large increases in soiling

References
INTRODUCTION
This project's goal is to quantify the impact of realistic damage scenarios on the performance of different crystalline silicon module technologies. Rough handling in the field may cause modules to degrade prematurely. The rate of that degradation is highly dependent on construction details of the module, particularly important is the metallization method used both on the solar cell and interconnecting solar cells in the laminate. A number of real-world damage scenarios were evaluated, and 3 were selected for detailed testing. A sample of the data generated is shown here. An effort was made to establish the long term impact to performance due to the rough handling damage.

INTENTIONAL ROUGH HANDLING
The following stressors were tested on conventional 72 cell multicrystalline silicon panels and found to do little or no damage in our initial test. This is by no means a guarantee that damage would not occur in different circumstances with different modules. To be clear, they are not recommended practices (yet they are routinely done in the field).

1. Installer Lean with Arm Supporting: installer leaning over a module to reach a clamp on the far side of the module while placing his/her hand on the glass to support his body weight.
2. Installer Lean with Knee Supporting: same as #1 but body weight is supported by the knee.
3. Hard Hat Carry, Glass Side Contact.
4. Installer Knee Bump: installer holds module vertically in portrait in front of his body and uses his knee to push at the center of the backsheet.
5. 12oz Water Bottle Drop on Glass from 3' height

Stressors that repeatedly resulted in damage (as seen in EL)

- Hard Hat Carry, Backsheet Contact (at point of contact only)
- Step on Glass Side (extensive damage)
- 90° Portrait Drop (Wind Blown Drop) (extensive damage)

Rough Handling methods chosen for detailed testing:
1. 10 Heavy Steps (Installer weight = 220 lbs, 100 Kg)
2. 12" Drop on Racking Supports – Lazy Installer Drop
3. 90° Portrait Drop on a pallet - Wind Blown Drop

SOLAR CELL CRACKS
Solar cell cracking results in potentially isolatable areas of the wafer. Increasing the number of busbars can limit the overall impact to Power. Thick plated metallization can also offer fault tolerance [1].

INCIPIENT CRACKS RECOVER

Crack Damage Recovers in Time!

OBSERVED CRACKS AND RECOVERY

Performance Under Mechanical Tension (PUMT)

Does PUMT Testing Introduce Damage?

CONCLUSIONS
• The Effective Degradation Rate of cracked solar cells is still largely unknown.
• The impact of Rough Handling strongly varies from module to module.
• The appropriate mechanical design can make modules more tolerant to solar cell cracking when roughly handled.
• The appropriate solar cell metallization technology can minimize performance degradation after solar cell cracking occurs.
• PUMT may be useful as an indicator of potential long term degradation, however much more testing is needed.

ACKNOWLEDGEMENTS
This work was funded in part by the SunPower Corporation. Accelerated aging work was done at NREL by Rajiv Dubey under the SERIUS program.

REFERENCES
Evaluation of PID chamber and field testing of CIGS modules

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Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (ZSW), Meitnerstr. 1, 70563 Stuttgart, Germany
Corresponding author: peter.lechner@zsw-bw.de

Motivation

• Thin-Film-PV modules can suffer from Potential-Induced Degradation (PID)
• IEC TS 62804-2 Draft as PID test for TF modules is under discussion
• Equivalence of transferred charge during chamber test and during field operation as metric for PID-stress severity

Approach

Evaluation of leakage currents and transferred charge for CIGS modules:
• Frameless types (I and II) glass/glass modules, mounted with edge clips/standard EPDM rubber and framed (type III)
• Two different module leakage current measurements (Electrometer at high potential side)
  - environmental chamber test at 85°C/85%rel.H/-1000 V
  - outdoor field test (Widderstall, Germany) at -1000 V (for E>5 W/m²)
• Calculation of PID test time required to simulate PID stress of 5/25 years in field
  - Site and climate specific impact on transferred charge not addressed in this work

Leakage current/charge fluctuations

• Chamber test reveals significant leakage current fluctuations up to -38%/+36 % (min/max values) coming from
  - module to module variation, fluctuation of chamber humidity,
  - test interruption for flasher measurement
  - not identified reasons
• Transferred charge in Outdoor tests reveals smaller fluctuations:
  - from module to module in the range of +/-8 %
  - from 2016 to 2017 in the range of only +/-3 %

Results and Discussion

Arrenius plot for leakage currents from field tests including averaged chamber test currents at 85°C/85%RH condition; CIGS type I (top), CIGS type II (bottom)

Table

<table>
<thead>
<tr>
<th>Item</th>
<th>Condition</th>
<th>CIGS type I</th>
<th>CIGS type II</th>
<th>CIGS Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement transferred charge</td>
<td>outdoor field</td>
<td>1 yr, -1000 V daytime</td>
<td>1.49 C/yr</td>
<td>0.17 C/yr</td>
</tr>
<tr>
<td>Transferred charge IEC TS 62804-2</td>
<td>Chamber</td>
<td>85°C/85%RH</td>
<td>1000 h @ -1000 V</td>
<td>26.9 C</td>
</tr>
<tr>
<td>Calculated acceleration factor</td>
<td>Chamber</td>
<td>158</td>
<td>891</td>
<td>258</td>
</tr>
<tr>
<td>Calculated PID test duration for 5 yrs field “short term PID test”</td>
<td>IEC condition</td>
<td>111 h</td>
<td>20 h</td>
<td>69 h</td>
</tr>
<tr>
<td>PID test duration for 5 yrs @-400 V</td>
<td>IEC condition</td>
<td>277 h</td>
<td>49 h</td>
<td>171 h</td>
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<td>PID test duration for 5 yrs @-1000 V</td>
<td>IEC condition</td>
<td>594 h</td>
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<td>343 h</td>
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<tr>
<td>Calculated PID test duration for 25 yrs service live “long term PID test”</td>
<td>IEC condition</td>
<td>1304 h</td>
<td>246 h</td>
<td>887 h</td>
</tr>
</tbody>
</table>

Arrhenius plot for leakage currents from field tests including averaged chamber test currents at 85°C/85%RH condition; CIGS type I (top), CIGS type II (bottom)

Field leakage current distribution:
- year-to-year (top) sample to sample variation (bottom)

Leakage current/charge fluctuations

• Chamber test reveals significant leakage current fluctuations up to -38%/+36 % (min/max values) coming from
  - module to module variation, fluctuation of chamber humidity,
  - test interruption for flasher measurement
  - not identified reasons
• Transferred charge in Outdoor tests reveals smaller fluctuations:
  - from module to module in the range of +/-8 %
  - from 2016 to 2017 in the range of only +/-3 %

Conclusion

• Following the principle of equivalent PID stress by equivalent transferred charge for chamber tests and field operation, the required IEC TS 62804-2 PID test duration for different framed and frameless CIGS modules ranges
  - from about 50 h to 280 h to cover PID-stress equivalent to 5 yrs field and
  - from about 250 h to 1,400 h to cover PID-stress equivalent to 25 yrs service life at -1,000 V in Widderstall/Germany
  - Fluctuation of measured charge can be significant and therefore test duration safety margins should be taken into account

ACKNOWLEDGMENT: This work was partially supported by the German Federal Ministry for Economics and Technology (BMWi), FZ 0324179
MECHANICAL LOAD TESTING OF SHINGLED CELL MODULES MADE USING ELECTRICALLY CONDUCTIVE ADHESIVES

Nadeem Haque - Solaria Corporation - Fremont, California

Shingled Cell Modules are made using Crystalline Silicon cell strips interconnected by electrically conductive adhesive. Module architecture allows for parallel connected strings. Modules outperform conventional modules in accelerated stress testing and show remarkable resiliency in mechanical load testing. Mechanical load testing results shown here.
Activities and Objectives

The project mission is to enhance ongoing research in solar technology reliability, linking worldwide efforts with those important for the now growing solar investments in Brasil. The objectives of this poster are to update on 3 areas that are current priorities:

1. Present our new climate zones maps, describe our monitoring stations, and identify the monitoring locations.
2. Provide example of the monitoring results (e.g., soilng rates) and the developed methodologies.
3. Examine the effects of uniform and nonuniform soilng conditions from our soilng stations and some laboratory simulations. This includes the identification of identified module temperature distributions and hot spot generation.

All “Dust” is not LOCAL

Phosphorous on the modules??

The chemistry & physical characteristics of dust differ from geographical region to geographical region throughout the world—even at sites within fractions of kilometers of each other.

Climate Zones, Monitoring Sites, and Stations

Figure 2. Climate zones, based upon KöppenGeiger (Meteorologische Zeitschrift 15, 259B83 (2006), showing chosen testlase dust monitoring locations (a) and additional potential monitoring sites (b) (based upon climate zone coverage and priority PV installation locations).

Figure 3. Crystallographic CDD and UV (Ultraviolet) monitoring stations (Belo Horizonte, Minas Gerais, Brazil). Capability to acquire Ip, Pmax, and entire IV characteristic.

Figure 4. Exposed stations in 2017, showing condition: (a) Upper – August 2017 Loss (b) September 17 (Modules after rain).

Figure 5. Average daily soilng ratio for poly crystalline silicon in relation to cumulative daily precipitations (Belo Horizonte, Brazil).

Figure 6. IR mapping of cSi module, showing hot spots and cold spots. (a) Initial thermal condition of module as expansion (b) Initial thermal condition of module as expansion followed by further heating to highest hot spots temperature of that region as tracked (c) as exceeded to cold spots (d) and hot spots (e) hot spots are identified by luminosity.

Soiling Rates

The soiling rates are quantified using short circuit data (SR) and power data (SR) measured in the clean and soled modules for the thinfilm and on the soled module and the selfsablizing reference cell for the cSi. These can be used to identify the whether the soilng is uniform or nonuniform.

The measured electrical parameters are normalized to the solar radiation (1000W/m²) and the temperature (25°C). This compares the performance of PV modules independent of geographic location, positioning, tilt, & nominal power. Representative data are presented for Belo Horizonte, Brazil.

Electrical and Thermal Characteristics:
Uniform and NonUniform Soilng

Non-Uniform Soilng and Hot Spots

Soiling patterns relate to hot spot generation. For selected soilng patterns on the modules, the temperature distributions relate to the IV characteristics (Fig. 6). Infrared (IR) spatial mapping shows the development of hot spots (heating of cells as a function of exposure to the sun’s radiation).

Modules After Precipitation

After rain, the modules tend to maintain the same module on the surface in the form of droplets. This means, but if the measurement is taken before complete drying, the SR data can be in error though the solar irradiance is acceptable. See such points on Figs. 5.

Summary

• Monitoring of the soilng rates (SR) is continuing, with data from 6 sites in selected climate zones (~10year).
• Studies of the IV characteristics indicate the importance of monitoring the Pmax for nonuniform soilng conditions for crystalline Si modules. Nonuniform soilng does not show differences in Ip, Pmax monitoring.
• Temperature mapping of the cSi module has been used to determine the potential of hot spots, with elevations in temperature >30°C over normal module temperature. The temperature change over time has been monitored using IR camera techniques, with initial cooling of ‘covered’ regions followed by these.
• As expected, frameless modules have benefits to avoid edge soilng conditions.
• We are continuing to develop site-specific monitoring (SR) for nonuniform soilng conditions for crystalline Si modules. A specific tool for the monitoring of uniform soilng conditions is under development (Solar Energy Europe). We are also in the process of developing a new monitoring tool to support the monitoring of uniform soilng conditions for crystalline Si modules.

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This poster contains no proprietary information.
Edge Sealant Metrology

- First Solar is forming 8 glass molds, configuring each mold to match the module width.
- The Keyence profilometer with blue laser technology creates a surface profile of the edge induced in the glass based on edge pinch data (shown on right).

- Measurements can be captured every 7 ms.
- The module is measured by a laser reflectance height sensor and thickness. From these thickness measurements, module edge pinch is calculated.
- Bead dimensional results are available on the HMI.
- Bead width is measured by finding both high and low points in a profile of module flatness to be sure that the trim process on a small case width (below, left) results in a profile of module flatness to be sure that the trim process on a small case width (below, left).

Edge Profiler Metrology

- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

Panel edge profiler metrology

- The module is captured by a vision system, which is also shown on the inspection result HMI screen.
- The profilometer collects the following outputs:
  - Trim quality
  - Module edge pinch
  - Module chips
  - Modules from each zone and color coded to determine module breakage.

