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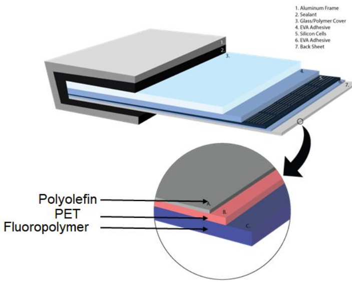
Field Experiences of PV Module Backsheets

Laura S. Bruckman

IEA PVPS Task 13 Webinar: Enabling 2nd Life Photovoltaics April 18th, 2024

PV Backsheet Degradation

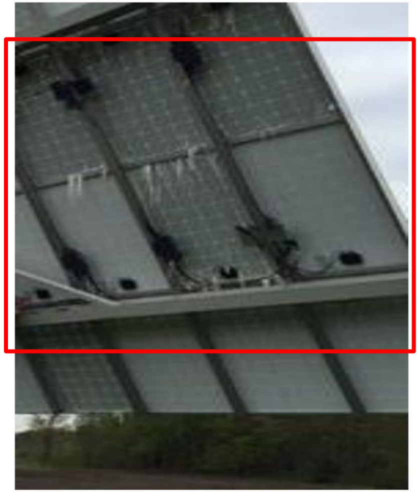


Common Degradation Response

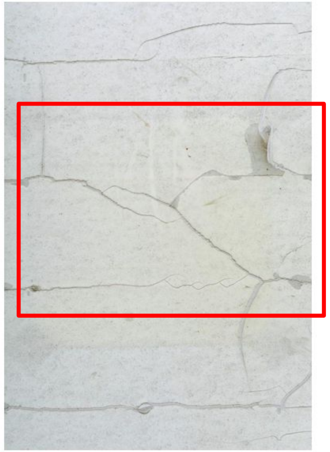
- Delamination
- Cracking
- Discoloration
- Hot spot
- Bubbling

Backsheet Structure

- **Air side layer**
  - Fluoropolymers: PVF, PVDF
  - Pigmented non-fluoropolymer: PET, PA (with TiO_2)
- **Core layer**
  - PET: mechanical strength and dielectric property
- **Cell side layer (inner layer)**
  - EVA: same with encapsulate, increase adhesion
  - Same as the air side layer
    - Symmetric structure



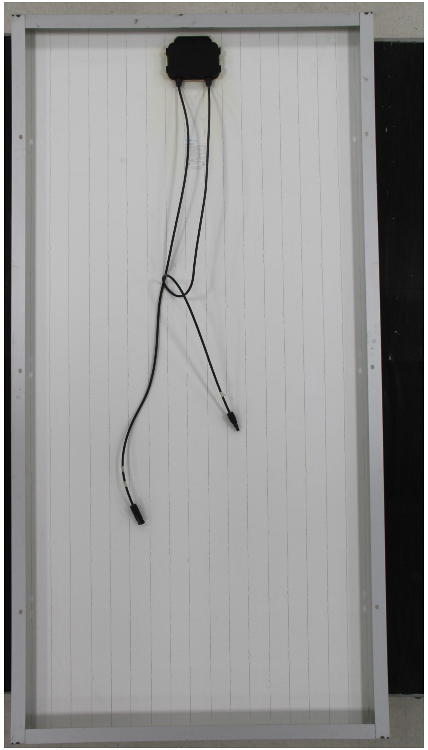
Delamination



Cracking

Hot Spot

Bubbling



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Retrieved Modules

CWRU EMSE Graduate Students: Yu Wang (Avery Dennison), Raymond Weiser (current PhD Student)

Field Retrieved Modules

Cross Sectional Retrieved Module Survey[1] :

- **33 Modules; 15 locations**
  - **Airside Layers:** THV (3), PA (8), PET (7), PVF (10), PVDF (5)
  - **Climatic Zones:** Aw, BSk, BWh, Cfa, Csa, Csb
  - 0 - 28 year Exposure
- **Inhomogeneous Backsheet Degradation**

Field Retrieved Studies:

- Biased Sample
  - Damaged / Replaced Modules
- Sample Size
- Lack of Complete of Bill of Materials (BoM)

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[1] Wieser, Raymond J., Yu Wang, Andrew Fairbrother, Sophie Napoli, Adam W. Hauser, Scott Julien, Xiaohong Gu, et al. "Field Retrieved Photovoltaic Backsheet Survey from Diverse Climate Zones: Analysis of Degradation Patterns and Phenomena." Solar Energy 259 (July 15, 2023): 49–62. https://doi.org/10.1016/j.solener.2023.04.061.

Comparison of Backsheet Materials

PVDF:

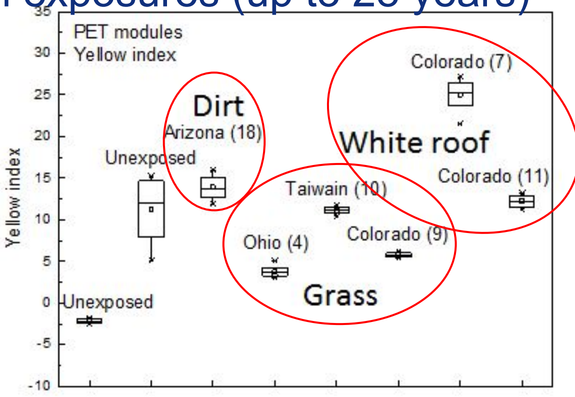
- Different yellowness index & gloss values potentially due to film crystalline phase (α & β)
- 4 of 5 backsheets have acrylic additives
- Similar measurement results for same type of film structure
  - Relative short exposure times (< 6 years) for all PVDF-based backsheets

PVF:

- Minimal changes to yellowness index and gloss for long-term exposures (up to 28 years)
- Small distribution of yellowness index and gloss-loss

PET:

- Extensive discoloration and gloss-loss
- Variability in yellowness index and gloss (location)

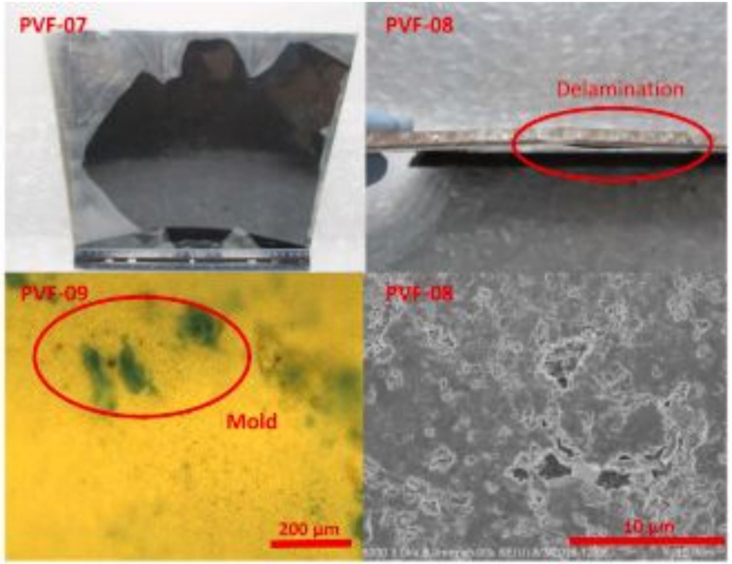


PA:

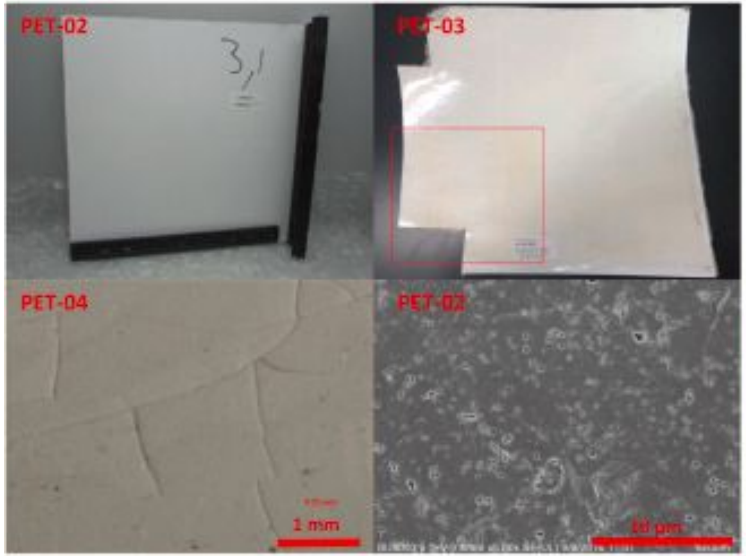
- Severe cracks and micro-cracking
- High yellowness index observed in particular backsheets
  - Changshu, China, concrete ground cover, pollution
- Gradually decrease in gloss with exposure time

Wieser, Raymond J., Yu Wang, Andrew Fairbrother, Sophie Napoli, Adam W. Hauser, Scott Julien, Xiaohong Gu, et al. "Field Retrieved Photovoltaic Backsheet Survey from Diverse Climate Zones: Analysis of Degradation Patterns and Phenomena." Solar Energy 259 (July 15, 2023): 49–62. https://doi.org/10.1016/j.solener.2023.04.061.

