Real-world and Accelerated Degradation of PV Module Backsheets

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Acknowledgements

Work from this talk:
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Devin Gordon, PhD (3M)
Addison Klinke, MS (data science consultant)
Lifetime Prediction of Materials with Data Science: PV Module Focus

Accelerated Exposures are “standard” for material durability

Companies don’t want to wait 3+ years to see if their material lasts
- Multiple real-world stressors
- History of failures

Utilize Data Science to move beyond “acceleration factor”
- Assumes reciprocity
- Misses combination of stressors
- Often assumes materials behave similarly

Need to build predictive models that relate
- Data driven models (Stress|Response)
- network Models (Stress|Mechanism|Response)

Combine accelerated with real-world data
PV Backsheet Degradation: Neet to Protect the Backsheet

Common Degradation Response

- Delamination
- Cracking
- Discoloration
- Hot spot
- Bubbling

22% global modules show visual defects (> 1.9 million modules)

Backsheet defects = 7.5% [1]

Open Data Science Tool Chain

Using Open-source tools

Reproducible Research
- Using Rmarkdown reports
- Python Jupyter Notebooks
- Add new data
- Recompile your report
- All new figures and report!
- Well Documented Code/Reports

High Level Scripting Languages: R, Python

Rstudio Integrated Development Environment
- Commercially Supported

Git Repositories for Code Version Control
- Share code scripts with colleagues
- Share project data and reports with others
Combines Lab data (Spectra, Images etc.) With Time-series Data (PV Power Plant Data)

High Performance PV Data Analytics: Petabyte Data Warehouse In A Petaflop HPC Environment

- In-place Analytics: Distributed R-analytics in Hadoop/HDFS
- In-memory Data Extraction: To Separate HPC Compute Nodes

IEEE JPV

A non-relational data warehouse for the analysis of field and laboratory data from multiple heterogeneous photovoltaic test sites

Yang Hu, Member, IEEE, Venkat Yashwant Gunapati, Pei Zhao, Devin Gordon, Nicholas R. Wheeler, Mohammad A. Hossain, Member, IEEE, Timothy J. Peshek, Member, IEEE, Laura S. Bruckman, Guo-Qiang Zhang, Member, IEEE, and Roger H. French, Member, IEEE
Field Surveys of Backsheets

CWRU: Yu Wang, Addison Klinke, Roger French, Laura Bruckman
UL: Liang Ji, Kent Whitfield, Ken Boyce,
NREL: Michael Kempe
Arkema: Camille Loyer, Adam Hauser, Gregory O’Brien
NIST: Andrew Fairbrother, Xiaohong Gu
NEU: Scott Julien, KT Wan
Field Survey Procedure

Field description

- Rack: a section of PV modules
- Column (length): horizontal direction
- Row (depth): vertical height and tilt angle

Field Survey:

- Measured 1300 + modules
- ~9 measurements each module
  - center, edges, junction box
## Field Information

<table>
<thead>
<tr>
<th>Site</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Climatic Zone</strong></td>
<td>Dfb: humid continental climate</td>
<td>Cfa: humid subtropical climate</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Brand &amp; Model</strong></td>
<td>r0t0akg</td>
<td>untww6o</td>
<td>t4lqg3w, qathm7f</td>
<td>a5uyujm</td>
</tr>
<tr>
<td><strong>Air-side Material</strong></td>
<td>PVDF</td>
<td>PA</td>
<td>PET, PET</td>
<td>PEN</td>
</tr>
<tr>
<td><strong>Ground Cover</strong></td>
<td>Grass</td>
<td>Grass</td>
<td>Grass</td>
<td>Gray rock</td>
</tr>
<tr>
<td><strong>Column Number</strong></td>
<td>82</td>
<td>80</td>
<td>26</td>
<td>48</td>
</tr>
<tr>
<td><strong>Row Number</strong></td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>
Field Survey Results

Non-uniform degradation
- gives insight into unique degradation stressors
- same climate zone

Need to understand relationship
- between the increased stress and the time

\[
Y = \beta_0 + \beta_1 L + \beta_2 L^2 + \beta_3 L^3 + \beta_4 (L - a_1)^3 + \\
+ \beta_5 (L - a_2)^3 + \beta_6 D + \beta_7 D^2 + \beta_8 t + \epsilon,
\]
Non-uniform Irradiance