Pep output 2: module glass offset

- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

The importance of module edge pinch

- A lamination process that produces a module with an incorrect amount of control in the corners. A corner that is too low or too high can result in a poorly functioning panel. A system to trim both the glass and the EVA at the same time is developed to prevent this from occurring.
- The profilometer with blue laser technology is used to generate a surface profile of the edge pinch. This information can be used for upstream process control and to ensure tolerances are appropriate for roll coating processes downstream.
- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

PEP Keyence laser reflectance height sensor

- The module is measured by a laser reflectance height sensor and thickness. From these thickness measurements, module edge pinch is calculated.
- Bead dimensional results are available on the HMI.
- Bead width is measured by finding both high and low points in a profile of module flatness to be sure that the trim process on a small case width (below, left).

Pep output 1: module trim quality

- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

PEP Keyence metrology configuration

- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

Edge pinch metrology measurement configuration

- A lamination process that produces a module with an incorrect amount of control in the corners. A corner that is too low or too high can result in a poorly functioning panel. A system to trim both the glass and the EVA at the same time is developed to prevent this from occurring.
- The profilometer with blue laser technology is used to generate a surface profile of the edge pinch. This information can be used for upstream process control and to ensure tolerances are appropriate for roll coating processes downstream.
- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

Pep output 3 & 4: module breakage and chips

- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.

Edge pinch metrology also captures module box

- In addition to module thickness and edge pinch, the sensors capture the distance from the trim line and the distance from the bottom to capture a profile of module features to be generated. This information can be used for upstream process control and to ensure tolerances are appropriate for roll coating processes downstream.
- The profilometer finds the module outer glass edges and sets a fixed perimeter for every module.
- Detailed zone data can be seen on the HMI screen.
- Detailed zone data can be seen on the HMI screen.
Evaluation of Different Models to Describe Reverse Breakdown Characteristics of CIGS solar cells

Klaas Bakker*a,b, Eduardo Gaona Peña*a, Alix Rasia*a, Arthur Weebera,b, Mirjam Theelen*c

* ECN Solliance, The Netherlands, b Delft University of Technology, Photovoltaic Materials and Devices Delft, The Netherlands, c TNO Solliance, Thin Film Technology, Eindhoven, The Netherlands

Motivation
- Partial shading on a CIGS module can force parts of the module to operate at reverse bias
- Reverse bias operation can cause damage in CIGS modules
- Quantify Reverse Bias Curve with meaningful parameters (like FF for an illuminated IV curve).
- Understand breakdown mechanism
- Mitigate negative effects by tuning reverse characteristic

Observations
- Illuminated: <5% failure early transition, steep curve
  - PF => high A, B > 0.3
  - FN => high C, D >12
- Dark: >75% failure late transition, flat curve
  - PF => low A and B
  - FN => low C large variation in D

Conclusion
- Large non-uniformity in EL, efficiency and reverse bias parameters
- Huge variation (range) in reverse bias parameters
- Parameters simplified model cannot be related to physical properties (e.g. barrier height)

Acknowledgements
The Eranet/TKI Urban Energy projects PEARL-TFPV and BIPVpod are acknowledged for financial support
Development of an Electrically-Condutive Backsheet for Back-contact based PV-Modules

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2 DSM Materials Science Center | P.O. Box 18 | 6160 MD Geleen | The Netherlands
Corresponding email: rob-r.janssen@dsme.com

Introduction
As the photovoltaics (PV) industry is getting more mature, module manufacturers are pressed by the market to increase module power output while remaining on their historical cost-reduction learning curve. Innovation is key to reach these stretched goals.

Back-contact cell technologies (e.g., interdigitated back contact and metal wrap-through) are well-documented ways to increase device conversion efficiency. Moving all contacts to the rear of the cell reduces front-side shading and therefore boosts the conversion efficiency. The power can then be elegantly transferred to an electrically-condutive back-sheet (ECB) serving the purpose of both protection from the environment and power extraction.

DSM is a company globally active in the fields of health, nutrition and materials. With its polyamides and thermoplastic polyester materials, it has a strong technology-driven market presence in many traditional engineering plastics areas such as in automotive and electronics. Moreover, in recent years it also developed into the leading supplier of anti-reflective coatings for photovoltaic glass. Driven by our ambition to expand further in the renewable energy area, we aim at developing a cost-effective, technically superior ECBS suitable for back-contacted PV modules.

Lay-out of Module with back-contact Metal-Wrap-Through cells

Followed research approach

Step 1: 2x2 cell mini-modules were built and degradation in power output in thermal cycling and damp-heat was measured

Module performance after 1000 hours 85°C/85%RH for different types of CBS

- Module performance is critically dependent on combination of polymer and metal used in CBS

Step 2: Equivalent circuit analysis revealed that module performance degradation after damp-heat testing is due to a (series) resistance increase of the contact between the Electrically Condutive Adhesive (ECA) and the ECB metal layer:

Principle of equivalent circuit analysis

Demonstration (series) resistance increase of the contact between ECA and ECB

Step 3: Building of cell-free model devices to study in detail the ECB-to-ECA contact resistance increase and its causes.

Cell-free model lay-out

ECB-to-ECA contact resistance increase

This study shows that the contact resistance increase is typically due to corrosion of both the metal layer of the ECB and the metal particles in the ECA. Both were shown to form CuO via XRD.

XRD and visual results show corrosion of ECB-metal and ECA-metal particles

Conclusions
- Degradation of module performance parameters during damp-heat testing was found to originate from a (series) resistance increase of the contact between the ECA and the ECB metal layer.
- We could correlate the oxidation of the contacts, that lead to the resistance increase of the polymer layer and to the corrosion sensitivity of the metals used.
- These results are an important steppingstone for the development of the development of ECBS suitable for back-contacted PV modules.

Example of copper based ECB patterned to interconnect MWT cells
CSI: Combined Stress with In-Situ Measurement Testing


1. TNO Solliance, High Tech Campus 21, 5656 AE Eindhoven, The Netherlands
2. Eternal Sun Group, Wolga 11, 2491 BK The Hague, The Netherlands

ABSTRACT
In order to optimize long-term stability of PV modules, their degradation behavior should be understood and minimized. Therefore, we have designed and built combined stress degradation setups, in which humidity, temperature, illumination and electrical loads are all used as combined stress on solar cells and modules. These setups also allow real-time monitoring of the electrical properties of the samples. We propose that the setups presented in this study are large improvements compared to the standard IEC tests, due to the combined exposure parameters as well as in-situ monitoring. These properties therefore greatly improve the predictive value of accelerated lifetime experiments.

INTRODUCTION
We believe that qualitative and quantitative understanding of the degradation mechanisms can best be obtained under combined stress conditions, combined with real-time monitoring of their properties, which results in combined stress testing with in-situ measurements (CSI). CSI enables:
1. Applying combined stresses on the module and its materials, showing the same failure modes as in the field and showing the accelerating/decelerating effect.
2. In-situ performance measurement shows the real-time degradation behaviour over time.

BACKGROUND
Accelerated lifetime test procedures from the IEC-61215 should ideally tell the industry and potential customers whether the requirements related to long-term performance stability are met. However, the consensus among researchers is that current IEC-61215 accelerated lifetime tests are mainly used to identify early failures, and are not a valid prediction method for lifetime and end-of-life failures. Furthermore, the official IEC tests do not focus on the fundamental understanding of the degradation process within a module. However, knowledge of the degradation mechanisms and the possibility to link these with the observed failure modes is very important. The conditions in the laboratory are meant to rapidly identify degradation effects in the field, however, these chosen conditions might actually lead to failure modes that do not occur in the field. Therefore, a large number of accelerated lifetime studies with variation in degradation conditions and sample composition is required to really predict module field performance.

METHODOLOGY
1. Preparation of own Test Samples, if facilities are present
2. Analysis of the solar cells before degradation - measure the ex-situ IV performance of the samples to determine the electrical parameters and the external quantum efficiency (EQE) for the exact current density and wavelength dependent absorption.
3. Placement of the samples into sample holders which are specifically designed to withstand the harsh conditions during the climate tests. Place the sample holders on the sample rack inside the hybrid degradation setup, which allows electrical contact between the solar cells and the measurement tools outside the setup.
4. Execution of the degradation experiment by switching on the solar simulator, heating the climate chamber, and turning on the humidity. Leave the samples in the setup for 100 to 1000 hours while measuring the IV curves.
5. Analysis of solar cells by plotting the IV parameters as a function of the exposure time and/or by measuring the IV performance, or taking microscopy pictures.
6. Definition of the failure mechanisms, modes and their impact on long-term stability of the samples by combining all the data.

RESULTS
Figure 1: The development of the efficiency of non-encapsulated CIGS solar cells as a function of exposure time to illumination plus dry heat (red) and damp heat (blue) taken at elevated temperatures.

Figure 2: Evolution of the cell efficiency of non-encapsulated CIGS solar cells as a function of time in the setup taken at elevated temperatures. Every color depicts a different type of CZTS solar cell.

Figure 3: Evolution of the efficiency and shunt resistance of two types of non-encapsulated CIGS solar cells exposed to damp heat plus illumination. The pink and purple lines represent the alkali poor samples, while the blue lines represent the alkali-rich samples. The values were obtained at elevated temperatures, while room temperature efficiencies are 30-80% higher.

Figure 4: Evolution of normalized open-circuit voltage and efficiency of four types of non-optimized unencapsulated CZTS solar cells as a function of time in the setup taken at elevated temperatures. Every color depicts a different type of CZTS solar cell.

CONCLUSION
We propose that the setups presented in this study are large improvements compared to the standard IEC tests, due to the combined exposure parameters as well as in-situ monitoring. These properties greatly improve the predictive value of accelerated lifetime experiments.

The four main advantages compared to standard tests are the following capabilities:
• Multi-stress exposure testing (i.e. temperature, humidity, illumination and electrical biases).
• Possibility for the tuning of stresses in order to simulate local climates (e.g. desert or polar conditions).
• Possibility for the tuning of electrical changes, e.g. to simulate effects of partial shading.
• Real-time monitoring of the PV performance, allowing simpler and faster testing, while also better understanding of the degradation mechanisms. It also allows stopping the tests directly after the occurrence of a failure, allowing both direct failure analysis and reduced testing time.

It is therefore proposed that lifetime studied with the presented setups can greatly improve the qualitative and quantitative understanding and prediction of long-term stability of solar cells and modules.

ACKNOWLEDGEMENTS
The authors would like to thank everyone who contributed to the project: TNO/Solliance, Eternal Sun, Delft University of Technology, ESI, Maltena Testeninstrument and ADA materials.

WANT TO KNOW MORE ABOUT SPIRE?
Check the QR-code for more info.

WANT TO KNOW MORE ABOUT THE SETUP?
Check the QR-code for more info.
Module Quality in Australia
Michelle McCann, Lawrence McIntosh and Mark Harper

Background

AUSTRALIAN MARKET
- One of the highest uptakes of roof-top PV;
- 1.8 million rooftop PV installations (20% of all residential dwellings) : 6.3 GW,*
- Growth in commercial / utility space is recent;
- Market is 'upside down' and relatively unsophisticated.

* Source: Clean Energy Regulator, 2017

CLEAN ENERGY COUNCIL’S TEST PROGRAM*
- Peak body, list of panels approved for sale in Australia;
- Over 5,000 panels on the list;
- Targetted testing (low cost, high volume and OEM):
  - 30 manufacturers;
  - 78% were under-power (inc tolerances);
  - 45% had substituted components;
  - 5 manufacturers had average 20 micro-cracks per panel;
  - 7 of 14 manufacturers in last 12 months were de-listed;
  - 9 de-listed due to other non-compliance with T&Cs;
  - 5 of 7 in last test round had misleading documentation.

FUTURE PLANS FOR PV LAB AUSTRALIA
- PID capability is being developed;
- Ongoing discussions with large farm owners / developers / engineers.

Results

% Deviation from nameplate power

- Almost all are new panels;
- None failed wet leakage BUT
  - some are close to failing and
  - we know water ingress is a problem in Australia*.

*24% of panels in a web-based survey of quality issues reported water ingress.
Source: Clean Energy Council, 2016.

MARKET SHARE
(Indicative, in 2016)

Where to from here?

IEC PV Standards Activities

John Wohlgemuth
PowerMark Corporation

Summary

IEC Technical Committee (TC) 82 writes PV Standards
PowerMark serves as Technical Advisor (TA) to US TAG of TC 82 under NREL Agreement ADC-8-82033-01.
IEC 61215 and IEC 61730 are so important that as soon as one edition got published work begins on the next edition.