Retrieved Module Observations



Weak Adhesion (PVF-07, -08, CSA, 28 years)
Mold (PVF-09, -08, CSA, 28 years)



TiO_2 filled PET with pitting (PET-02 CFA, 4 years) and clear outer-layer with microcracking (PET-03, BSK, 6.5 years)

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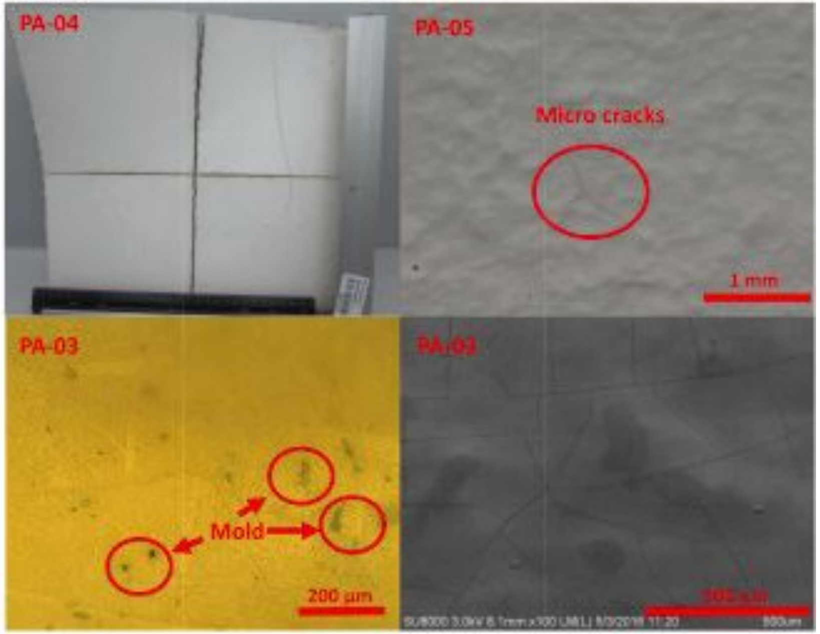
Wieser, Raymond J., Yu Wang, Andrew Fairbrother, Sophie Napoli, Adam W. Hauser, Scott Julien, Xiaohong Gu, et al. "Field Retrieved Photovoltaic Backsheet Survey from Diverse Climate Zones: Analysis of Degradation Patterns and Phenomena." Solar Energy 259 (July 15, 2023): 49–62. https://doi.org/10.1016/j.solener.2023.04.061.

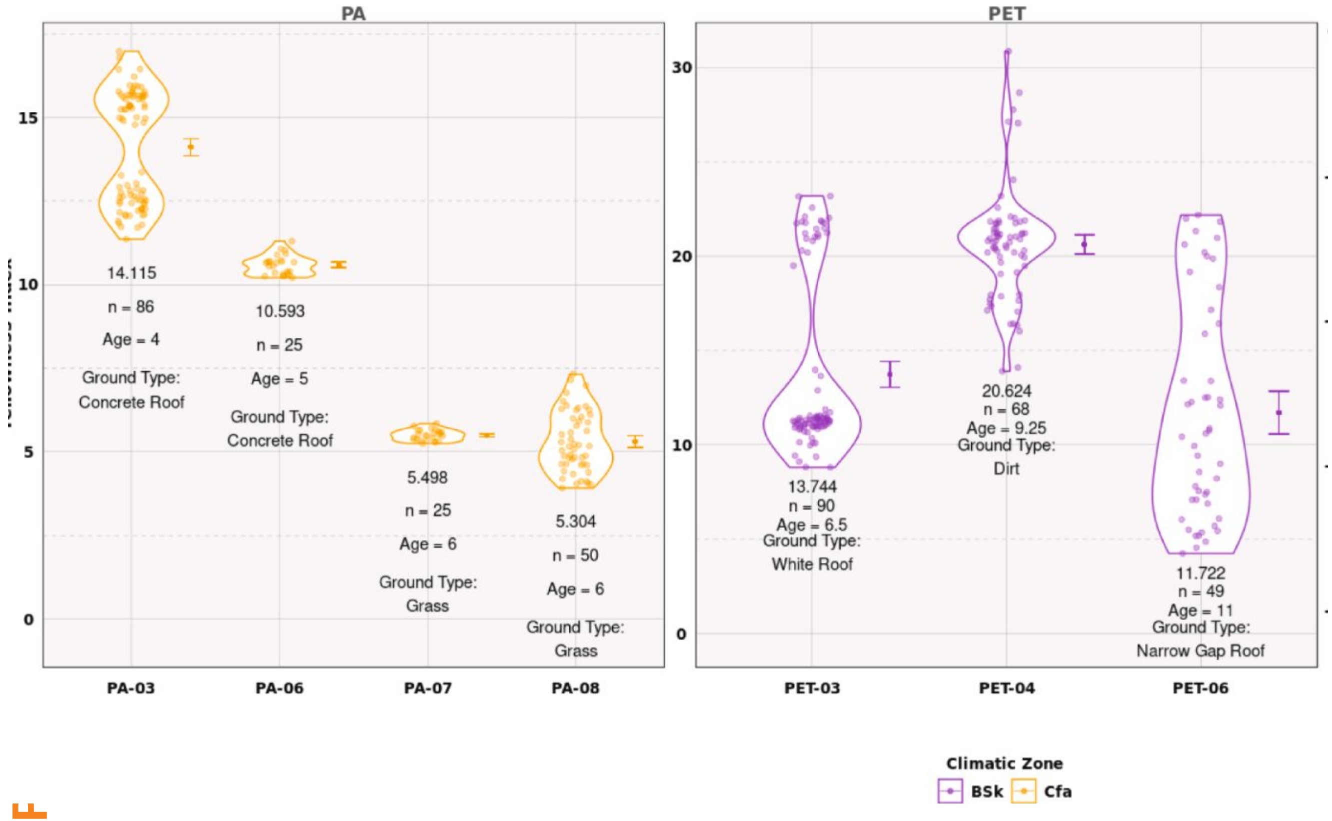
Retrieved Module Observations



Severe Cracks (PA-04, AW, 4 years), Microcracks (PA-05,CSA, 5 years), and mold/microcracks (PA-03, CFA, 4 years)

Wieser, Raymond J., Yu Wang, Andrew Fairbrother, Sophie Napoli, Adam W. Hauser, Scott Julien, Xiaohong Gu, et al. “Field Retrieved Photovoltaic Backsheet Survey from Diverse Climate Zones: Analysis of Degradation Patterns and Phenomena.” Solar Energy 259 (July 15, 2023): 49–62. https://doi.org/10.1016/j.solener.2023.04.061.

Non-uniformity



PA had increased yellowing

- mounted above Concrete
- increased NO_2

PET widely variable degradation

PVF

Wieser, Raymond J., Yu Wang, Andrew Fairbrother, Sophie Napoli, Adam W. Hauser, Scott Julien, Xiaohong Gu, et al. "Field Retrieved Photovoltaic Backsheet Survey from Diverse Climate Zones: Analysis of Degradation Patterns and Phenomena." Solar Energy 259 (July 15, 2023): 49–62. https://doi.org/10.1016/j.solener.2023.04.061.

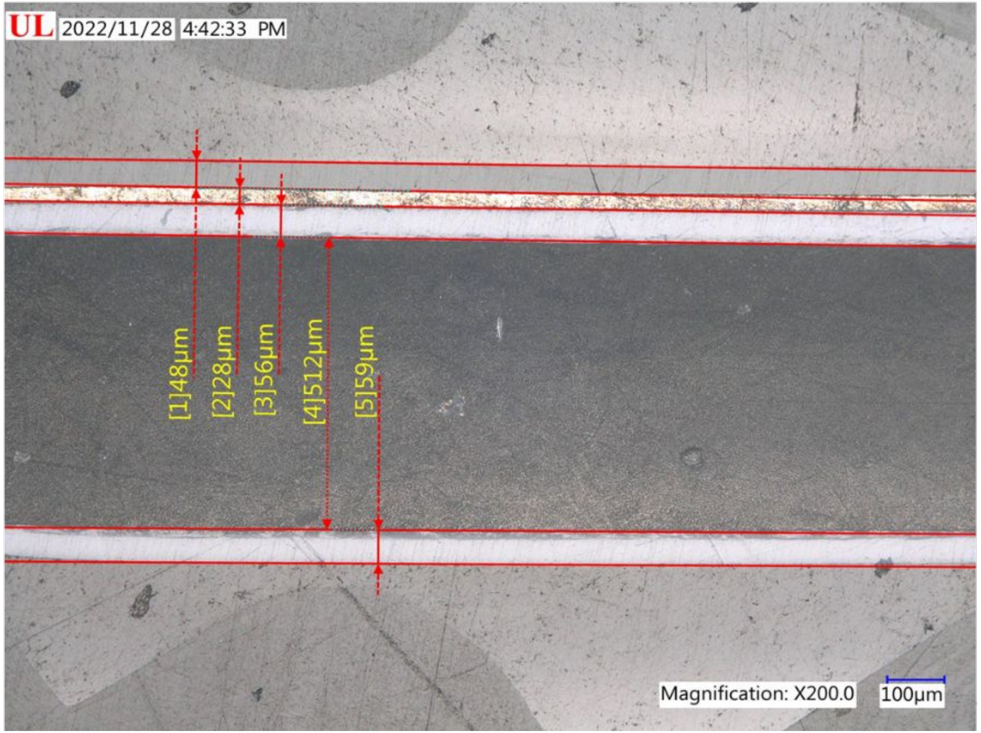
Set 2: Optical Microscopy Module from Taiwan

Layer structure

Sample ID	Layer structure
ITRI-1	**PET/Al/PET/EVA/PET (48um/28um/56/um/512um/59um)** **Dry Insulation Test: Failed**
ITRI-2	
ITRI-3	
ITRI-4	
ITRI-5	

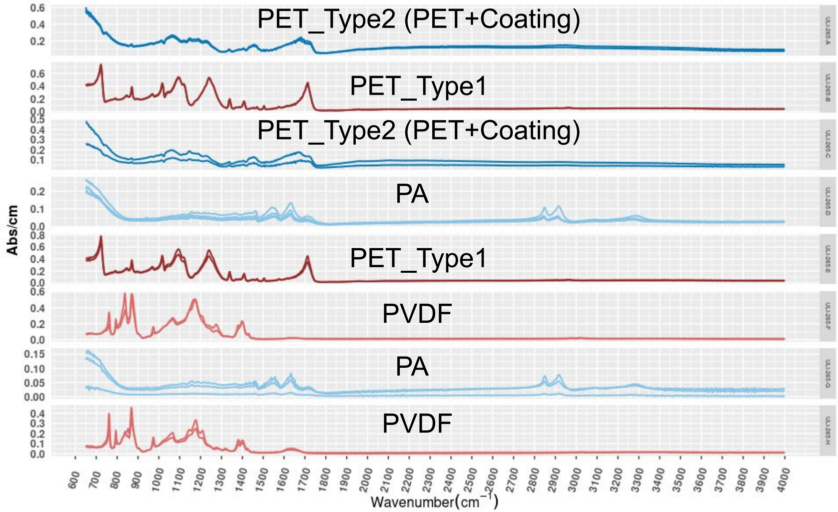
Module ITRI-3

PET1 (outer)
Al
PET2 (inner)
EVA
PET3 (inner)