Similar rear-side irradiance distribution with YI pattern
- Measurement: rear-side irradiance measured in site D
- Simulation: physical model for ordinary PV rack

Different temperature distribution YI pattern
- Measurement: no significant difference of temperature in site D
- Simulation: Higher temperature at center of rack

Inhomogeneous rear-side irradiance
- May cause non-uniform backsheet degradation
- Within one rack in the PV site

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Conclusion

Generalized spatio-temporal model

- Adjusted R\(^2\) range: 0.31-0.89
  - Low adjusted R\(^2\) due to noise in measurement and minimal degradation
- Identify the backsheets with a higher degradation rate

Non-uniform backsheets degradation

- For columns and rows in a rack
- Inhomogeneity of rear-side irradiance
  - May lead to non-uniform backsheets degradation
- Ground cover and air-side material
  - Affect the non-uniform backsheets degradation

Current Research is expanding these field survey data

- Increase dataset and model
Retrieved Modules & Accelerated Exposures

http://datascience.case.edu

http://sdle.case.edu
Retrieved Backsheets

40 modules of 19 brands
6 outer layer materials

**PVDF**
- Crystalline phases (coupons phase)
- Acrylic additives (5 of 6)
- Wide range of YI values (< 6 years)

**PVF**
- Minimal changes in YI (< 28 years)

**PET**
- Discoloration (< 18 years)
- Wide variety of YI values, cracking delamination
- Coupons had microcracking

**PA**
- Micro and Macro cracking, delamination
- Pollution impact on YI
- < 6 years
- Cracking in coupons, not films
## Accelerated Exposures on Coupons

<table>
<thead>
<tr>
<th>Exposure</th>
<th>Irradiation (W/m²/nm at 340 nm)</th>
<th>Chamber Temperature</th>
<th>Relative humidity</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH</td>
<td>0</td>
<td>85°C</td>
<td>85%</td>
<td>Damp Heat</td>
</tr>
<tr>
<td>Xenon-1</td>
<td>0.8</td>
<td>65°C</td>
<td>20%</td>
<td>102 minutes light, 18 min water spray in the light</td>
</tr>
<tr>
<td>Xenon-2</td>
<td>0.8</td>
<td>65°C</td>
<td>20%</td>
<td>100% light, no water spray</td>
</tr>
<tr>
<td>Xenon-3</td>
<td>0.8</td>
<td>80°C</td>
<td>20%</td>
<td>102 minutes light, 18 min water spray in the light</td>
</tr>
<tr>
<td>Xenon-4</td>
<td>0.8</td>
<td>80°C</td>
<td>20%</td>
<td>100% light, no water spray</td>
</tr>
<tr>
<td>Xenon-5</td>
<td>0.25</td>
<td>80°C</td>
<td>20%</td>
<td>102 minutes light, 18 min water spray in the light</td>
</tr>
<tr>
<td>Xenon-6</td>
<td>0.8</td>
<td>65°C</td>
<td>50%</td>
<td>102 minutes light, 18 min water spray in the light</td>
</tr>
<tr>
<td>Xenon-7</td>
<td>0.5</td>
<td>65°C</td>
<td>20%</td>
<td>102 minutes light, 18 min water spray in the light</td>
</tr>
<tr>
<td>Xenon-8</td>
<td>0.8</td>
<td>65°C</td>
<td>50%</td>
<td>100% light, no water spray</td>
</tr>
</tbody>
</table>
Cracks of Polyamide (PA/PA/PA): Retrieved and Films

PA/PA/PA cracking in accelerated exposures
- Xenon-3: Removal of air-side layer, degradation and crack of core layer
- Xenon-4: Micro cracks Degradation of sun-side and core layer between cells
- No Cracking in films
- Chromatography confirmed molecular weight loss

Stress or core layer degradation: key to cracks on PA/PA/PA
PA/PA/PA Surface Images under Accelerated Exposures

Xenon-3
- high irradiance & water spray
- 2000 hrs (Surface erosion)
- 4000 hrs (Crack formation)

Xenon-4
- high irradiance & no spray
- 4000 hrs (Micro cracks)

Xenon-5
- low irradiance & water spray
- No Cracking

Size Exclusion Chromatography
- Show MW decrease

Wang, Yu et. al “Predictive Models for Backsheet Degradation in Indoor Accelerated Exposures.”, in prep, 2019
Pollution Effect on Backsheet