IEC PV Standards published in 2017

IEC 60904: Series: Photovoltaic devices – Measurement Principals: ALL
  PARTS (1, 1-1, 2, 3, 4,5,7, 8, 8-1, 9, 10)
IEC 60904-1-1: Measurement of current-voltage characteristics of multi-junction PV
IEC 60904-8-1: Measurement of spectral responsivity of multi-junction PV devices
IEC 61724-1: Photovoltaic system performance - Part 1: Monitoring
IEC 62670-3: CPV - Performance measurements and power rating
IEC 62688: CPV modules and assemblies - Safety qualification
IEC 62788-1-6: Encapsulants - Test methods for determining the degree of cure in Ethylene-Vinyl Acetate
IEC 62805-1: Method for measuring PV glass - Part 1: Measurement of total haze and spectral distribution of haze
IEC 62805-2: Method for measuring PV glass - Part 2: Measurement of transmittance and reflectance
IEC 62817: Photovoltaic systems - Design qualification of solar trackers – CVS
IEC 62920: Photovoltaic power generating systems - EMC requirements and test methods for power conversion equipment
IEC 62979: Photovoltaic modules - Bypass diode - Thermal runaway test

IEC PV Technical Specifications published in 2017

IEC TS 62446-3: PV systems - Outdoor infrared thermography
IEC TS 62788-2: Polymeric materials - Frontsheets and backsheets
IEC TS 62788-7-2: Environmental exposures - Accelerated weathering tests of polymeric materials
IEC TS 62916: Photovoltaic modules - Bypass diode electrostatic discharge susceptibility testing
IEC TS 63049: Terrestrial PV systems - Guidelines for effective quality assurance in PV systems installation, operation and maintenance
IEC TS 62257-7: Generators

New version of IEC 61215 series
Add cyclic mechanical load test before 50 thermal cycles
Add PID testing for crystalline Si modules
Explain how to test bifacial modules
Explain how to test flexible modules
Clarify the requirements related to power measurements
Add weights to junction box during 200 thermal cycle test

Publically Available Specification (PAS)
IEC PAS 62257-10: Silicon solar module visual inspection guide

Requirements for Participation in IEC
Join your National TAG
In the US, this means joining ANSI TAG for TC 82
For more information, contact John Wohlgemuth at JWPVReliability@ieee.org

Amendments to IEC 61730 series
Add weathering tests per IEC 62788-7-2
Add measurement method for dti
Add requirement for RTI/RTE for junction box and connector materials
The IECRE

Verifying the safety, performance and reliability of renewable energy equipment and services
What is IECRE

IECRE is a Conformity Assessment System based on International Standards prepared by the IEC (International Electrotechnical Commission) for equipment and services used in renewable energy (RE) applications. The system aims to facilitate the international trade of equipment and services in the marine, solar photovoltaic (PV) and wind energy sectors, while maintaining the required level of safety. Each of these sectors will be able to operate IECRE Schemes that cover products, services and personnel, to provide testing, inspection and certification.

IECRE was created in 2014 to address the specific requirements of this sector, but also in recognition that the ever-increasing demand for electricity, and the need to reduce the share of fossil fuels in power generation, have led to rapid development and growth of the RE sector.

How does it work

Standard-based assessment: IECRE uses International Standards which are globally relevant in concept and in practice. This makes it possible to reduce barriers to trade caused by different certification criteria in different countries, and helps industry access new markets. By avoiding multiple and sometimes duplicative testing, manufacturers and users can save time and costs and receive confirmation that equipment and services are safe and reliable.

Mutual recognition and global acceptance

IECRE certification has worldwide acceptance. IECRE Members use the principle of mutual recognition (reciprocal acceptance) of test results and the resultant certifications to obtain certification or approval at national level.

This means that all certification bodies throughout the world, which operate within IECRE, accept the IECRE Test Reports and Certificates that are issued by an accepted IECRE Testing Laboratory or associated Certification Body, if applicable. These test reports and certificates can be used in national certifications, without the need to repeat the tests themselves.

Qualified assessors

IECRE Test Reports and Certificates instil confidence that the testing laboratory or certification body has the competency to carry out tests or certifications, and is using procedures which comply with IEC International Standards and the rules and procedures of the IECRE Conformity Assessment System.

All IECRE Testing Laboratories and Certification Bodies go through a rigorous process of peer assessment of their capabilities in different and clearly defined areas of competency, in order to obtain
IECRE qualification and acceptance, and to then be able to provide an IECRE Test Report or Certificate. These test reports or certificates then form the basis for the issuance of a national certificate by an accepted IECRE Certification Body which has also undergone peer assessment.

**Transparency**

IECRE keeps and maintains records of all test reports conducted by accepted IECRE Testing Laboratories and the resultant certificates of conformity issued by the accepted IECRE Certification Bodies. The online database allows immediate validation of the test report and the verification of the certificate of conformity which has been issued, and by whom.

**Who benefits**

IECRE Conformity Assessment activities provide a meaningful, transparent, effective and independent third party review and evaluation of wind, solar PV and marine energy projects. This helps to ensure investment in more reliable, consistent and cost-effective equipment in the RE.

- Industry saves time and reduces cost by eliminating unnecessary tests and approvals. Certification can be carried out by one certification body and is accepted in many countries worldwide.
- For governments, it contributes towards reducing trade barriers caused by different certification criteria in various countries, and helps countries meet their obligations of the World Trade Organization Agreement on Technical Barriers to Trade.
- Manufacturers and suppliers can provide the assurance that their products are compliant with relevant safety standards, are of the required quality and are interoperable with other products, services and installations.
- End users are assured that they are getting quality, safe, reliable RE equipment and services.

**End user stakeholder group - the importance of participation**

The IECRE System is consensus based, and industry developed. This means that there are opportunities for RE companies, and other establishments that support the industry to get involved.

The end user stakeholder group includes: RE equipment owners, operators, developers, insurers, financiers, regulators, service providers and academia.

Participation will allow stakeholders to:

- understand new requirements and expectations resulting from evolving rules in advance of implementation, providing a tangible competitive advantage.
- have a voice in the development of future requirements for RE systems using IECRE-approved technologies.
- exchange with other industry experts who deal with similar challenges.
- leverage the system to improve project ROI.
- promote the deployment of these Standards while having a stronger voice in setting certification Standards.

Contact your member body to find out more about participating in the IECRE end users stakeholder and technical advisory groups.

Find out more: [www.iecre.org/members/bodies](www.iecre.org/members/bodies)
IECRE value proposition

Renewable energy stakeholders

<table>
<thead>
<tr>
<th></th>
<th>Manufacturers</th>
<th>CBs / Test labs</th>
<th>Developers / owners / operators</th>
<th>Financing / insurance</th>
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<td></td>
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<tr>
<td>International Standards</td>
<td>Users can demonstrate that designing to IEC International Standards provides market differentiation and products/services are globally accepted</td>
<td>Provides the basis for conformity assessment, testing and certification</td>
<td>IECRE documents are designed to IEC requirements and provide transparency and instil confidence</td>
<td>Reduces overall transaction cost by lowering expenses for design and due diligence and provides integrated system assessment</td>
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<tr>
<td>Manufacturing is</td>
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<td>assessed</td>
<td>IECRE records and specifies the quality management system, offering a basis for market differentiation</td>
<td>Standardizes conformity assessment and provides mutual recognition, resulting in efficiency and increased opportunities</td>
<td>IECRE records the quality and performance of equipment in a consistent manner providing purchasing confidence</td>
<td>Internally consistent manufacturing quality assessment reduces transaction costs and risk</td>
</tr>
<tr>
<td>Certification bodies (CBs), inspection bodies (IBs) and test labs (TLs) peer assessment</td>
<td>IECRE reports are mutually accepted. Reduces redundant review, harmonizes interpretation of Standards and provides a pool of CBs, IBs and TLs, resulting in market differentiation and global acceptance</td>
<td>IECRE improves processes with potential efficiency gain. Increases work opportunities. Mutual recognition of test reports increases market opportunities</td>
<td>IECRE provides harmonized, qualified vendors for assessment and testing. Reduces vendor qualification costs. Mutual recognition lowers redundant work</td>
<td>Reduces risk and cost. The result: greater confidence in transparent assessment</td>
</tr>
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</table>
International Standards used

Several IEC technical committees (TCs) produce the International Standards which are used by IECRE and form a basis for design, quality assurance and technical aspects for certification. These include:

**IEC TC 82**: Solar photovoltaic energy systems. Standards cover all the elements in the entire photovoltaic energy conversion system. This includes the interface with the electrical system(s) to which energy is supplied. For example, terminology and symbols; testing; design qualification; methods to evaluate PV module performance in different weather conditions; new technology storage systems; system commissioning; maintenance and disposal; system and component safety criteria including for grid-connected systems on buildings and utility-connected inverters; aspects of environmental protection.

**IEC TC 88**: Wind energy generation systems. Standards cover safety, measurement techniques and test procedures for wind turbine generator systems; design and performance requirements; acoustic noise measurement techniques; measurement of mechanical loads; communications for monitoring and control of wind power plants. They also provide design requirements for offshore wind turbines, gearboxes and wind farm power performance testing.

**IEC TC 114**: Marine energy - Wave, tidal and other water current converters. Standards cover system definitions; measurements of mechanical loads; guidance for design and analysis of an ocean thermal energy conversion (OTEC) plant; design and safety, including reliability and survivability; electrical power quality requirements; power performance assessment, for wave, tidal and other water current converters; resource assessment requirements.
About the IEC

The IEC, headquartered in Geneva, Switzerland, is the world’s leading publisher of International Standards for electrical and electronic technologies. It is a global, independent, not-for-profit, membership organization (funded by membership fees and sales). The IEC includes 170 countries that represent 99% of world population and energy generation.

The IEC provides a worldwide, neutral and independent platform where 20,000 experts from the private and public sectors cooperate to develop state-of-the-art, globally relevant IEC International Standards. These form the basis for testing and certification, and support economic development, protecting people and the environment.

IEC work impacts around 20% of global trade (in value) and looks at aspects such as safety, interoperability, performance and other essential requirements for a vast range of technology areas, including energy, manufacturing, transportation, healthcare, homes, buildings or cities.

The IEC administers four Conformity Assessment Systems and provides a standardized approach to the testing and certification of components, products, systems, as well as the competence of persons.

IEC work is essential for safety, quality and risk management. It helps make cities smarter, supports universal energy access and improves energy efficiency of devices and systems. It allows industry to consistently build better products, helps governments ensure long-term viability of infrastructure investments and reassures investors and insurers.

Key figures

- 170 Members and Affiliates
- >200 Technical Committees and Subcommittees
- 20,000 Experts from industry, test and research labs, government, academia and consumer groups
- 10,000 International Standards in catalogue
- 4 Global Conformity Assessment Systems
- >1 million Conformity Assessment Certificates issued
- >100 Years of expertise

A global network of 170 countries that covers 99% of world population and electricity generation

Offers an Affiliate Country Programme to encourage developing countries to participate in IEC work free of charge

Develops International Standards and runs four Conformity Assessment Systems to verify that electronic and electrical products work safely and as they are intended to

IEC International Standards represent a global consensus of state-of-the-art know-how and expertise

A not-for-profit organization enabling global trade and universal electricity access
Further information

Please visit the IEC website at www.iec.ch for further information. In the “About the IEC” section, you can contact your local IEC National Committee directly. Alternatively, please contact the IEC Central Office in Geneva, Switzerland or the nearest IEC Regional Centre.