Set 3: Retrieved Modules

Sample ID	Wet Insulation Resistance Results	Comment	Material
ULI-265-A	Failure		PET_Type2 (PET+ Coating)
ULI-265-B	Pass	Repair	PET_Type1
ULI-265-C	Failure		PET_Type2 (PET+ Coating)
ULI-265-D	Failure	Severe cracking on Backsheet	PA
ULI-265-E	Pass	Repair	PET_Type1
ULI-265-F	Pass		PVDF
ULI-265-G	Failure	Severe cracking on Backsheet	PA
ULI-265-H	Pass		PVDF



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Set 3: Retrieved Modules

Wet Insulation

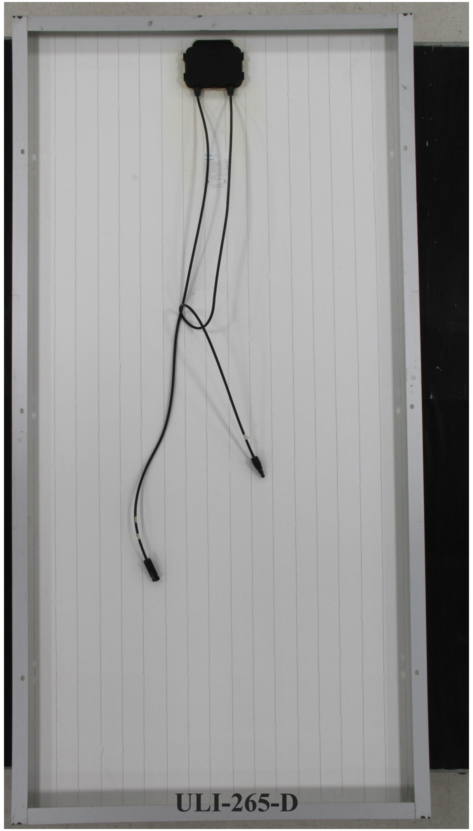
- **Failure**

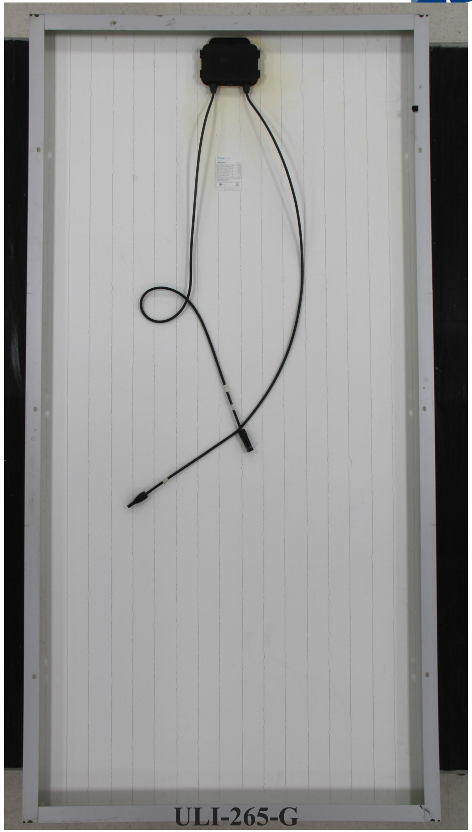
PA Backsheets

- TSM-275PA14

Same pattern of cracking

- Deep longitudinal cracks





Set 3: Retrieved Modules

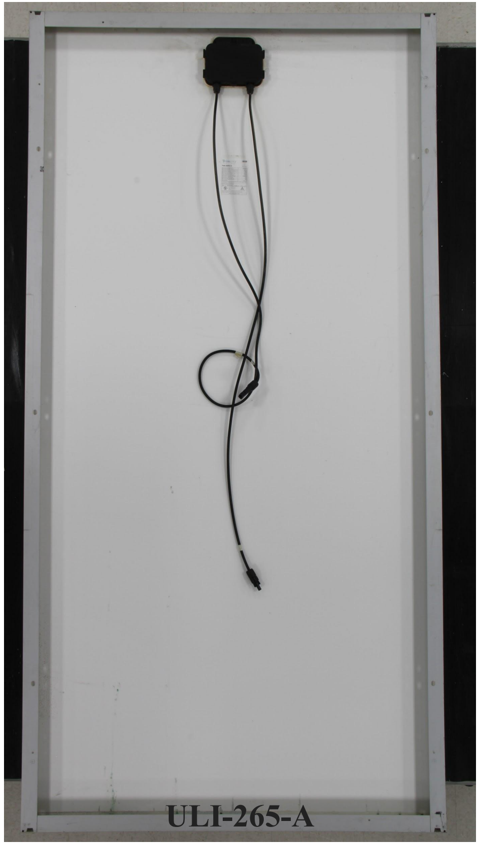
Wet Insulation Testing

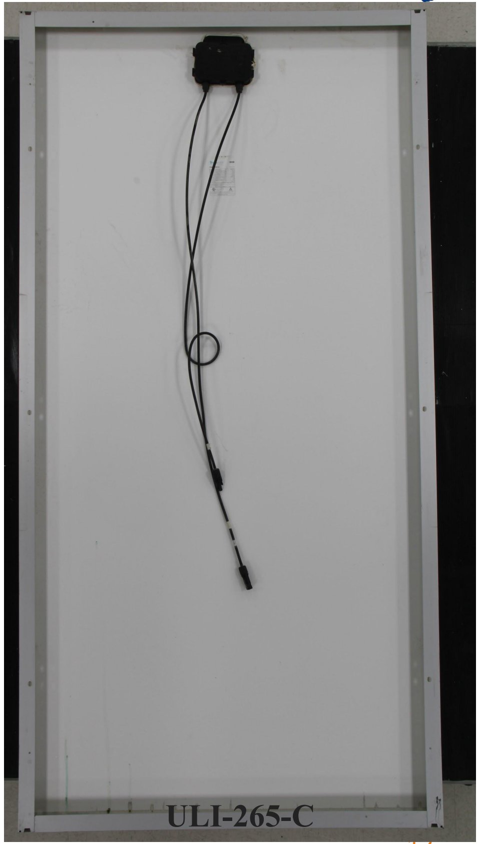
- **Failure**

PET_Type2 Backsheets

- TSM-285PA14

No visible Crack





Set 3: Retrieved Modules

Wet Insulation

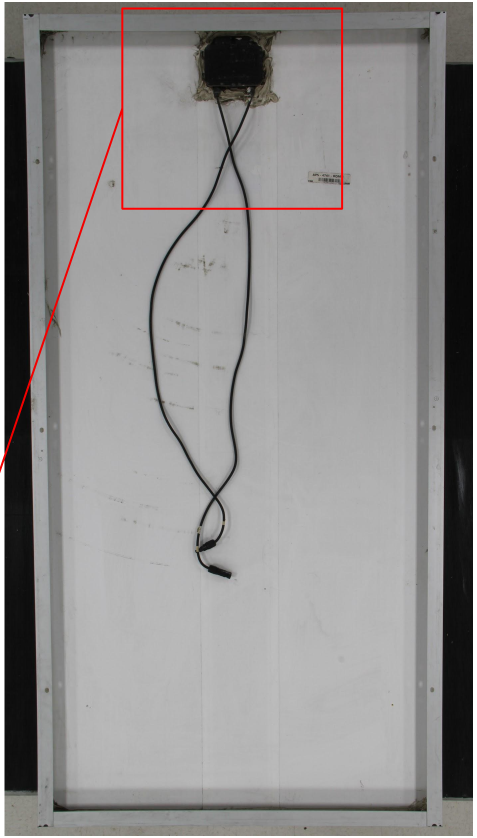
- **Pass**

PET_Type1 Backsheets

- TSM-285PA14

Same pattern of cracking

- Longitudinal cracks



ULI-265-B

ULI-265-E

Zelin(Zack) Li[a], Raymond J. Wieser[a], Xuanji Yu[a], Stephanie L. Moffitt[b], Ruben Zabalza[c], Xiaohong Gu[b], Laing Ji[c], Colleen O'Brien[c], Adam W. Hauser[d], Greg S. O'Brien[d], Roger H. French[a], Michael D. Kempe[e], Jared Tracy[f], Kausik R. Choudhury[f], William J. Gambogi[f], Laura S. Bruckman[a] , Kenneth P. Boyce[c]

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[b]Engineering Laboratory, National Institute of Standards & Technology, Gaithersburg, MD

[c]Renewable Energy, Underwriters Laboratories Inc., Northbrook, IL, USA

[d]Fluoropolymers R&D, Arkema, Inc., King of Prussia, PA, USA

[e]Photovoltaics Research, National Renewable Energy Laboratory, Golden, CO, USA

[f]E. I. du Pont de Nemours and Company, Wilmington, DE, USA

Field Survey Study Protocol

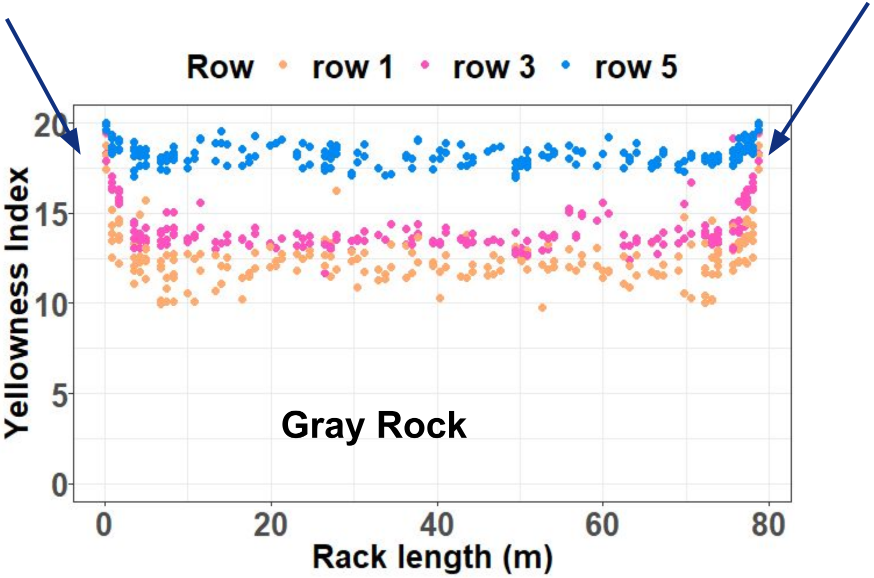
CWRU EMSE Graduate Students: Yu Wang (Avery Dennison), Raymond Weiser (current PhD Student), Zack Li (graduated Master's), Xuanji Yu (Previous Post Doc)

Motivation: Initial Survey

Is degradation uniform over a field?