Air pollutant

- NO$_2$ causes yellowing of polyamide$^{[1]}$
- More prominent effect of NO$_2$:
  - Roof mounted modules
  - Potentially higher irradiance & temperature
- Lower yellowness index value
  - With grass ground cover

Effect of Water Spray on PET Backsheets

Water spray removes degraded materials for PET
- No observable degradation product peaks observed in Xenon-3 FTIR
- Small decrease of PET peaks
**netSEM modeling of PET: Network Structural Equation Modeling**

**netSEM** is modified Structural Equation Modeling
- sociology
- adds nonlinear relationships between variables (semi-supervised)

**PET exposed to 0.8 w/m²/nm at 340 nm, 80°C**
- with water spray (A)
- without water spray (B)

**ATR-FTIR indicated**
- Surface removal of degraded products with water spray
- Identify degradation products without water spray
Degraded Surface Loss: Water Spray

Degradation product observed in DI water

- Parallel Factor Analysis
- Excitation/Emission Fluorescence
- Relative concentrations of
  - Mono- (A) or di-hydroxy (B) species

Conclusion

Mismatch between field data and accelerated exposures in some cases

- Duplication of PA/PA/PA crack in Xenon-3 successfully
- Severe bond cleavage observed in PVF/PET/EVA in Xenon-3

Effect of Water: delivery method and water amount is key to accelerated tests

- Parallel factor analysis identified degradation products

Compare accelerated exposures to real-world exposures
Semi-Supervised Machine Learning

Extraction of Crack Parameters

Quantitative Comparison of Accelerated and Real-World Behavior

Graduate Student
Addison Klinke

Yu Wang (Backsheets)
Types of Cracking Observed

- 23 different backsheet types
- > 900 samples
- Accelerated Real-world Exposures

Data Collection Using Nanovea ST400

Optical Profilometry Theory
- Axial chromatic aberration: focuses wavelengths at different depths
- Reflected light passes through spatial filter
- Only the in-focus wavelength passes through with high efficiency
- Non-destructive and non-contact

Measurement Methodology
- Measure height (z-axis) every 1.0 μm in x-direction
- Repeat for 10 equally spaced “lines” in the y-direction
- Time-efficient yet robust to local variations in cracking
- Ideal for parallel cracks with minimal deadhesion
Crack Quantification Algorithm and Extraction of Parameters: R

Localized Regression
- Non-parametric statistical technique that weights model at each point towards the closest data
- Friedman’s Super Smoother optimizes the span parameter for each x-value (sample width)
- Iterative application allows simultaneous outlier detection to decrease computational time (average 2.7 iterations)

Computation
- Fleets of parallel Slurm jobs run in about 6 minutes on CWRU’s High Performance Computing Cluster
- Over 52,000 cracks measured (at a rate of 17.3 cracks/minute)

Measured Crack Features / Parameters
- Average depth, width, and area
- Min, max, and average spacing
- Number of cracks
- Normalized depth and number of cracks

\[ D_n = \frac{d_{\text{avg}}}{d_{L\text{UVA}_{<360}}} \]
\[ C_n = \frac{c_{\text{avg}}}{\text{UVA}_{<360}} \]
Automatically Generated Reference Plots - Parallel Cracks (FPE2)

- Parallel cracks and consistent surface (no deadhesion) are easily handled by the algorithm
- Most samples had these characteristics
Automatically Generated Reference Plots - Blistering (FPE2)

- Data points associated with blistering are successfully detected as outliers
- Super Smoother follows the expected surface
Automatically Generated Reference Plots - Delamination (FPE2)

- Delamination (right side of profile) results in large trough
- Incorrectly handled by outlier detection → now part of the “surface” is on the inner/core layer interface
Crack Progression Over Time: Residual Plots (FPE1 Cyclic QUV)

- Density, depth, and number of cracks increases with exposure
- Can visualize propagation of cracks through backsheet layers

Legend: Cracks — Layer Boundaries ● Model Data ○ Outliers
Convolution Neural Network for Image Analysis

Image Analysis of Backsheet Cracking
- Convolution neural network
- Identification of cracking patterns
- Discoloration

Field Survey Application
- Image analysis of backsheets

Figure 6. Six examples of crack inspection task performed on the test images using the trained Model 0. The different colors in the (b) and (c) column images indicated different crack classes shown in the color bar.
Thank You!