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Backsheet Degradation in Accelerated Sequential Testing of Full-size Commercial Modules

Kaushik Roy Choudhury¹, William Gambogi¹, T.-John Trout¹ and Ryan Desharnais²
(1) DuPont, Wilmington, DE, USA; (2) DNV-GL LLC, Berkeley, CA, USA

Sequential Accelerated Weathering Test Protocol

Module Accelerated Sequential Test (MAST)

- 9 months duration
- Damp Heat
- UVA

Tests and Measurements performed by DNV-GL

Test Details

Modules
2 tier-1 full-size commercial modules with PET-based backsheet
2 tier-1 full-size commercial modules with PVDF-based backsheet
2 tier-1 full-size commercial modules with TEDLAR®-based backsheet

Exposure: DH / UVA/ n(UVA / TC)
DH = Damp Heat, 85C, 85%RH, 1000 hours
UVA = UVA fluorescent exposure from the backsheet side, 70 ± 3C BPT, 65 kWh/m²
TC = Thermal Cycling, 40C, 85C, ramp and hold per IEC61215, 200 cycles
n = 1x, 2x, 3x

Measurements
- Color (L*, a*, b*), at 10 points on the module backsheet
- Visual Assessment (looking for discoloration, cracking and delamination)
- Electricals: Flash I-V, EL

Loss of Backsheet Mechanical Properties

PVDF-based backsheet (after 3rd round of TC200)
- Visible cracks on backsheet over ALL of the bus-bar ribbons in EACH cell of BOTH modules tested
- All cracks are in the longitudinal (MD) direction of the module

Yellowing of PET Backsheets

- No cracks in PET-based and TEDLAR®-based modules
- PVDF polymer crystallizes when extruded, resulting in weak TD elongation strength


Conclusions

Backsheet degradation observed in accelerated sequential testing of full-size modules
Degradation matches results from minimidules
Degradation matches observations from the field
Unsupervised Extraction of Quantitative Crack Parameters from Optical Profilometry Data of Photovoltaic Backsheets

Addison G. Klinke\textsuperscript{1}, Abdulkerim Gok\textsuperscript{1,2}, Silas I. Ifeanyi\textsuperscript{1}, Laura S. Bruckman\textsuperscript{1}

1. SDLE Research Center, Department of Materials Science and Engineering, CWRU, Cleveland, OH, 44106, USA
2. Department of Materials Science and Engineering, Gebze Technical University, Gebze, Kocaeli, 41400, Turkey

INTRODUCTION

- Backsheets are critical to the long term outdoor durability of photovoltaic modules
- Cracks compromise the electrical safety and mechanical integrity of backsheets
- Currently only qualitative observations are available
- Quantitative parameters would allow crack classification and create unbiased features for use in statistical models
- Our analysis technique uses profilometry data to quantify
- Crack parameters are automatically extracted by an algorithm running on CWRU’s high performance distributed computing cluster
- Our algorithm excelled at characterizing parallel cracks with minimal deadhesion, and only an estimated 4% of crack detections were false positives

EXPERIMENTAL SETUP

23 backsheets studied with 9 unique layering configurations and 12 different suppliers

Exposures

- Real-world 6 steps of 2 months = 1 year total
  - Real-World 1x: Natural, full-spectrum solar irradiance and exposure to all weather conditions
  - Real-World 5x: Identical to Real-World 1x with the addition of front surface aluminum mirrors to increase the irradiance approximately five times

Accelerated: 8 steps of 500 hours = 4,000 hours total

- Hot QUV: Continuous irradiance and a chamber temperature of 70°C
- Cyclic QUV: Cyclic exposure of 8 hours of Hot QUV followed by 4 hours of darkness and condensing humidity at 50°C

Axial Chromatic Optical Profilometry: Nanovea ST400

RESULTS

Crack Parameters

- Average crack depth, width, and area ($d_{avg}$, $w_{avg}$, and $a_{avg}$)
- Minimum, maximum, and average crack spacing ($d_{min}$, $d_{max}$, and $d_{avg}$)
- Number of cracks ($c$)

Performance Metrics

Normalize crack number and depth by photodose ($UVA_{360}$) and backsheet inner layer thickness ($d_{L}$)

ALGORITHM PERFORMANCE AND VALIDATION

- 52,139 cracks detected in only 6 minutes with distributed computing
- Crack parameters measured at a rate of 17.3 cracks per minute (accounting for measurement time)
- Combined outlier detection and surface model procedure took an average of 2.7 iterations and a maximum of 5
- On average 99% of the raw data was used for crack detection

MATERIAL PERFORMANCE

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Layers</th>
<th>Exposure</th>
<th>$D_n$</th>
<th>$C_n$</th>
<th>Rank</th>
<th>$D_s$</th>
<th>$C_s$</th>
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<td>1.91</td>
<td>5.40</td>
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<td>12</td>
<td></td>
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</tbody>
</table>

Rank values are reported in 10^{-3}/MJ/m^2 and 10^{-2}/MJ/m^2, respectively, and were measured at the final step of exposure (4,000 hours or 12 months)

KEY FINDINGS

- Adding humidity and temperature variation formed up to 3x as many cracks on a photodose basis compared to dry, constant temperature exposures
- Cracks in real-world and accelerated exposures with equal photodoses had similar depths; however, the number of cracks formed in accelerated exposures was far greater
- The best and poorest performing measured backsheets configurations were PVF/PET/EVA and PET/PET/EVA, respectively
- None of the six PVF/PET/PVF backsheets cracked in any of the four exposures
- Future work: mechanistic explanation of cracking via FTIR analysis and <$S$|<$M$|<$R$> network modeling

ACKNOWLEDGMENTS

This research was performed at the SDLE Center (funded through Ohio Third Frontier, Wright Project Program Award Tech 12-004) at Case Western Reserve University. The authors would also like to acknowledge the support from the Department of Energy’s SunShot program. This work made use of the High Performance Computing Resource in the Core Facility for Advanced Research Computing at Case Western Reserve University.


**Severity Test for Non-uniform Wind Loads on Photovoltaic Module**

*Shu-Tsung Hsu*

---

**Abstract**

The issue of typhoons has received considerable critical attention since the associated strong winds generally damage PV modules severely. Previous IEC standards examined the effect of static uniform-loads (IEC 61215-2:2016) or dynamic uniform-loads (IEC TS 62782:2016) on PV modules in low wind-velocity, but overlooked the high wind-velocity or non-uniform wind-loads on PV modules. The purpose of this study is to analyze the relationship between wind-velocity (V) and wind-pressure (P) on PV modules, and consider the effect due to wind direction angle (β) and inclined angle (α) of PV platform. This work has successfully developed a new test method named non-uniform mechanical loads (NUMIL) test, which can simulate the non-uniform wind-loads by the test data named mean surface-pressure pattern (MSPP) for PV modules. All MSPPs can be evaluated directly by test results of wind-tunnel experiment and CFD simulation, and meet the requirements for different wind-velocity due to flow-similarity. Results of this study revealed that such severity wind-test for PV module strongly rely on the choices of major environmental factors such as wind velocity (V), wind direction angle (β) and inclined angle (α). Both aspect ratio (L/W) and clearance height (H) can also be considered. In addition, the experimental results showed that the module and the fixtures are closely related to the external forces of MSPP. Currently, a standard shall about wind test named SEMI Doc. 6298 is also discussing by SEMI Reliability Test Method Task Force (TF) in IEC.

**Non-uniform Wind-Loads (α, β)**

<table>
<thead>
<tr>
<th>Country</th>
<th>Location</th>
<th>Test Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taiwan</td>
<td>2016</td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>2016</td>
<td></td>
</tr>
</tbody>
</table>

**Mean Surface Pressure Pattern (MSPP)**

\[
C_{MSPP} = \frac{(P_1 - P_3)}{0.5 \rho V^2} = \frac{(P_2 - P_3)}{0.5 \rho V^2}
\]

Front wind (β = 180°)

Back wind (β = 0°)

- (a) Diagram of NUMIL system with 18 (3x6) independent loads (max. force ±12,000 Pa) by pistons, and each piston with four suction cups.
- (b) Non-uniform wind-test of single PV module.
- (c) Calibration curve for each single module.
- (d) PV module, α: relative inclined angle; β: relative orientation point (0, 0).

**Discussion**

Post test (Dev. = (post – pre) / pre x100%) after NUMIL test: (1) 5V (BERGER Pulsed, 87°C 1000 Vm, 25°C, AM1.5G) (2) EL (Z4 – PLUS, Based on current = 8 A) (e) relative inclined angle; m: relative original point (0, 0).

**Conclusion**

- Severity test for non-uniform wind-loads on PV module strongly rely on the choices of environmental factors such as wind velocity (V), wind direction angle (β) and inclined angle (α). In addition, aspect ratio (L/W) and clearance height (H) can also be considered.

**Future Work**

- Evaluation for different type of PV modules: c-Si vs IT, mono vs poly, single-glass vs double-glass, multi-Bip, half-cut solar cell, etc.
- Develop MSPP for floating system, and study the coherent effect due to wind and wave together.

---

Accelerated Testing Using Multiple Sequential Stresses and Comparison to Field Performance
DuPont Photovoltaic and Advanced Materials, Wilmington, DE, USA

Sequential Test Protocol Development

**Module Accelerated Sequential Test (MAST2)**
- **6 months duration**
  - 1000 hours Damp Heat
  - UVX
  - 544 hours 95C BPT
  - 1000 hours in a Humidity Chamber

**New Accelerated Sequential Dynamic Mechanical Load Test**

**Results**
- UVX: No change
- DML 1: No change
- DML 2: No change
- DML 3: No change

**Glass/Glass modules are more prone to delamination induced by mechanical load combined with UV exposure, thermal cycling and humidity**
- Glass/Glass structures are more rigid and cannot dissipate stresses
- Glass/Glass structures are not breathable and trap EVA degradation products

**Future Directions**
- Higher irradianc
- New equipment with higher intensity and full size module capability
- Higher temperature
- New stress conditions

**Weathering Test for Inner Layer Cracking**
- Weathering of two single-cell mini-modules (above) showing cracking of the inner layer of the backsheet for two commercial PET-based backsheet
- Backsheet exposures using glass/EVA filter show similar cracking
- Exposure Conditions: Front side exposure in xenon weatherometer at 90C BPT, 120W/m² UV, 102m UV and 18m UV + water front spray, 3500h (~ 3y outdoor equivalent)
- Cracking of inner layer of PET backsheet after 7y in field in USA. Cracking was observed in the border near the frame and between cells over the entire module area

**Fielded Module Examples**
- Yellowing in PET Backsheets observed in the field
- Cracking in 1s PVDF Backsheet
- Cracking in PA Backsheet

**Weathering Test for Inner Layer Cracking**
- Front side exposure in xenon weatherometer at 90C BPT, 120W/m² UV, 102m UV and 18m UV + water front spray, 3500h (~ 3y outdoor equivalent)

**Future Directions**
- Higher irradianc
- New equipment with higher intensity and full size module capability
- Higher temperature
- New stress conditions
Unsupervised Extraction of Quantitative Crack Parameters from Optical Profilometry Data of Photovoltaic Backsheets

Addison G. Klinke¹, Abdulkerim Gok¹,², Silas I. Ifeanyi¹, Laura S. Bruckman¹

1. SDLE Research Center, Department of Materials Science and Engineering, CWRU, Cleveland, OH, 44106, USA
2. Department of Materials Science and Engineering, Gebze Technical University, Gebze, Kocaeli, 41400, Turkey

INTRODUCTION

- Backsheets are critical to the long term outdoor durability of photovoltaic modules
- Cracks compromise the electrical safety and mechanical integrity of backsheets
- Currently only qualitative observations are available
- Quantitative parameters would allow crack classification and create unbiased features for use in statistical models
- Our analysis technique uses profilometry data to quantify
  - Crack parameters are automatically extracted by an algorithm running on CWRU’s high performance distributed computing cluster
- Our algorithm excelled at characterizing parallel cracks with minimal deadhesion, and only an estimated 4% of crack detections were false positives

EXPERIMENTAL SETUP

- 23 backsheets studied with 9 unique layering configurations and 12 different suppliers
- Exposures
  - Real-world: 5 steps of 2 months = 1 year total
    - Real-World 1x: Natural, full-spectrum solar irradiance and exposure to all weather conditions
    - Real-World 5x: Identical to Real-World 1x with the addition of front surface aluminum mirrors to increase the irradiance approximately five times
  - Accelerated: 8 steps of 500 hours = 4,000 hours total
    - Hot QUV: Continuous irradiance and a chamber temperature of 70°C
    - Cyclic QUV: Cyclic exposure of 8 hours of Hot QUV followed by 4 hours of darkness and condensing humidity at 50°C
- Axial Chromatic Optical Profilometry: Nanovea ST400

RESULTS

- Crack Parameters
  - Average crack depth, width, and area
    - Minimum, maximum, and average crack spacing
  - Number of cracks
- Performance Metrics
  - Normalize crack number and depth by photodose (Dn, Cn) and backsheet inner layer thickness (dL)
- Reference Plots
  - Automatically generated by algorithm
  - Can flatten by plotting residuals from the surface model (useful to compare crack depth with backsheet layers)