- Are retrieved modules representative?

How do climate zones impact degradation?



3) Y. Lyu, A. Fairbrother, M. Gong, J.H. Kim, A. Hauser, G. O'Brien and X. Gu. Drivers for the cracking of multilayer polyamide-based backsheets in field photovoltaic modules: In-depth degradation mapping analysis. *Progress in Photovoltaics.* Published March 9, 2020. DOI: 10.1002/pip.3260

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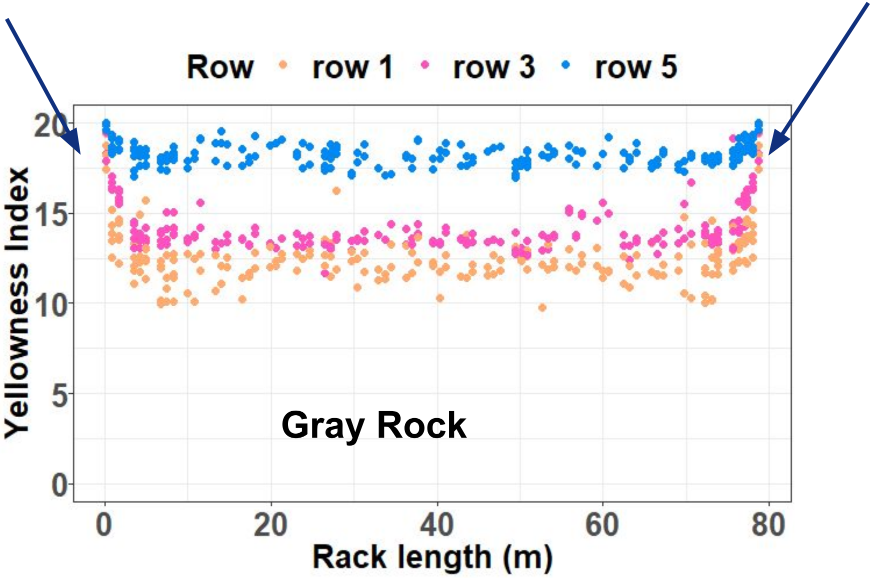

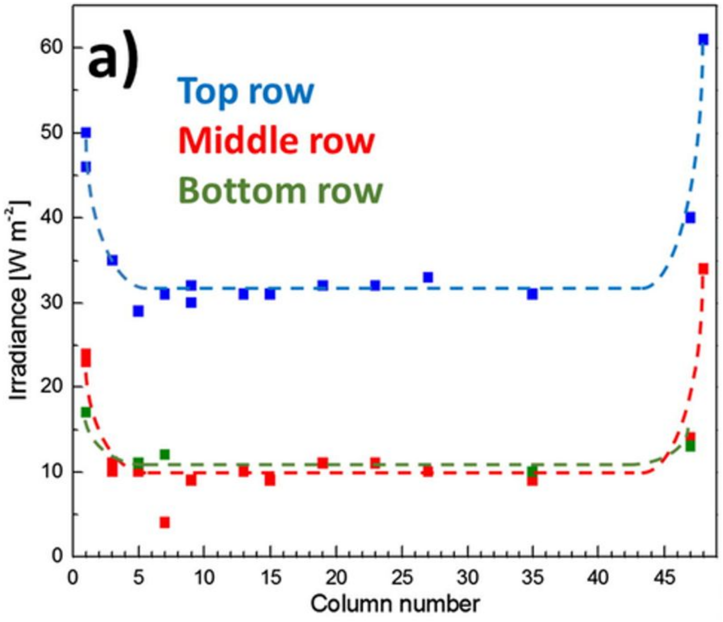

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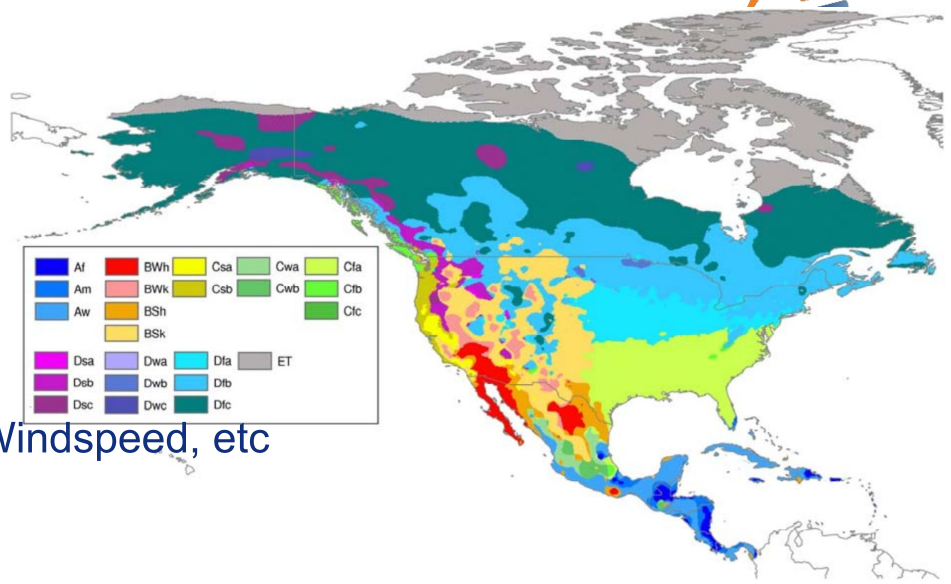
Site Selection

Sites with a wide variety of conditions

- Temperature Fluxuations
- Precipital Water
- Levels of Irradiance

Climate Zone Classification

- Based on annual weather patterns
- Temperature, Precipitation, Irradiance, Windspeed, etc

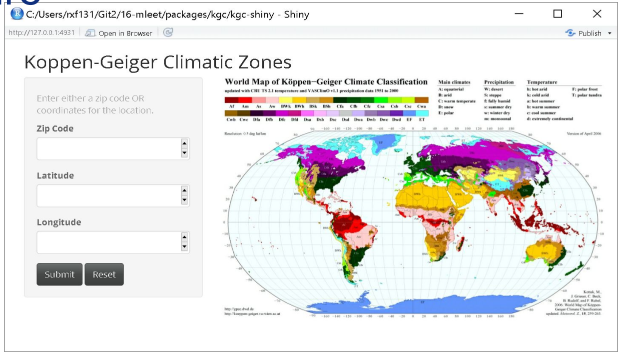


Köppen-Geiger

- Widely Used - developed for agriculture
- Updated Frequently
- Simple

Kgc on CRAN

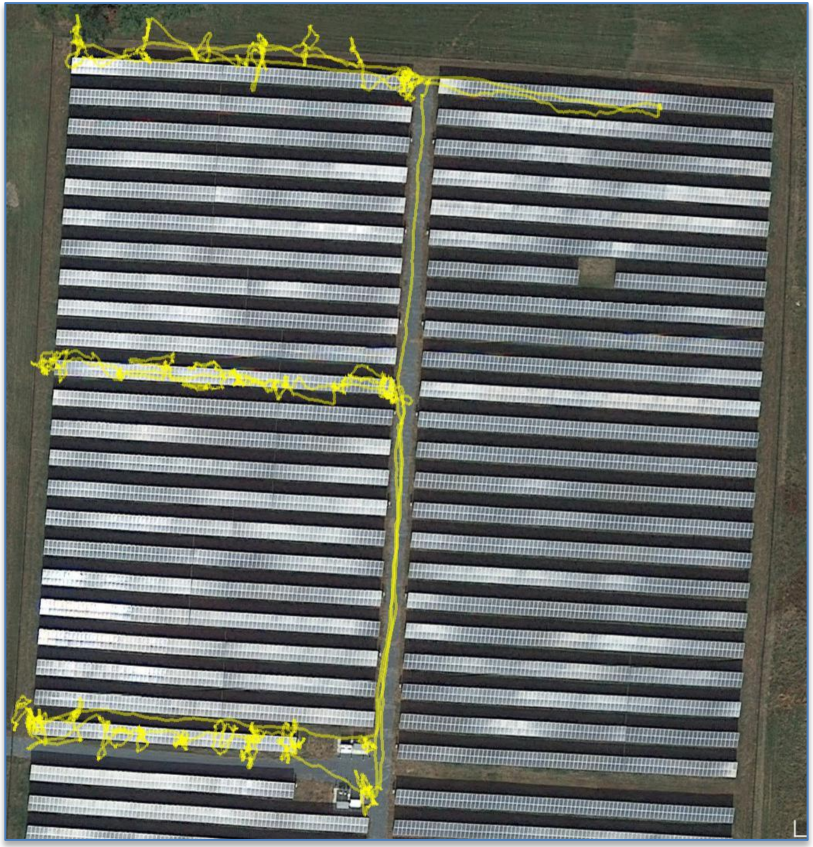
- R Climate Zone Package



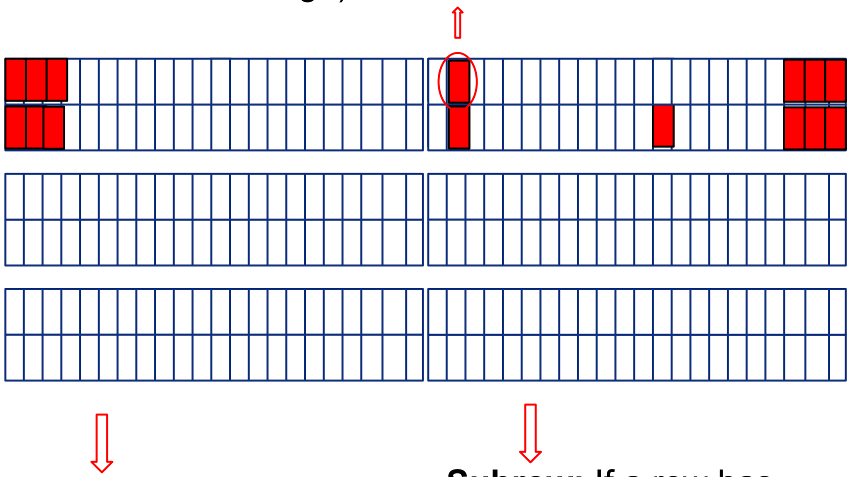
Köppen-Geiger[6]

6) Rubel, Franz, and Markus Kottek. 2010. "Observed and Projected Climate Shifts 1901-2100 Depicted by World Maps of the Koppen-Geiger Climate Classification." *Meteorologische Zeitschrift* 19 (2): 135–41. https://doi.org/10.1127/0941-2948/2010/0430.