ALGORITHM PERFORMANCE AND VALIDATION

- 52,139 cracks detected in only 6 minutes with distributed computing
- Crack parameters measured at a rate of 17.3 cracks per minute (accounting for measurement time)
- Combined outlier detection and surface model procedure took an average of 2.7 iterations and a maximum of 5
- On average 99% of the raw data was used for crack detection

MATERIAL PERFORMANCE

<table>
<thead>
<tr>
<th>Sample Name</th>
<th>Layers</th>
<th>Exposure</th>
<th>Dn (10⁻³/MJ/m²)</th>
<th>Cn (10⁻²/MJ/m²)</th>
<th>Rank</th>
<th>Dn</th>
<th>Cn</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPE1</td>
<td>PVF/PE/PVA</td>
<td>Cyclic QUV</td>
<td>1.32</td>
<td>8.00</td>
<td>6</td>
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<td>FPE2</td>
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<td>1.48</td>
<td>10.5</td>
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<tr>
<td>FPE3</td>
<td>PVF/PE/PVA</td>
<td>Cyclic QUV</td>
<td>1.14</td>
<td>4.98</td>
<td>7</td>
<td>10</td>
<td>10</td>
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<tr>
<td>FPX1</td>
<td>PVF/PE/PVA</td>
<td>Real-World 5x</td>
<td>3.99</td>
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<td>17</td>
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<td>8</td>
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<td>FPX2</td>
<td>PVF/PE/PVA</td>
<td>Real-World 5x</td>
<td>1.70</td>
<td>8.95</td>
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<tr>
<td>FPX3</td>
<td>PVF/PE/PVA</td>
<td>Real-World 5x</td>
<td>1.84</td>
<td>12.9</td>
<td>12</td>
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<td>FPX4</td>
<td>PVF/PE/PVA</td>
<td>Hot QUV</td>
<td>0.55</td>
<td>0.64</td>
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<td>1</td>
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<tr>
<td>FPX5</td>
<td>PVF/PE/PVA</td>
<td>Hot QUV</td>
<td>0.95</td>
<td>0.57</td>
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<td>2</td>
<td>2</td>
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<tr>
<td>FPX6</td>
<td>PVF/PE/PVA</td>
<td>Hot QUV</td>
<td>1.18</td>
<td>2.93</td>
<td>5</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>FPX7</td>
<td>PVF/PE/PVA</td>
<td>Hot QUV</td>
<td>1.95</td>
<td>5.40</td>
<td>13</td>
<td>12</td>
<td>12</td>
</tr>
</tbody>
</table>

KEY FINDINGS

- Adding humidity and temperature variation formed up to 3x as many cracks on a photodose basis compared to dry, constant temperature exposures
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- The best and poorest performing measured backsheet configurations were PVF/PE/PVA and PET/PE/EVA, respectively
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ACKNOWLEDGMENTS

This research was performed at the SDLE Center (funded through Ohio Third Frontier, Wright Project Program Award Tech 12-004) at Case Western Reserve University. The authors would also like to acknowledge the support from the Maloney Academy of Materials Science & Engineering at Case Western Reserve University.
Degradation of Fielded PV Modules from Across the Globe

Kaushik Roy Choudhury1, William Gambogi1, Thomas Felder1, Steven MacMaster1, Lucie Garreau-Iles2, Hongjie Hu3, Rahul Khatri4 and T.-John Trout1

(1) DuPont, Wilmington, DE, USA; (2) Du Pont de Nemours International S.A., Geneva, Switzerland; (3) DuPont (China) Research & Development and Management Co. Ltd., Shanghai, P.R.C; (4) E.I. Du Pont India Pvt. Ltd., Gurgaon, India

Global Field Assessment Program

Global program assessing fielded module performance
• Study module and component degradation to develop data for backsheets
• Developed multi-step Visual inspection protocol
• Statistical analysis of fields and aggregate data

2018 Field Data Analysis

Over 1 GW and 4 MM panels inspected (cumulative)
Total defect rates ~22.5%; backsheet defects ~9.5%
Compared to 2016 Field Report, backsheet defects increased by ~27%
• Polyamide defects increased by ~18%
• PVDF defects increased by ~51%
• Defects in glass/glass modules included

Effect of Climate on Defect Rates

Polymeric components (Backsheet and Encapsulant) show strong trends with climate
• Hot arid > Tropical > Temperate
• Backsheet defects are > 2.5X higher on roof systems
• Roof Systems are typically 15 °C higher than Ground Mounted
• Dominant factors are Temperature and UV

2018 Field Case Studies

PVDF 5 Years
• 69 installations, NA, 1 MW
• 36% modules with cracks and delamination
• Linked to loss of PVDF mechanical property

PET 9 Years
• Arizona, NA, 35 kW
• 40% delamination and cracking, up to 80% P loss
• Linked to PET degradation

Polyamide 6 Years
• China, 22 MW
• 40% backsheet cracked
• Cracks progressed in severity 1-4 Y
• Polyamide defects increased by ~18%
• PVDF defects increased by ~51%
• Defects in glass/glass modules included

Conclusions

Polymeric components degrade over time till critical point of failure is reached
Polymeric components show higher degradation in climates with increased temperature and UV
Total Backsheet defects increased by 27% in two years
Defects in Polyamide and PVDF based backsheets increased by 18% and 51% resp.
Glass/glass modules showing high defects despite relatively young age
The result shows that the correlation coefficients among some combinations are over 0.9. We evaluate and compare the performances of different combinations based on the cross-correlation coefficients, to determine which indoor accelerated test is most closely related to real world conditions at each site. The results show that the correlation coefficients for some combinations are over 0.9.

### Introduction:
- We propose a method to calculate the Cross-Correlation Scale Factor (CCSF) between indoor and outdoor PV degradation models.
- The CCSF is further applied to obtain the correlation coefficients between models for outdoor modules located in three global climate zones and indoor accelerated tests using damp-heat and thermal cycle exposures for five commercial module brands.
- We evaluate and compare the performances of different combinations based on the cross-correlation coefficients, to determine which indoor accelerated test is most closely related to real world conditions at each site.
- The result shows that the correlation coefficients among some combinations are over 0.9.

### Cross-correlation Scale Factor (CCSF) Calculation Method

Denote the indoor model and outdoor model to be

\[ Y_{in} = f_1(X_{in}) + \epsilon \]

\[ Y_{out} = f_2(X_{out}) + \epsilon \]

where \( f_1 \) and \( f_2 \) are unknown functions of \( X_{in} \) and \( X_{out} \) respectively.

\( \epsilon \) is the error term.

We calculate \( X_{out} \) from \( X_{in} \) with the least error, called the CCSF, \( c^* \).

The x range is limited to common data between models.

Based on the ordinary least square regression method, we minimize:

\[ Error(c) = \sum (Y_{in} - Y_{out})^2 \]

Where

\[ Y_{in} = f_1(X_{in}) \]

\[ Y_{out} = f_2(X_{out}) \]

Obtaining c with the least error, called \( c^* \),

\[ c^* = \arg \min c \sum (Y_{in} - Y_{out})^2 \]

Power ROC is determined by slope & intercept.

### Cross Correlation of multiple Indoor & Outdoor System

**Conclusions & Future Work**
- I-V, Pmp time series & stepwise datasets connect outdoor and indoor exposures directly at the mechanistic level.
- This gives a basis to determine the CCSF to dilate indoor time to agree with outdoor on the \( <S|R> \) pathway of the predictive model.
- NetSEM mechanistic pathways \( <S|M|R> \) give us the ability to confirm that similar mechanisms are activated indoors as outdoors.

**References:**
Practical assessment of power rating uncertainties for industrial silicon modules

Harrison W. Wilterdink, Adrienne L. Blum, Cassidy L. Sainsbury, Ronald A. Sinton
Sinton Instruments, Boulder, CO, USA

MOTIVATION:

- What is the uncertainty of a production module power rating? (Often a topic of mind-numbing complexity; can it be assessed more simply?)
- Power rating traceability is maintained by chain of calibration transfers:
  - Uncertainty propagation through calibration chain:
    - Calibration transfer to golden modules by accredited laboratories is complex: uncertainties $\approx 1\% - 2\%$
    - But calibration transfer to silver/production modules is less complicated—several systematic effects ratio out—between nominally identical modules when calibrating based on $P_{\text{MAX}}$ (rather than $I_{sc}$).

### Adaptation of prior work [1], noting random vs. systematic effects and indicating those that ratio out

<table>
<thead>
<tr>
<th>Factor</th>
<th>Standard uncertainty</th>
<th>Effect on calibration + measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference module $I_{sc}$</td>
<td>$\pm 0.98%$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Reference module $P_{\text{MAX}}$</td>
<td>$\pm 1.03%$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Non-uniformity of irradiance</td>
<td>$\pm 1%$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Temperature accuracy</td>
<td>$\pm 0.5\degree C$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Temperature non-uniformity</td>
<td>$\pm 1\degree C$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Electronic measurement accuracy</td>
<td>$\pm 0.2%$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Contact resistance</td>
<td>$\pm 20\text{-mQ}$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Spectral-mismatch</td>
<td>$\pm 0.3%$</td>
<td>Systematic</td>
</tr>
<tr>
<td>Measurement reproducibility</td>
<td>$\pm 0.2%$</td>
<td>Random</td>
</tr>
<tr>
<td>Drift of reference module</td>
<td>$\pm 0.3%$</td>
<td>Random</td>
</tr>
<tr>
<td>Total (random effects in quadrature)</td>
<td>$\pm 1.39%$</td>
<td></td>
</tr>
</tbody>
</table>

- Result: surprisingly accurate measurements!
  - Total uncertainty dominated by reference module
  - Flash test contribution is from measurement reproducibility (an aggregation of several random effects):
    - Advantage: can be characterized on a case-by-case basis using standard gage studies
    - Note—drift effects are best mitigated by employing several rotating reference modules

### EXPERIMENTAL VERIFICATION:

- **Samples/tools:**
  - 10 commercial modules: multicrystalline Si ($p$-type), aluminum back-surface field (Al-BSF) cell design
  - Sinton Instruments’ FMT-500 industrial flash module tester

- **Measurement procedure:**
  - Perform sequential calibration transfers between modules to create $N$ silver modules
  - Calibrate flash tester to one silver module, measure the power of the entire sample set; repeat for each silver module
  - If hypothesis is true (all systematic effects ratio out), we expect no difference in average module power, regardless of which silver module is used to calibrate the flash tester

### PRELIMINARY RESULTS:

- Negligible difference in average $P_{\text{MAX}}$ ($= 0.01\%$)

### CONCLUSIONS:

- Preliminary results suggest no significant systematic effects present in module calibration + measurement; work is ongoing:
  - More data collection, better quantification of effects
  - More refined analysis: sample-by-sample analysis of variance

### ACKNOWLEDGEMENTS:

The authors would like to thank the State Key Laboratory of PV Science and Technology of Trina Solar for supplying the modules used in this study.

### REFERENCES:


Durability Assessment of Adhesive Mounting of Solar Modules for Residential Rooftops

Honeker, C.1; Watts, A.1; Lloyd, A.1; Schmid, C.1; Booth, D.2
1 Fraunhofer Center for Sustainable Energy Systems CSE, 5 Channel Center Street, Boston, MA 02210, USA, Phone: +1 617-575-7263, choneker@cse.fraunhofer.org
2 H.B. Fuller, 4401 Page Avenue, Michigan Center, MI 49254, USA

HISTORY of Adhesive Mounting in Photovoltaics (PV)

Adhesive Mounting is not new to PV
- Uni-Solar (2007)
- Beamreach (2016)
- Lumeta (2010)
- Conventional Modules (current PVRD2 Project)

Traditional (Rail-less) Approach
- Locate Rafter
- Locate Mount Positions (Chalking)
- Place Mounts
- Install Flashing
- Place Mounts

Adhesive Mounting Approach
- Locate Mount Positions (Chalking)
- Locate Mount Positions (Chalking)
- Place Mounts
- Adhesive Moduls
- Adhesive Moduls

Elements of traditional rail-based mounting
Comparison of installation steps of the two approaches
Standard flashing for asphalt shingles
Failure modes for conventional penetrating mounting systems

RESULTS

Adhesive Mounting: Loadpath Geometry
Mounting structure is designed to distribute load so that stress level < critical stress for any loadpath element

Adhesive/Shingle Strength - Thermal Cycling
Adhesion increase with high temperature exposure is thought to be due to wetting of shingle

Outdoor Testing
- Note shingle "bleaching" outside of adhered area
- ~ 2 year exposure in Albuquerque, NM
- Brown color is desert dust that has accumulated under the module
- Shingles "protected" by adhered PV

NEXT STEPS: APPROACH TO EVALUATING DURABILITY

OPEN QUESTIONS
- Identifying field failure modes
- Needed to develop the appropriate accelerated test protocols
- Discrepancy between PV and Shingle aging conditions
  - Typical shingle tests:
    - Dark Oven (70°C) (ASTM D5147, D5869)
    - Xenon Arc (0.35 W/m²·nm & spray cycle) (ASTM D4798)
    - Freeze-thaw (ASTM D4798)
  - Typical PV tests:
    - IEC 61225-1, UL 1703 (DH, TC, HF)
  - It is possible that shingles will not survive the PV standards
- How should PV mounting standards (e.g., UL 2703) be modified to accommodate adhesive mounting.
  Will there be an IEC standard for PV mounting systems?