Field Study Protocol (Submitting to ASTM Standard)



Module Number: Position of the module in the row (from the edge) i.e., Module 30



Rack: A continuous set of modules without physical spacing between mounting structures

Subrow: If a row has multiple modules stacked vertically, each row will receive a subrow designation. The top most row will be designated A, the next B, etc…

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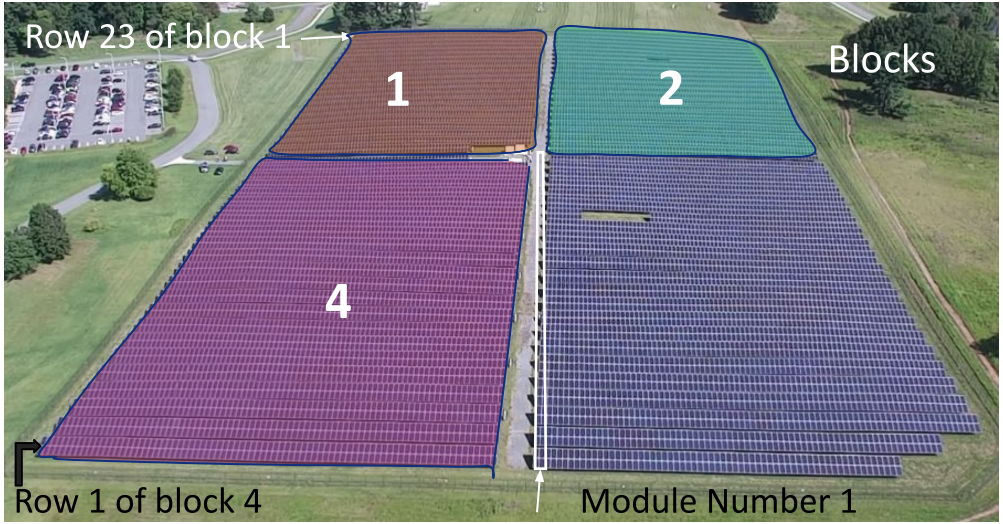
Field Survey Protocol: Nomenclature (Examples)

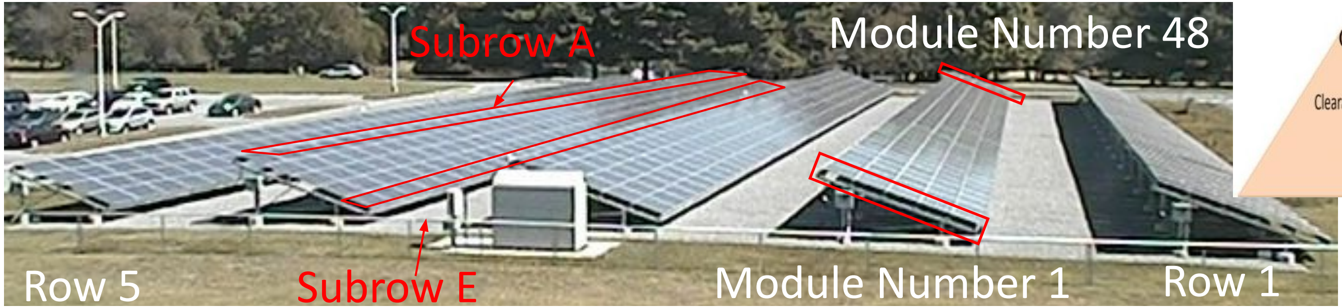


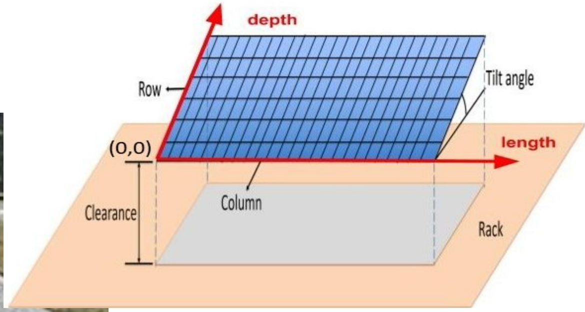
Frontside unshaded

- Row 1 of Block 4
- Row 1

Rearside unshaded

- Row 23 of Block 1
- Row 5





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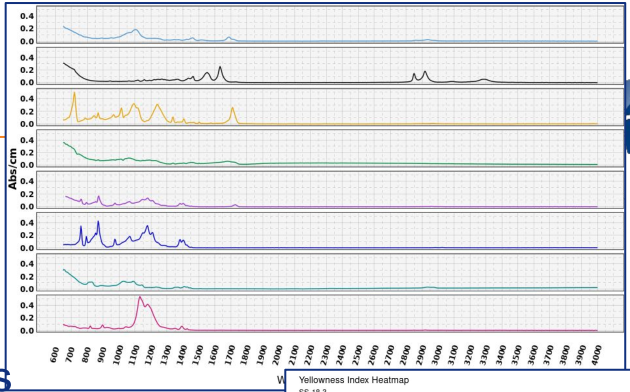
Materials Characterization

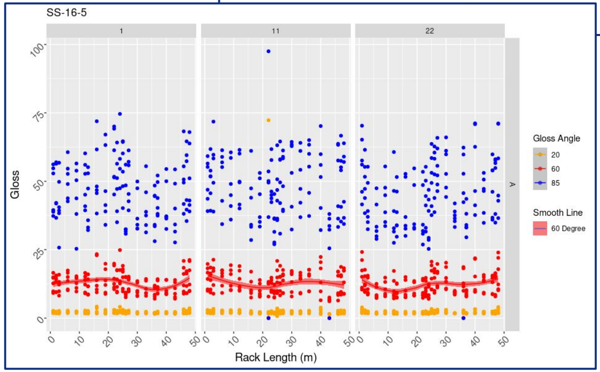


Attenuated Total Reflection
Fourier Transform Infrared (ATR-FTIR)

- Identify the composition of backsheet material
- Used for polymer
- Only works for the surface/outer layer of backsheets

Yellowness Index

- Polymer will have a color change after degradation
- Shows the degree of color change



Gloss

- Shows the surface roughness of backsheet materials
- Affected by the smoothness and flatness of the surface
- Additional insight into the degradation of the material

Raman (started)

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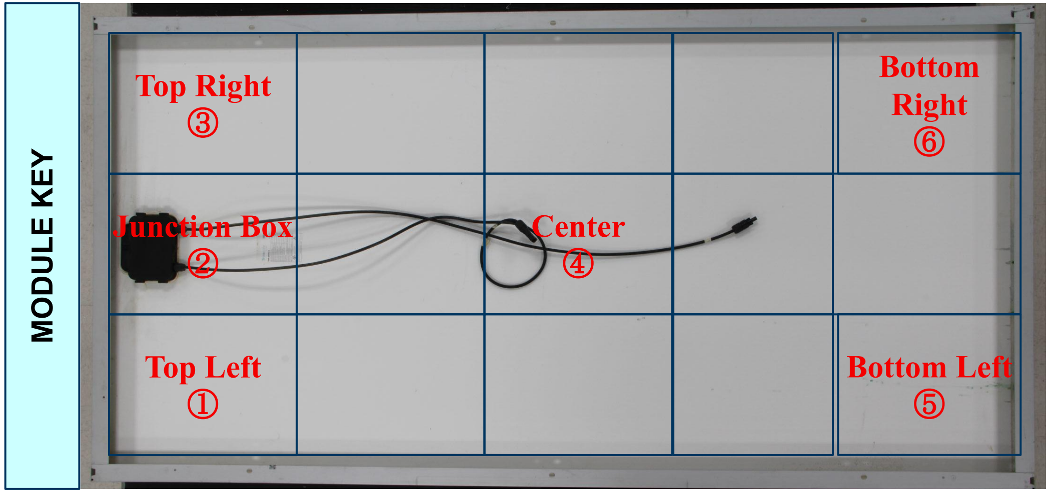
Field Survey Protocol: Measurement Positions

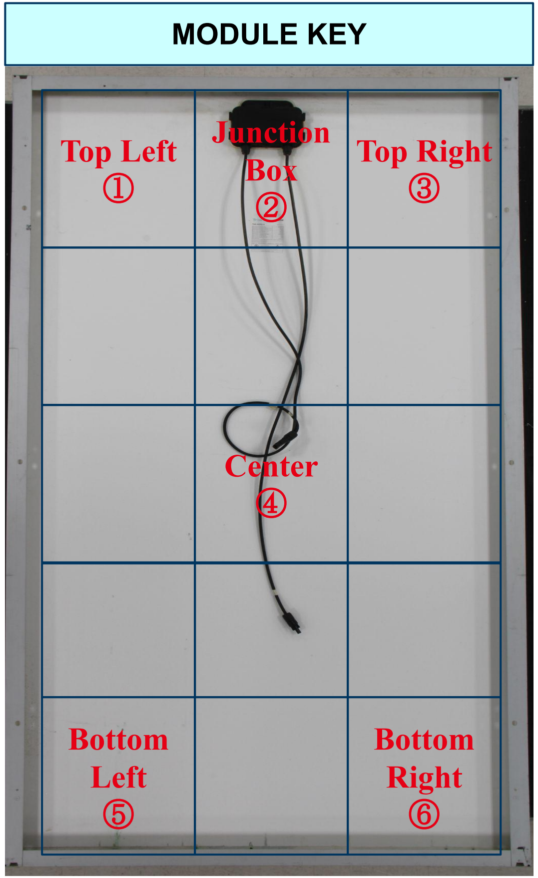
Multiple measurements done for each module

Not every site has same positions measured

- Due to mounting constraints

Recommended locations





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Field Survey Observations

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Overview of Completed Surveys

41 sites surveyed

- 7 Climatic zones
- 8 Material types
  - 7 polymers
  - 1 glass
- 4 sites visited multiple time points