This material is based upon work supported by the U.S. Department of Energy’s Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technology Office SunShot Initiative Award Number DE EE0008173.
Sealing the Roof – More than Just Waterproofing

Know Your Substrates

Roofing materials are not adhesive-friendly!

**Asphalt** – large variety of shingles, pre testing should occur. Oils can bleed out over time.

**Metal** – aluminum, steel, galvanized steel, painted metals, etc. Easy to bond to, but not all the same.

**EPDM** – commonly used in commercial roofs, high PE content, makes this a difficult material.

**PVC** – poly vinyl chloride, full of plasticizers that will leach into the adhesive.

**TPO** – high PP content, like EPDM, this makes chemical bonding difficult.

**MS Polymer** – modified siloxane (strong adhesive)

**Acrylic**

**Silicone** – poly di methyl siloxane (stable in all environments)

**Butyl Sealants** – poly iso butylene (water sealing)

Why Seal the Roof?

Waterproofing any penetrations

- Load Transfer

Protect from Movement/Seismic

Manage difference in materials

Cost

Different Roof Materials Require Different Solutions

Composite shingles will have many holes drilled through them to get to the rafters. Shingles will not self heal and a butyl sealant or some other adhesive/sealant is needed to protect from rain and snow.

Commercial roofs made of PVC/TPO/EPDM may require large amounts of material to seal the roof. These materials can be subject to different loads. Even self ballasting installations can be subject to movement with seismic events or in cold weather with ice that can form under the ballasts. A properly applied sealant can support the PV array under these conditions.

Some roof systems can be deceptive. A tile roof will used the materials under the tile. This may be felt paper, tar paper or some other underlayment.

Not All Sealants Are the Same

<table>
<thead>
<tr>
<th>MS Polymer</th>
<th>Silicone</th>
<th>Acrylic</th>
<th>Butyl or PIB</th>
</tr>
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<tbody>
<tr>
<td>Asphalt</td>
<td>X</td>
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<tr>
<td>Metal</td>
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<td>X</td>
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</tr>
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<td>EPDM</td>
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</tr>
<tr>
<td>Tar Paper</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>PVC</td>
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<td></td>
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</tr>
<tr>
<td>TPO</td>
<td>X</td>
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</tr>
</tbody>
</table>

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## Capability 5: Field Deployment

**Bruce King, Birk Jones**  
Sandia National Labs

### DuraMAT Capabilities

| 1. Data Management & Analytics, DuraMAT Data Hub  
| 2. Predictive Simulation  
| 3. Advanced Characterization & Forensics  
| 4. Module Testing  
| 5. Field Deployment  
| 6. Techno-Economic Analysis |

### Capability Goals

- Identify degradation in historical PV systems  
- Confirm the durability of new module materials and designs  
- Validate the field relevance of laboratory degradation mechanisms and acceleration factors  
- Links to all Capabilities

### Accomplishments

- Demonstrated proof of concept for Flash Thermography  
- Technique is anticipated to provide supplemental degradation information from fielded modules  
- Restructured Data Aggregation infrastructure to facilitate reliable and fast sharing with DuraMAT Data Hub

### Next Steps

- Non-Destructive Inspection  
- Explore more advanced techniques and test scalability  
- Investigate imaging of defects  
- Investigate other field inspection methods  
- Local Database Management  
- Integrate more Photovoltaic Systems and provide user-friendly access

### Capability Development

**Non-Destructive Inspection**

- Field Deployment infrastructure is ready for the deployment of modules and coupons  
- However, there are no on-site analytical capabilities to assess material degradation  
- Capability Development focuses on identifying Non-Destructive field inspection techniques

**Field Data Modernization**

- Existing data collection systems are not interconnected and rely on local storage  
- Mismatched data structures between platforms hinders data mining  
- Local storage was not designed to facilitate external sharing beyond Sandia’s firewall

### Project intent

- Develop a suite of non-destructive module field evaluation methodologies.  
- Mechanical degradation of the module package (delamination, cracking, etc)  
- Physical/chemical materials degradation (embrittlement, oxidation, etc).

### Candidate methods

- Flash Thermography  
- Ultrasonic Diagnostics  
- FTIR  
- Raman Spectroscopy  
- Reflectance  
- Wet leakage current

### Flash Thermography – Proof of Concept

- Flash Thermography Setup using a FLIR camera and two flash lamps to provide the heat source  
- Investigated three panels; Historic mc-Si, glass, textured backsheet  
- Modern mono-Si, glass, smooth backsheets  
- Thin-film, glass-glass  
- Investigated front, rear and rear transmission

### Telemetry Modernization

**Project intent**

- Reliable – Automate collection and storage activities using commercial off-the-shelf and custom tools  
- User friendly – Provide access to stored data that allows for simple and fast queries.  
- Compatible – Enable automatic transfers to partners

### Integrated Systems

- Outdoor PV systems (MPP & I-V Curves)  
- EL/IR Imaging  
- SPIRE Flash Tester  
- Solar Tracker  
- Light Soaking Chamber

### Data Routing Overview

Real-time collection, transfer, and storage of data for improved user access and availability.

### Data Acquisition, Transfer, and Storage

**Data Acquisition**

- Commercial – Campbell Data Loggers  
- Custom - Raspberry Pi, Beagle Bone, Etc.  
- Indoor Testbed software

**Local Storage**

- Local memory  
- MySQL

**Data Routing (Bridge)**

- Campbell Software  
- Python Code

**Data Storage (DB Server)**

- SQL Microsoft

**Findings - Highlights**

Glass-Backsheet (x-Si)

- Cells, gridlines, bus bars are easily visible  
- Transmission through glass diffuses image; use of IR paint may improve resolution  
- Smooth back sheet provides best image  
- Textured back sheet creates artifacts that interfere with image  
- Rear transmission yielded diffused images

Glass-Glass (thin film)

- Difficult to image due to highly reflective front surface

**Glass-Backsheet (x-Si)**

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Advanced Characterization & Forensics

1. General Characterization and Forensics
   - Insight into PV module degradation can come from proper combination of standard characterization techniques
   - Application + correlation of standard techniques not fully utilized by PV industry
   - Initial XPS study suggests possible change in the O:\Si coordination

2. Interfaces and Surfaces
   - 3 primary interfaces of interest
     - Glass/Coating — Environment
     - Encapsulant — Cell
     - Backsheet — Environment

3. Advanced Characterization Techniques and Method Developments
   - High throughput methods
     - Current methods limit the number of samples resulting in experiments being defined by the method and not the materials
     - Rapid characterization results in more data being generated, accelerating materials improvements
   - Motorized Goniometer for High Throughput Contact Angle Measurements
   - Advanced Method Development
     - Identification of degradation mechanisms may require methods beyond the limitations of standard techniques
     - Building beyond standard techniques will allow for greater detail, such as spatial resolution (i.e. surface vs. bulk) and temporal resolution (i.e. in situ)
   - Gas sorption (BET)
   - X-ray photoelectron spectroscopy (XPS)
   - X-ray absorption fine structure (XAFS)
   - Surface area
   - XPS
   - Pores filling up?
   - Rise in \( \text{Si}\)

Capability 3 Tasks & Timeline

1. General Characterization and Forensics
   - Provide access to characterization tools existing at national laboratories, including those outside the current DuraMAT team, and provide useful characterization of PV materials.
   - Key collaborators: Peter Hacke, Nick Bosco, and Cap2-predictive simulations

2. Interfaces and Surfaces
   - Apply interface and surface characterization tools and methods to understand and therefore mitigate failures at interfaces.
   - Key collaborators: Peter Hacke, Nick Bosco, and Cap2-predictive simulations

3. Advanced Characterization Techniques and Method Development
   - Further understanding of failure + degradation mechanisms in module materials w/ development of new characterization techniques
   - Key collaborators: Margaret Gordon, Bruce King, Patrick Burton, Andriy Zakutyayev

DuraMAT Capabilities

1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

Capability Goals

- Identify initial focus areas — 3 main interfaces
- Industry, National Lab, and Academic engagement
- Preliminary data investigating anti-soiling coatings collected
- Monthly webinars focused on the module surface
- Planned experiments to explore encapsulant/foul interface and backsheet failure mechanisms

Accomplishments

1. Discussed w/ DuraMAT stakeholders, identify essential interfaces/materials for further study
2. Source materials w/ technoeconomic value (Cap6) from DuraMAT stakeholders
3. Characterize pristine interfaces/materials w/ advanced tools available in Cap3. All data stored by Cap3-Data Hub
4. Stress interfaces/materials through field tests and/or accelerated aging in collaboration with Cap4 and 5. Characterize and compare aged samples w/ pristine sample data
5. Reassess, if knowledge from steps 3 + 4 fail to identify the degradation mechanism, design new/improved/advanced tools
6. DuraMAT stakeholders use insight gained from characterization of pristine + aged samples in development of new materials, Cap3 uses data for model validation
7. Assess results and impact, repeat cycle for further improvement or begin cycle again to identify new material/interface

Cost Drivers

- Materials & Industrial partnerships w/ development of new materials
- Source materials w/ technoeconomic value
- Improve methods limit the number of experiments being defined by the method and not the materials
- New high impact concepts in solar photovoltaics (PV) module packaging
- Provide advanced materials characterization not currently available to DuraMAT stakeholders. This is used to rapidly improve materials improvement and validation by providing high-quality, in-depth characterization of module materials
- Long term: The knowledge gained provides a path to improved materials design by DuraMAT stakeholders and may ultimately lead to the discovery of new materials and successful adoption of materials from other industries.

Outcomes and Impact

- Discover, Develop, and De-Risk module materials, architectures, accelerated testing protocols, data analytics, and financial models to reduce the LCOE of solar energy.

SLAC National Accelerator Laboratory, Sandia National Laboratory, National Renewable Energy Laboratory
Development of Low-Cost, Crack-Tolerant Metallization Using Screen Printing

Omar K. Abudayyeh1, Andre Chavez1,2, John Chavez1, Francesco Zimbardi1, Brian Roussaville1, Vijaykumar Upadhyaya1, Ajeet Rohatgi3, Byron McDanold4, Timothy Silverman5, Sang M. Han1,2,3
1Osada Energy; 2University of New Mexico; 3Georgia Institute of Technology; 4National Renewable Energy Laboratory

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Industry Goals

- Produce screen-printable silver ink with crack-tolerance to substrate fractures.
- Incorporate low-cost, multi-walled carbon nanotubes for electromechanical reinforcement.
- Develop capability to electrically bridge cracks forming in PV cells for increased lifetime.
- Reduce LCOE by lowering cell degradation rate.

Accomplishments

- Demonstrated crack-bridging for commercial space solar cells.
- Translated the technology to silver ink used on terrestrial PV.
- Target terrestrial Si PV market > $25B for economic impact.
- Reduce module degradation for increased lifetime.
- Established partnership with DuPont.

Outcomes and Impact

- Demonstrate increased module reliability against stress-induced cell fractures.
- Make specialized ink products available for integration on commercial Si PV modules.
- Target future partnerships with cell production companies.
- Provide new materials and integration solutions for terrestrial PV.