Climate Zones	Number
Cfa	19
Csa	2
Csb	3
BSk	11
Dfa	7
Dfb	1
AM	1

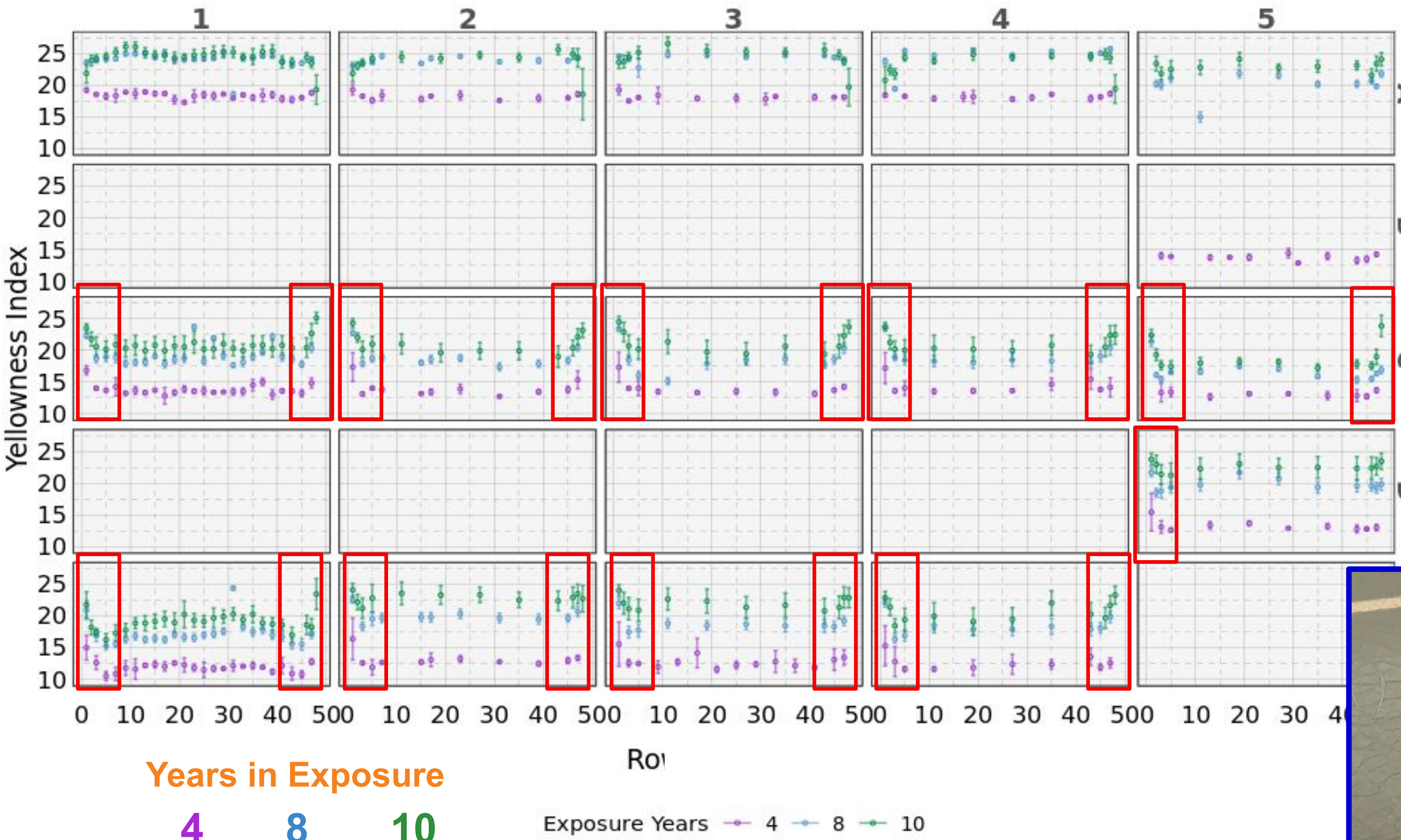
Material Types	Number
PEN	3
PET	10
PVF	5
PVDF	3
Acrylic PVDF	7
FEVE	7
THV	3
Test Bed	2
Glass	1

3,467 modules

- **17,684 measurements**

OSF Shared Data

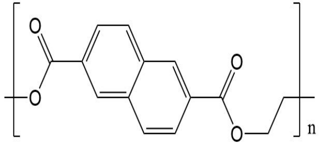
Saptiotemporal Degradation



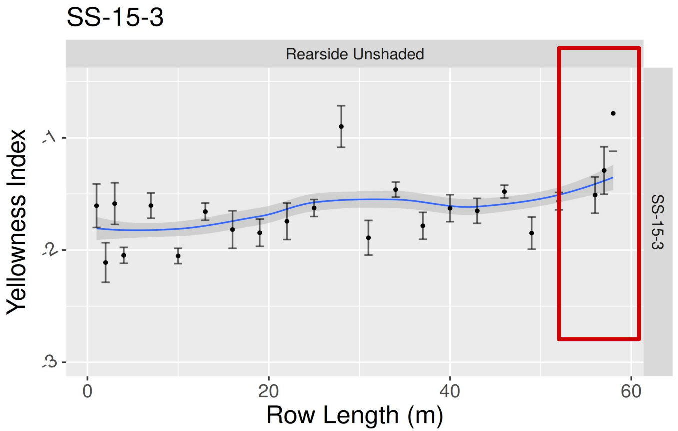
Years in Exposure

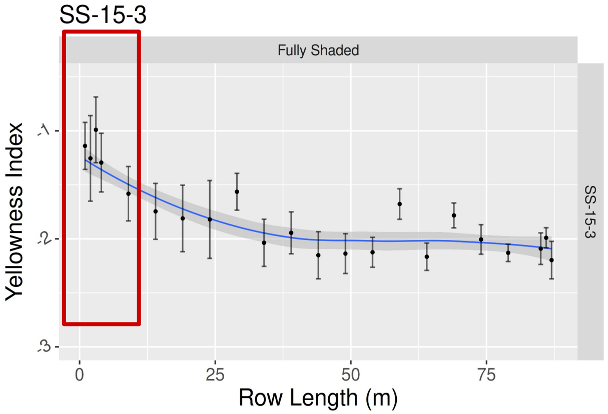
4 **8** **10**

Polyethylene naphthalate (PEN)

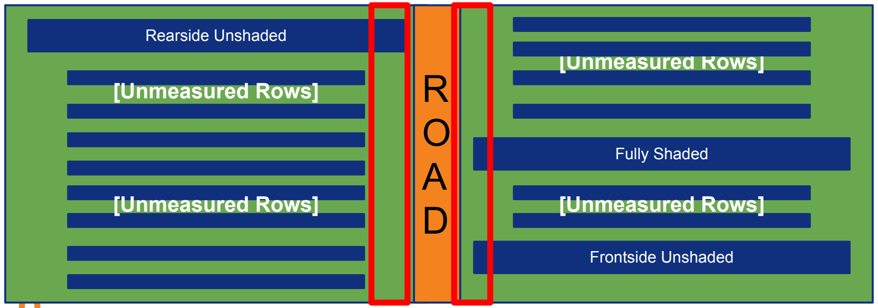


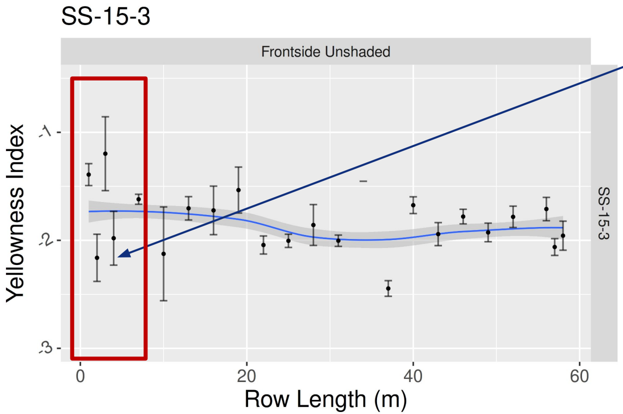
Nonuniform: Irradiance Exposure due to Road





Inference by eye: 83.4 % CIs

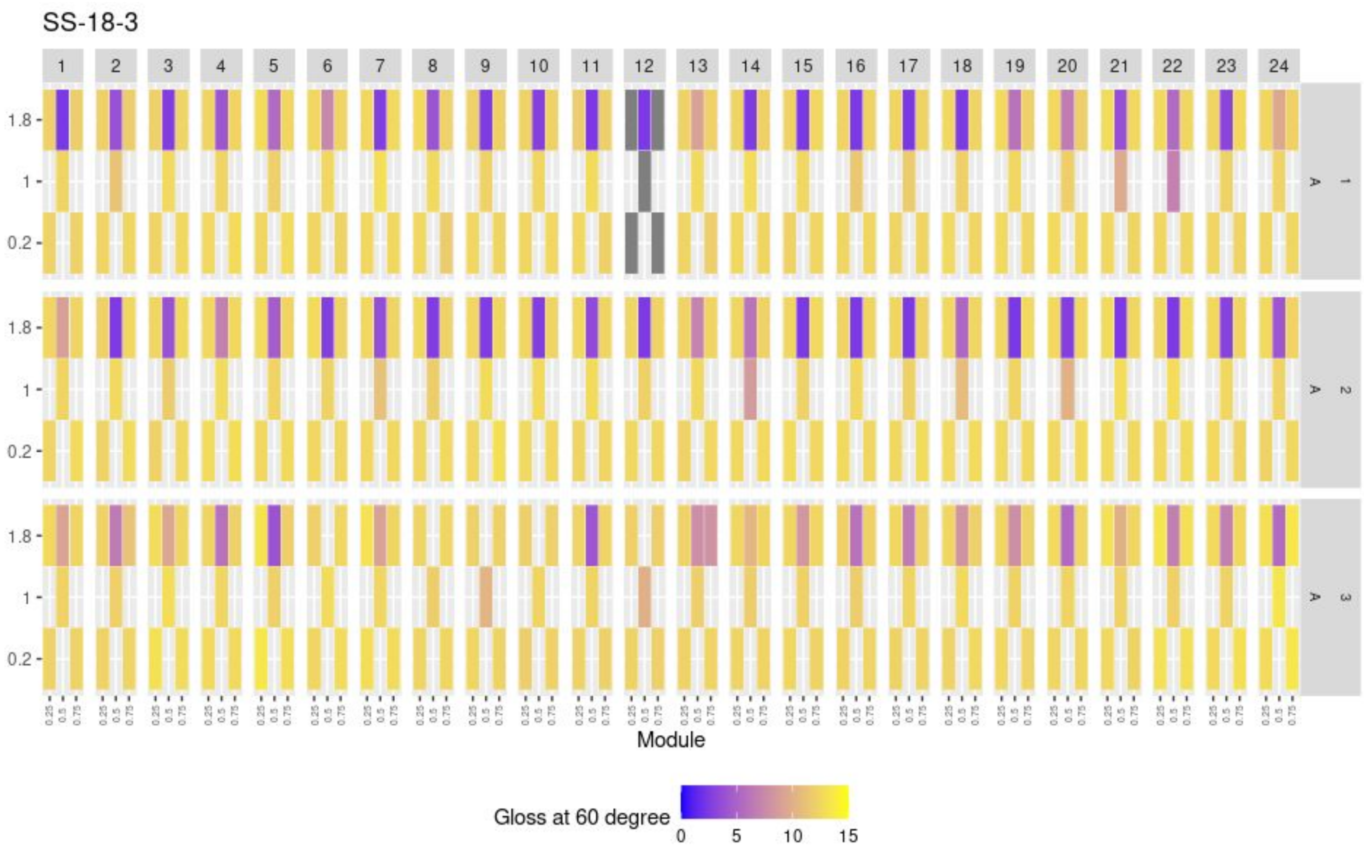




Module Replacement

PVF

Gloss at the Junction Box

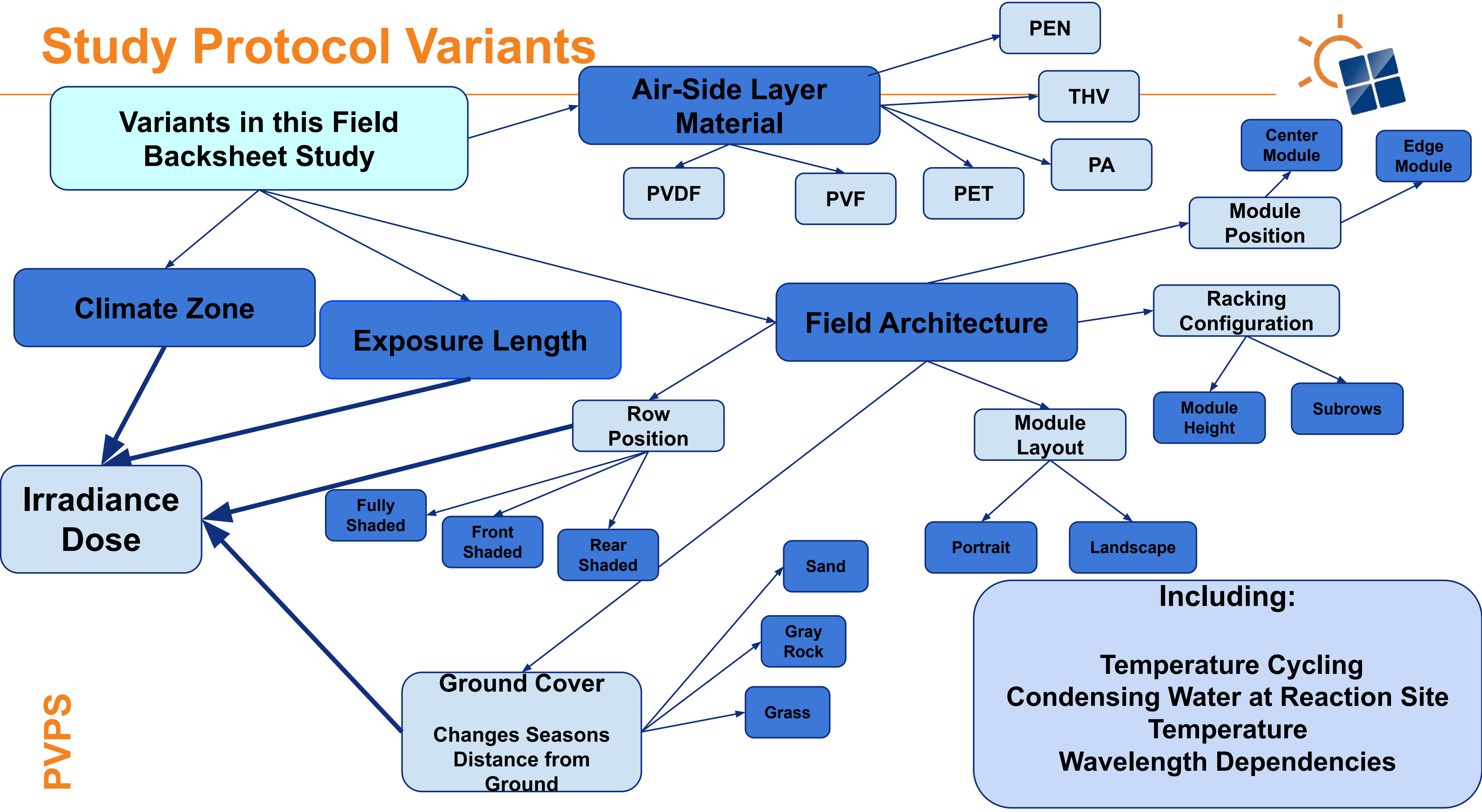


Gloss heatmap

- Has the same trends as YI

Significant & clear trends

Study Protocol Variants



Read-side Irradiance Simulation

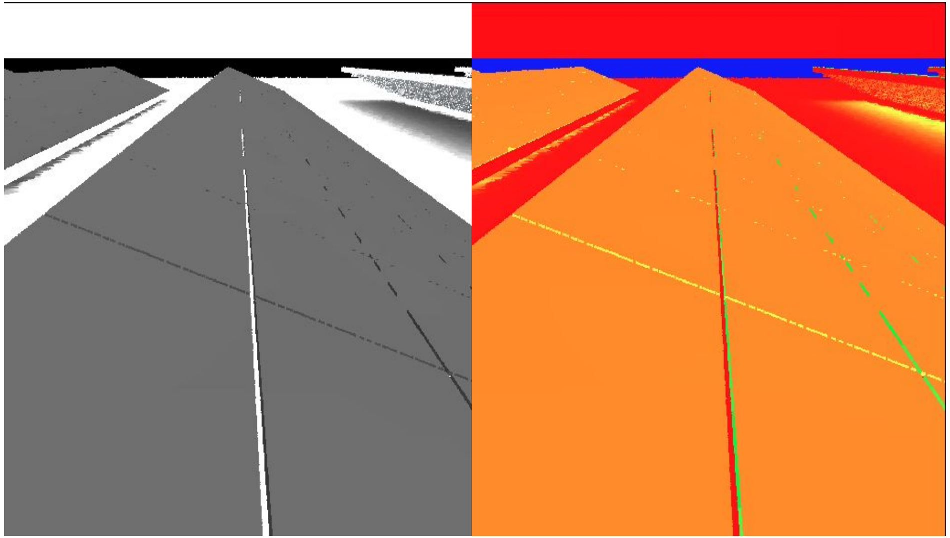
CWRU EMSE Graduate Students: Raymond Weiser (current PhD Student), Zack Li (graduated Master's), Xuanji Yu (Previous Post Doc)

Simulation Parameters

bifacial_radiance package from NREL

Generated a model of radiance distribution

- Sky
  - Location
  - Albedo
- Module
  - Size of module & cell
  - Gap between the modules & cells
  - Number of subrows, etc.
- Scene
  - Number of rows
  - Number of modules per row
  - Tilt & Azimuth, etc.



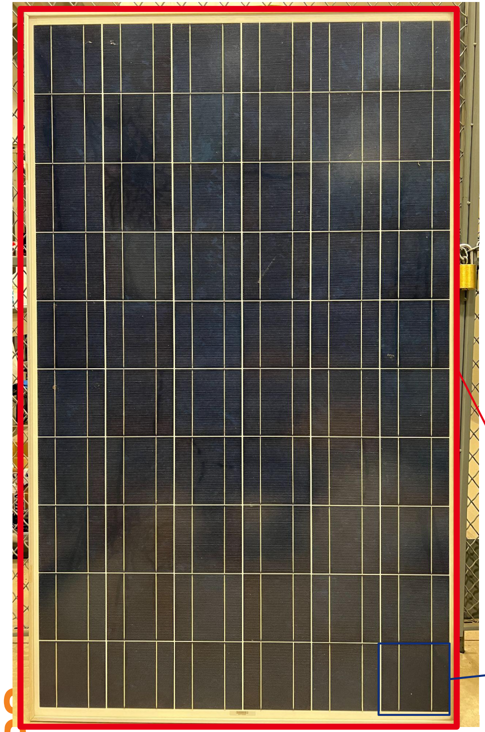
HDR **HDR with False Color**

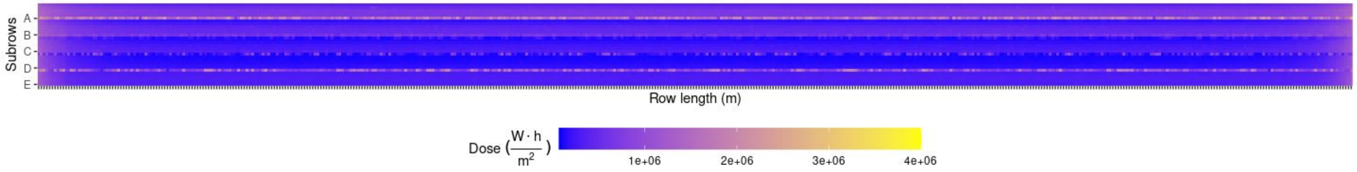
Weather data source

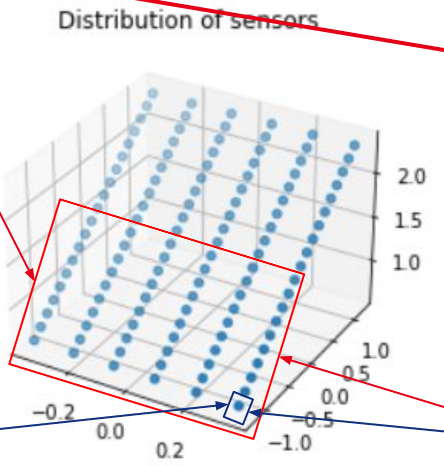
- Typical Meteorological Year (TMY)