Capability Development

Ink Formulation

Silver Paste Dual Mixer

Cell Integration and Characterization

Baseline Data

Materials Characterization

Resistance Across Cleaves and cracks (RACK)
- Gridline pulled at micron increments
- Electrical resistance measured until complete gridline failure

Mini-Module Testing

in-situ Electroluminescence Camera
- Construct four-cell mini-modules (one set with ordinary metallization paste and one with crack-tolerant paste)
- With in-situ electroluminescence imaging, mechanically cycle the modules to drive mechanical fatigue of metallization at crack sites
- Use number of cycles to permanent grid line failure to characterize metallization durability

Cost Drivers

- Ink Formulation and Material Characterization for Al-GaS Cells (Disable)
- Cell Integration and Characterization for Al-GaS Cells (Disable)
- Quarterly Progress Report
- Poster Workshop 1 (Albuquerque, NM)

Project Timeline

DuraMat Begins
- Repet Development Cycle with PERT Cells
- Quarterly Progress Report

11/15/2017

Poster Workshop 1
(Albuquerque, NM)

11/15/2018

Final Technical Report

11/15/2018

Summary

Durability by deliberate design; Perfecting a process that is engineered to last

Osada Energy LLC provides materials engineering solutions to improve solar cell and solar module reliability. Our specialized metal matrix composites have been proven to electrically bridge stress-induced cracks that appear in solar cells over time; the composites also self-heal to regain electrical continuity. As the solar market is rapidly shifting towards thinner platforms for lower costs and making its way into wearable power systems and unmanned aerial vehicle market, our materials engineering solutions promise substantially improved reliability for solar power systems.
Advanced Module Architecture for Reduced Costs, High Durability and Significantly Improved Manufacturability

PROBLEM STATEMENT
- Studies have demonstrated that the main factor determining PV operational life is the encapsulation material, specifically, the ability for the encapsulation to keep out moisture
- Commercially available laminators for modules have:
  - Low throughput due to longer cycle time
  - Single polymer for lamination does not satisfy all requirements

There is a need to develop new module architecture and associated manufacturing process to increase module reliability and improve levelized cost of electricity

VALUE PROPOSITION
- Study conducted by NREL
  - Breakdown of costs for module assembly
  - Facilitate Sunshot goal of 3 cents/kWh
- Estimated capital investment reduced by 6X
- Decrease in material cost calculated to be ~1.85 cents/Watt
- Tool footprint reduced by 20X
- Higher module reliability

TECHNOLOGY OVERVIEW
- Prototype of manufacturing process tool
  - Motion system, polymer dispense and nozzle
  - Substrate motion and indexing system
  - Back glass positioning, pressing and process control

PROJECT OVERVIEW
- Demonstrate prototype manufacturing process to fabricate new module architecture
- Includes edge seal and interlayer polymer
- Significantly improve process cycle time compared to the current industry standard
- Decrease processing hardware
- Accelerated testing
- Reduced manufacturing cost
- Improved module reliability
- Facilitate the SunShot goal of 3 cents/kWh

RESULTS
- Development of prototype tool hardware is in progress
- Computational fluid dynamic simulation of nozzle is in progress

PROJECT OBJECTIVE
- Demonstrate a prototype manufacturing process to fabricate new module architecture
  - Includes edge seal and interlayer polymer
  - Significantly improve process cycle time compared to the current industry standard
  - Decrease processing hardware
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  - Improved module reliability
  - Facilitate the SunShot goal of 3 cents/kWh

MILESTONES

INDUSTRY IMPACT
- New module architecture and associated manufacturing technology
  - Enable lower cost modules
  - Higher module reliability
  - Higher throughput due to lower processing time
  - Tool footprint reduced by 20X
  - Estimated capital investment reduced by 6X
  - Decrease in material cost calculated to be ~1.85 cents/Watt
  - Enable PV manufacturers (e.g., First Solar) to test the technology, evaluate return on investment and initiate commercialization

Facilitate the Sunshot goal of levelized cost of electricity
3 cents/kWh
Degradation of Organic Photovoltaic Materials (OPV)

Motivations: OPV promising especially for niche applications, but degrade when illuminated in the presence of O2 and H2O


Our modeling work investigates possible degradation mechanisms

Summary

- Static DFT calculations confirm feasibility of Mechanisms 3 & 4 (especially 3)
- If radical species that originate from photon interaction with H2O and O2 present, degradation of active OPV material is fast (~400 atoms) needed for accurate predictions

Parasitic Reactions at Battery Anode Interfaces

Motivations: must block electron tunneling from anode to electrolyte in lithium batteries – electrolytes are metastable! Interfaces are stabilized by sacrificial, parasitic reactions that form passivating solid electrolyte interphase ("SEI")

Spatial Heterogeneities and Onset of Passivation Breakdown at Lithium Anode Interfaces

Model "SEI" films: grain boundaries in Li2O and LiF films deposited on Li metal

If mobile e- live in grain boundaries passivation fails

12% strain cracks Li2O film at GB region

Nanocracks in Li2O film predicted to accommodate Li filaments; LiF films less tendency to insert Li metal

Summary

- DFT calculations predict electron tunneling (passivation breakdown) in Li2O defects in the SEI
- Interfaces are stabilized by sacrificial, parasitic reactions that form passivating solid electrolyte interphase ("SEI")
- In some cases SEI protection films break down, conducts e-, spatial heterogeneities (defect/hot spots) are examples

Parasitic Reactions at Battery Anode Interfaces

Motivations: Mn(II) can dissolve from cathode surface, diffuse to anode, and catalyze destruction of some anode SEI components [Chem. Mater. 29, 2550 (2017)]

DFT calculations provide strong evidence that liquid electrolyte molecules readily decompose on cathode oxide surfaces under mild charging conditions [Jung, J. Phys. Chem. C 116, 9582 (2012)]

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Parasitic Reactions at Battery Anode Interfaces

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Mn(II) can dissolve from cathode surface, diffuse to anode, and catalyze destruction of some anode SEI components [Chem. Mater. 29, 2550 (2017)]
Scalable Packaging Materials for Roll-To-Roll Processed Thin Films Solar Cells

Material Graham4, Michael Sulikki5, Jinho Hah1, Jack Moon1, C. P. Wong1, Suresh Sitaraman1, Matthew Reese2, Sean Garner3, Scott Jones4, Doojin Vak5


Introduction
Manufacturing flexible, thin-film photovoltaics at scale has the potential to make solar electricity price-competitive with conventional electricity generation. However, the sensitivity of these PVs to environmental conditions has created the need to develop encapsulation and edge-seal materials that can adequately protect these devices while being compatible with high-throughput, roll-to-roll manufacturing processes. Therefore, the goal of this work is to understand the long-term performance of commercial adhesives and barriers for flexible PV cells. Additionally, modified adhesives and encapsulants will be made at Georgia Tech for comparison to commercially available options.

Materials for Packaging

Barrier Materials:
- Corning Willow Glass
- 3M Ultra Barrier

Adhesive/Encapsulant Material Classes:
- Polyethylene terephthalate (PET)
- Polyurethane (PUR)
- Inorganics
- Ionomer
- Polyethylene Vinyl Acetate (EVA)
- Ethylene Vinyl Acetate (EVA)
- Most common PV encapsulant
- - Transparent
- - UV stability issues
- - Moisture reaction
- - UV stable
- - Strong adhesion
- - Proprietary Adhesives
- - UV curable barrier adhesive

Calcium Testing and Mechanical Testing

Calcium Test Specimens

- Measurements taken regularly throughout experiment
- Degradation distance from average of 20 measurements (5 per side)

Mechanical Test Specimens

- T-peel testing of 1 cm wide samples, constant extension at 100mm/min:

UV/Ozone Treatment

- NOVASCAN: UV Ozone System
- Contact Angle
- XPS (control)
- XPS (30 min)

Poly(terephthalate) (PET) Chemical Structure

- Introduced Functional Groups
  - C=O Bonds (hydroxyl) \( \rightarrow 2.20 \% \text{ to } 12.39 \% \)
  - C-O Bonds (carboxyl) \( \rightarrow 2.86 \% \text{ to } 9.49 \% \)

Discussion and Future Work

- Initial approaches for rapid screens of moisture permeation and mechanical properties (assembly, high throughput measurement, required sample dimensions/quantities,…) are mostly established.
- Test at multiple temperatures to obtain diffusion coefficient and solubility parameters.
- PB Edge seals show best performance to date followed by UV curable transparent adhesive.
- Will use PDMS/silicone adhesives to test the performance of various fillers getters on barrier adhesive properties.
- Increase throughput screening of commercial and modified materials by end of year 1.
- Mechanical testing has shown that there is significant variation in both the adhesive strength and failure modes of the materials tested. More work is needed to understand the effects of sample geometry, dwell time, processing, and aging conditions.
- Conduct mechanical tests to determine interfacial fracture toughness in addition to peel strength.
- UV/Ozone treatment on 3M Barrier Film (PET side) at room temperature for at least 5 minutes showed a transition from hydrophobic to hydrophilic behavior.
- Continue to develop methods to chemically enhance the adhesion of 3M barrier to substrates by modifying the surface.
- Understood the impact of the chemical treatments after long term aging under humidity and solar illumination.

Optical Calcium Testing

Calcium Corrosion Testing for Permeation Through Adhesive: \( \text{Ca}(s) + 2\text{H}_2\text{O}(g) \rightarrow \text{Ca(OH)}_2(aq) + \text{H}_2(g) \)

- Degradation Distance vs. Exposure Time
- 60°C/90%RH Exposure Time (hrs.)
  - Diffusivity and WVTR

Mechanical Testing

- T-peel test specimens of 1 cm wide samples, constant extension at 100mm/min:
- PIB
- Proprietary Adhesive
- PDMS

Tapered Peel Specimens

- Future Studies: effects of UV exposure, humidity aging, temperature, processing conditions.
- Tapered peel specimens
- Adhesion strength and fracture energy for each material.
Failure mechanisms in electrically conductive adhesive interconnects
Arizona State University (ASU)

Zachary Holman1, Kathryn Fisher1, Mariana Bertoni1, Nick Bosco2, Timothy Silverman2
1Arizona Stat University; 2National Renewable Energy Laboratory

**University Goals**
- Failure mechanism(s) of ECA interconnects not known
- Several flavors of ECA material (e.g., silicone- vs. epoxy-based); failure mechanisms of each may be different
- Standard IEC tests may or may not be appropriate to accelerate ECA failure
- Our approach: ECA and module materials set → materials measurements and FEA model → accelerated tests

**University Accomplishments**
- Project started in October, 2017
- Team assembled and ready to go
- Discussions with industry at 7th Workshop at Metallization yielded likely ECA materials set to study, industry partners

**Outcomes and Impact**
- Outcomes will include preferred accelerated testing protocols, accelerated testing of select ECA materials, and recommendations for subsequent field testing
- Close collaboration with Dupont, Eurotron, Coveme, and CelLink ensures that project remains relevant to PV industry
- Several GW capacity online using ECA; this project has the potential to ensure that those modules last for 40 years

**DuraMAT Capabilities**
1. Data Management & Analytics, DuraMAT Data Hub
2. Predictive Simulation
3. Advanced Characterization & Forensics
4. Module Testing
5. Field Deployment
6. Techno-Economic Analysis

**Two module designs are gaining traction in the market today that employ electrically conductive adhesive (ECA) interconnects instead of established tabbing technologies:**
1. Modules with conductive back sheets (CBS) that string together back-contacted silicon cells with a patterned metal foil,
2. Modules with shingled cells that increase packing density by overlapping the cell edges

CBS modules have very low cell-to-module losses and the potential to nearly eliminate silver usage or copper plating in IBC modules, and shingled modules increase efficiency by eliminating wasted space.

**Timeline**

**Project begins**

Q1-2018

Set up FEA model
- Define systems to study
- Determine model framework
- Obtain materials
- Model systems and predict failure mechanisms

Q3-2018

DOE: test failure mechanisms

Q4-2018

DOE: module construction for field tests

Q1-2019

Verify the model
- Fabricate test structures
- Update model
- Fabricate modules

Q4-2019

Accelerated lifetime testing
- Complete degradation tests
- Analyze results

**Capability Development**

- Physical models of the failure mechanisms of ECA interconnects in silicon PV modules
- Accelerated testing procedures for these interconnects
- Tested modules with a range of interconnect materials combinations
- Recommendations for reliable module fabrication

**Cost Drivers**

- Physical models of the failure mechanisms of ECA interconnects in silicon PV modules
- Accelerated testing procedures for these interconnects
- Tested modules with a range of interconnect materials combinations
- Recommendations for reliable module fabrication

- 5 ECA with different chemistries, conductor types and fill ratios chosen
- In process of acquiring samples and signing NDAs
- Experiments to measure materials properties in accordance with ASTMs underway (NREL)
- X-ray characterization tests being set up (ASU)
A Hub for Sharing and Exploring Experimental and Time-Series PV Reliability and Durability Data

Robert White1, Kris Munch1, Nick Wunderlin2, Dave Evanson1, Courtney Paising3, Chris Webber1, Michael Rahi2, David Rager1, Chris Delisle4, Tim Silverman5, Bill Sekulic4, Rob Eger3

1Lawrence Berkeley National Laboratory; 2Sandia National Laboratory; 3SLAC National Accelerator Laboratory; 4US Department of Energy

Capability Goals

To be a successful virtual laboratory consortium, DuraMAT members and partners must have the ability to securely and efficiently share and explore the data from their research. These methods are needed to efficiently archive experimental data and time-series fielded PV array data and any design must support and merge those systems. The data infrastructure must also provide the ability to store analysis tools capable of providing insights to both time-series and experimental data.

Outcomes and Impact

The DuraMAT project has developed a set of guidelines and best practices to inform the members. These policies will help ensure that data is as contextually complete as possible, containing full sets of data and metadata that will allow others to re-analyze, examine or reproduce any findings. In addition, following these guidelines will facilitate timely availability of data with the least effort and ensure that automated processing scripts (for metadata extraction, data format conversion) operate correctly. The simplest guideline is that all files need to contain data elements that are fully described. In some cases this may mean columns are provided with headers and units (when appropriate), and any single values are accompanied with a description. We have built JSON formatted, data standards files that can be used to programmatically generate the metadata interface and, at a later date, to provide the foundation to convert data coming from the data hub into the NIST or other data standards to feed outside repositories.

Data Hub

The Data Hub became an operational prototype in October of 2017 and was then opened consortium-wide in November of 2017. All current funded projects are now installed on the hub and datasets are being uploaded by researchers to their projects. Rebuilding the complex PVDAQ system, while maintaining its current operational ability, into a time-series based database is a complicated task. Development of the time-series database is now on its implementation phase while undergoing import and search testing locally and in the cloud. The Data Hub is currently in operation. We are seeing users beginning to upload datasets and configure projects.

Data Security

The data hub can archive a broad range of data formats and files ranging from experimental results to reports. We have developed a set of guidelines and best practices to inform the members. These policies will help ensure that data is as contextually complete as possible, containing full sets of data and metadata that will allow others to re-analyze, examine or reproduce any findings. In addition, following these guidelines will facilitate timely availability of data with the least effort and ensure that automated processing scripts (for metadata extraction, data format conversion) operate correctly. The simplest guideline is that all files need to contain data elements that are fully described. In some cases this may mean columns are provided with headers and units (when appropriate), and any single values are accompanied with a descriptive key. We have built JSON formatted, data standards files that can be used to programmatically generate the metadata interface and, at a later date, to provide the foundation to convert data coming from the data hub into the NIST or other data standards to feed outside repositories.

Concept and Development

The core of the DuraMat consortium is the ability to share and archive data efficiently and securely with other members and partners. This framework creates a “virtual lab” forum to facilitate and enable the distribution of work across the consortium. The data hub provides the platform to communicate research and to possibly leverage data beyond its original intent, enabling new understanding.

To develop the data hub we began by analyzing a variety of software platforms available against an exhaustive set of criteria covering everything from programming languages to customization and from security to workflow. The final decision for DuraMAT, and for the other EMNs, was to focus development around the CKAN software platform. This provides a consistent, easy-to-use interface common to any researchers working across the EMNs.

The DuraMAT data hub is currently in operation. We are seeing users beginning to upload datasets and configure projects.

Data Standards

The simplest guideline is that all files need to contain data elements that are fully described. In some cases this may mean columns are provided with headers and units (when appropriate), and any single values are accompanied with a descriptive key. We have built JSON formatted, data standards files that can be used to programmatically generate the metadata interface and, at a later date, to provide the foundation to convert data coming from the data hub into the NIST or other data standards to feed outside repositories.

Researchers

Analysis tools form the bridge between data and understanding. We are implementing the tools for DuraMAT using the Python/Jupyter notebook format which allows for easy dissemination of both methods and results within a single container.

The data hub is fully operational it will provide researchers, and eventually the public, a portal into the most complete datasets on PV durability and reliability anywhere. There are few PV field system databases in the world with such an extensive dataset for exploring PV reliability and durability data. Once the new time-series database is operational it will be able to provide a comprehensive view of data from PV systems that can inform decisions about research goals, operational performance, and financial screening.

Researchers

Analysis Tools

Over twenty years, the PVDAQ database has accumulated and archived data from over 2000 PV systems scattered across a variety of locations and climates within the United States. Currently there are additional sites and systems (nationally and internationally) in the queue to be added to the database. At present the system has an easy intuitive interface using geographic locations or by searching for system names. Users can view a plot or download data for any selected system. A rudimentary API is also available to access data directly from the tables for participating PVDAQ members. Additionally the system provides a means for participating members to record events (cleaning, repairs, etc.) for a particular system that can give context to any performance changes. While effective and important data can be gleaned from the current system, it became a victim of its own success. As part of the DuraMAT project we have decided to leverage this wealth of data by rearchitecting the system and improving scalability, processing speed and accessibility.

Data Hub

The new database system has been re-engineered to take advantage of a federal cloud-based infrastructure now available at NREL. Utilizing utility scale computing allows us to keep cutting edge computing power and re-scalable architecture without the cost of maintaining the systems directly. The cloud infrastructure is fed-ramp certified and accessible by all the national labs, consortium members, partners, and the public.

Data Hub

Researchers

Analysis Tools

Researchers

Analysis Tools

Researchers

Analysis Tools

Researchers

Analysis Tools

Researchers

Analysis Tools

Researchers

Analysis Tools
Advanced Multifunctional Coatings for PV Glass to Reduce Soiling and PID Losses

Robert A. Fleming, Sr.; Craig J. Pop, Stephanie J. Moffitt, Laura T. Scheibels, Cory S. Thomson

DuraMAT Capabilities
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Industry Goals
- Development and understanding of multifunctional anti-soiling/self-cleaning and reflective (AR) coatings for PV Glass
- Working with National Lab partners, a testing protocol for evaluating the performance and properties of anti-soiling coatings is being developed
- Partnered with Advanced Characterization & Forensics

Accomplishments
- Investigating the fundamental interactions that enable anti-soiling/self-cleaning behavior using advanced surface morphology and chemistry characterization at SLAC and the artificial soiling capabilities of Sandia National Lab
- Pursuing potential induced degradation (PID) mitigation strategies using a novel back-side panel glass coating

Outcomes and Impact
- Once the testing protocol is established and validated, the properties of anti-soiling/self-cleaning coatings on the market can be evaluated
- Insights gained can drive the adoption of anti-soiling/self-cleaning coatings, identify geographic regions where specific coating chemistries are optimal, lead to novel material designs, etc.

Cost Drivers
- A Pathway To 3 Cents per kWh
  - 0.50 $ / kWh
  - 0.60 $ / kWh
  - 0.70 $ / kWh
  - 0.80 $ / kWh
  - 0.90 $ / kWh
  - 1.00 $ / kWh
  - 1.10 $ / kWh
  - 1.20 $ / kWh

WattGlass High-Performance AR Coating
WattGlass has developed a high-performance AR coating for solar PV modules with multiple benefits over current solutions:
• 100% water-based — no harsh solvents
• Industry-leading optical performance — greater than 3% improvement in transmittance
• Resistant to particulate soiling — a combination of a superhydrophobic surface chemistry and nanocoating surface roughness results in particulate contamination not strongly adhering to the coating surface, and which does gets easily washed away with water

Soiling Studies
Preliminary coating studies performed at SLAC using a home-built soiling chamber and AZ road dust:
• 3 cycles of soiling with IL road dust shows a slight accumulation of rain-splashed droplets, but no major change in morphology
• 5 cycles of AZ road dust, with intermittent washing and a final mechanical wipe, results in a loss of nanoscale scattering contrast — analysis ongoing

Techno-Economic Analysis
Information obtained from the artificial soiling studies, as well as field tests, will determine anticipated soiling/de-soiling rates for the WattGlass coating across a wide variety of geographic regions.

PID Mitigation Studies
- System Design Issues at Higher Voltages
  - Current trend of PV panels towards operating voltages in excess of 1 kV opens up many opportunities for improvements of utility scale system designs, but also increases the risk of PID at the module level
  - Cellon Shift Due to Leakage Currents
  - Na-Ion migration from the glass cover through the EVA encapsulant has been attributed as a major source of PID

PID Optimization Cycle

In-plane Grazing Incidence Small Angle X-ray Scattering (GIXS) was used to characterize the coating morphology and structure.

Small Angle X-ray Scattering Experiments at SLAC

Soilability Experiments with Sandia National Lab
• Soilability of Coatings and Mini-Modules with 'Standard Grime'
• Different mixtures of visible pigments to mimic the soiling compositions of various geographic regions, based on the USDA soil taxonomy
• Transmission Loss Measurements
• One-time, Quantum efficiency, and ESL vs.
• Soilability of the coupons assessed by washing with water, mechanical wiping, controlled airflow, etc.

Artificial Soiling Experiments with Sandia National Lab
After soiling studies, samples are returned to SLAC to characterize any changes in surface morphology and chemistry.

Timeline
Month
1 2 3 4 5 6 7 8 9 10 11 12

PID Optimization Cycle

Covers Fabricated and Delivered to SLAC
Baseline Chemistry and Morphology Characterization at SLAC
Soiling Studies at Sandia
Follow-up Characterization at SLAC
Testing Protocols Developed
Techno-economic Analysis
Coated Glass Delivered to 3 Solar for Mini-module Build
Na-Ion Barrier Feasibility Study
PID Optimization Cycle

Cost Drivers
- A Pathway To 3 Cents per kWh
  - 0.50 $ / kWh
  - 0.60 $ / kWh
  - 0.70 $ / kWh
  - 0.80 $ / kWh
  - 0.90 $ / kWh
  - 1.00 $ / kWh
  - 1.10 $ / kWh
  - 1.20 $ / kWh
Highly-conductive, Low-cost Polymer Adhesive Composites with Complex Dimensional Fillers (University of Akron/Sandia National Laboratory)

**University Goals**

Electronic-conductive adhesives (ECAs) are a critical component in fiber optic cable, for the attachment, vibration dampening and other applications. Sylgard is one of the most prominent ECAs to date, but it’s high cost and low electrical conductivity present challenges for widespread use. The goal of our work is to develop novel fillers and polymerization processes that enable in-situ creation of highly conductive, cost-effective, and durable electronic adhesives. The project team will work closely with sandia to develop digital tools and characterization techniques that are applicable to a broad range of ECAs. The team will also work to develop a novel adhesive formulation for use in the Advanced Materials Laboratory (AML) at Sandia. This adhesive will be based on commercially available ingredients and will be suitable for use in a variety of applications.

**Outcomes and Impact**

By achieving these objectives, we will be able to develop new ECAs that can revolutionize the electronics industry. The project will enable the creation of high-performance, low-cost ECAs that can be used in a wide range of applications, including aerospace, automotive, and telecommunications. The project will also contribute to the development of new technologies for the fabrication of electronic devices, which will have a significant impact on the global economy.

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**DuraMAT Capabilities**

**1. Data Management & Analytics, DuraMAT Data Hub**

**2. Predictive Simulation**

**3. Advanced Characterization & Forensics**

**4. Module Testing**

**5. Field Deployment**

**6. Techno-Economic Analysis**

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**Synthesis and Characterization of Edge-Functionalized 2D Fillers**

**Edge Functionalized Nanoplatelet Graphene Materials**

**Large Scale Synthesis of Silver Nanoparticles and Nanowires**

**Electroless Deposition onto 2D Materials**

**Characterization of Conductive Adhesive**

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**Work plan to next quarter:**

- Silver Nanowire/Nanoparticle integration
- Optimized, uniform nickel coating recipe
- Further elucidation of percolation threshold (differing Edge-Functional Carbon length)
- Uniform Nickel Coating
- Basic coating of other alloys (copper, silver, etc.)
- Edge-Functional coating integration into silver-flake polymer adhesives