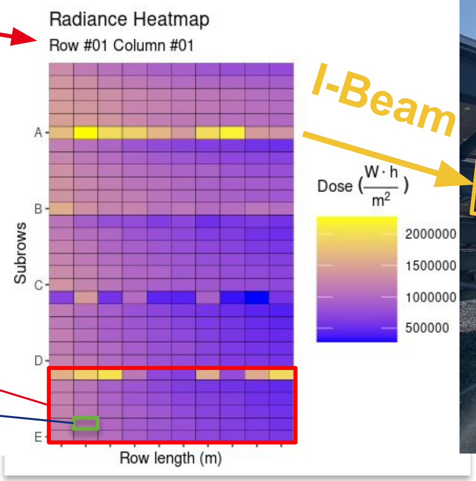
Spatial Distribution of Exposure

60 sensors for each module



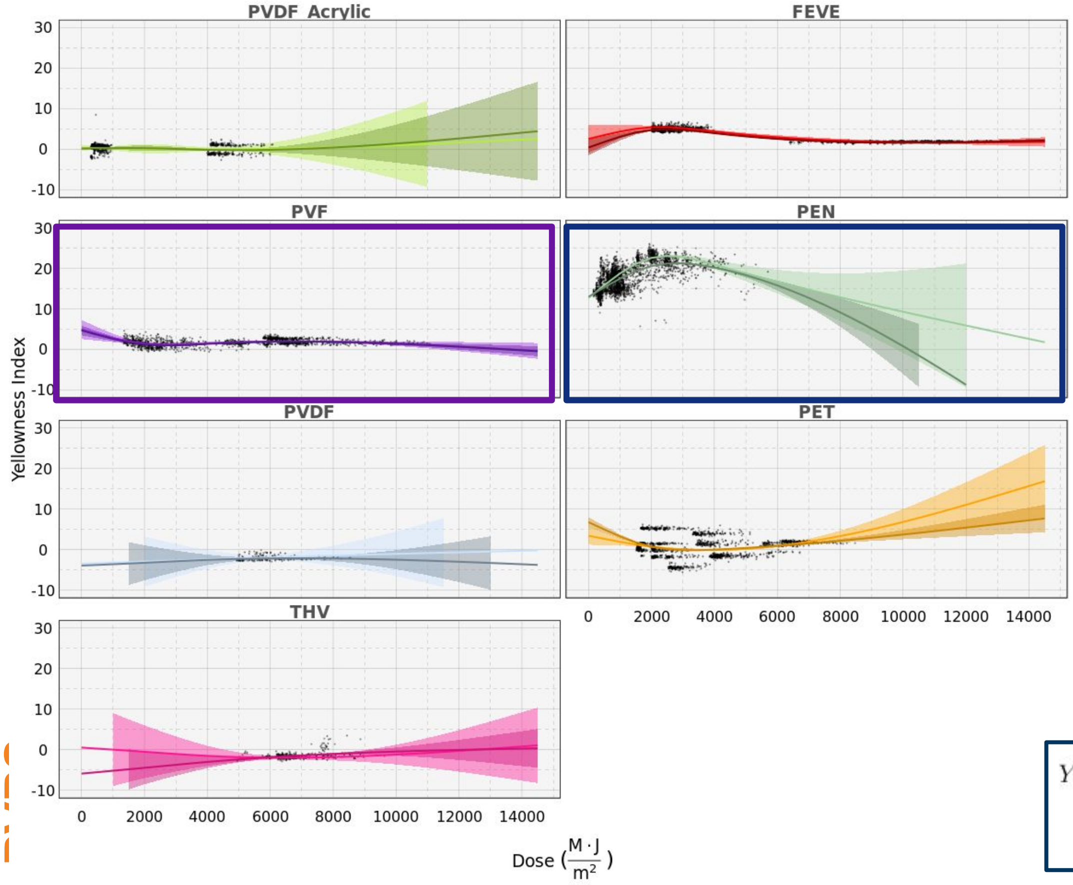


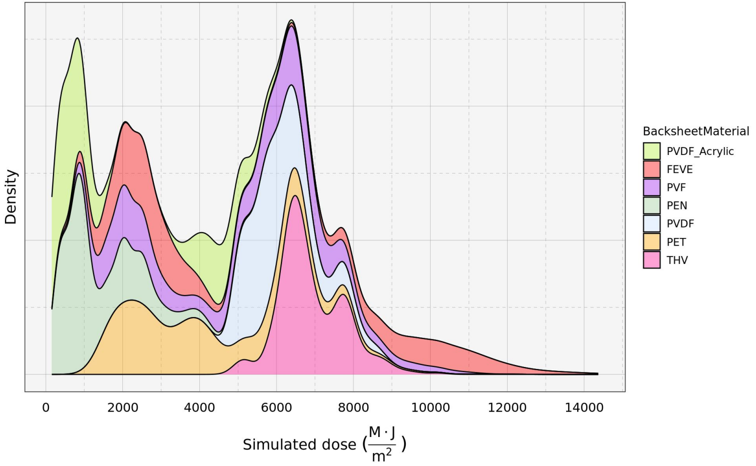




PVRC

Yellow Index vs Dose for Different Materials





Fluoropolymer: more stable than other materials
PET: Variability manufacturing

$$Y(CW, TAET, IR_{Dose}, M_i, JB_i, t) = \beta_0 + \beta_1(CW \times t) + \beta_2(TAET \times t) + f(IR_{Dose}, M_i, JB_i)$$

Spatiotemporal Equation: Modeling Results

$$Y(CW, TAET, IR_{Dose}, M_i, JB_i, t) = \beta_0 + \beta_1(CW \times t) + \beta_2(TAET \times t) + f(IR_{Dose}, M_i, JB_i)$$

CW: Time of contact wetness (hours/exposure time)

TAET: Time at elevated temperature 35°C (hours/exposure time)

IR_{Dose}: Sum of simulation irradiance for the exposure time in each field (MJ/m^2)

M_i: Type of Material

JB_i: A logical variable for the measurement whether locate at junction box

t: exposure time in the field (year)

f(x): Smooth Function

Data source
- 23 surveys
- 1806 modules
- 10836 measurements
- 7 types of materials

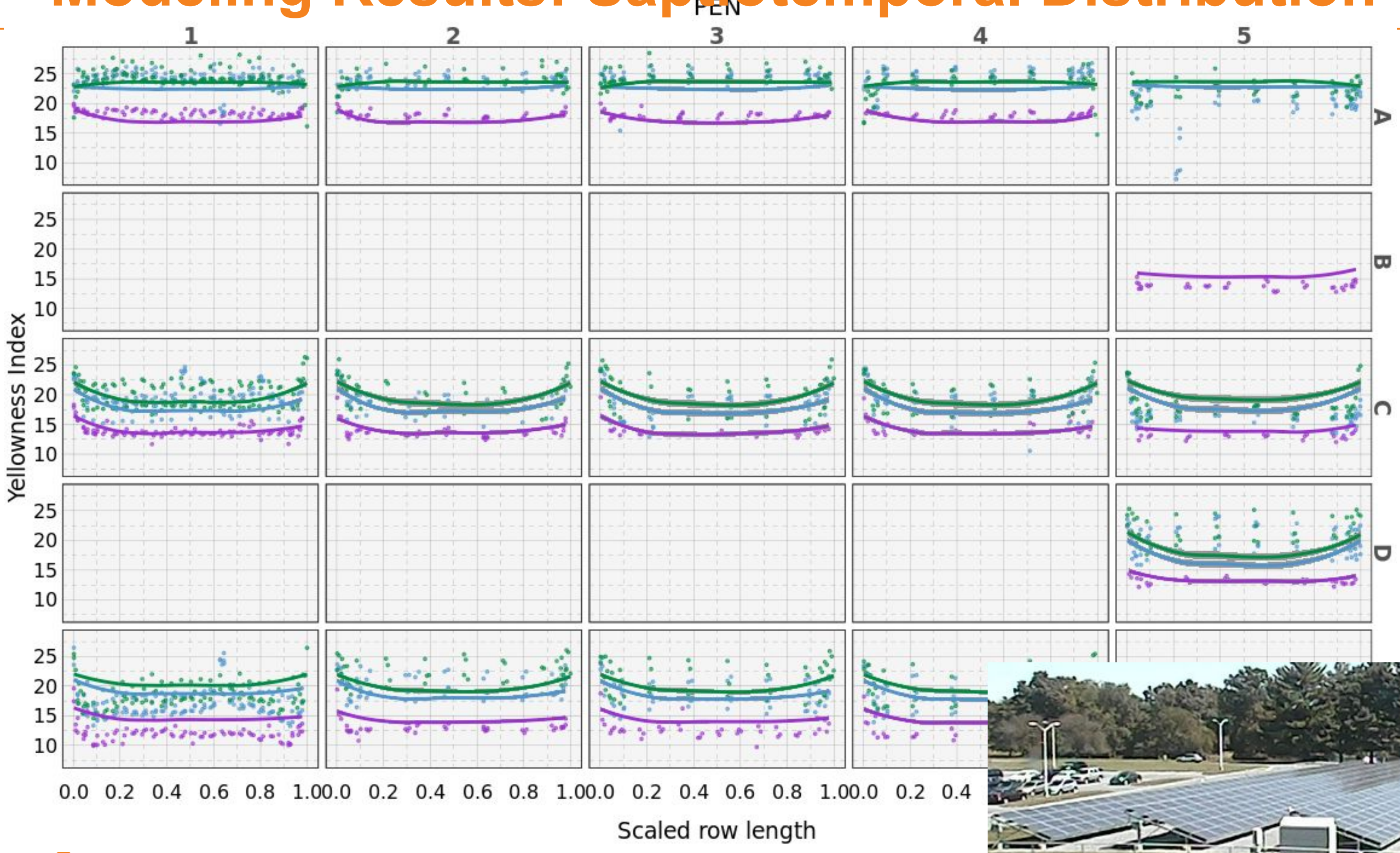
Training set
- **8127 measurements**

Testing set
- **2709 measurements**

Adjusted R^2: 96.2%

Training RMSE: 1.78
Testing RMSE: 1.80

Modeling Results: Saptiotemporal Distribution



- 2022
- 2020
- 2016

Optimized Study

- Open Science Framework
- ASTM Standard
- Available for companies

Data Integration:

- Field Survey Data
- SolarGIS Satellite Irradiance Data, Dew

Thank you!

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IEA PVPS