

# Degradation patterns and phenomena of backsheets from diverse climate zones



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# My Research Group

Many Thanks to the Post docs, Graduate, Undergraduate, and High School Students Working on the Projects!

## Post-doctoral Research Associates

- Pawan Tripathi, Xuanji Yu, Erika Barcelos

## Graduate Students

- PhD: Sameera Nalin Venkat, Tian Wang, Arafath Nihar, Will Oltjen, Liangyi Huang, Weiqi Yue, Raymond Wieser, Tommy Ciardi, Kristen Hernandez, Nat Tomczak, Hein Htet Aung, Hope Omodolor, Yangxin Fan, Deepa Bhuvanagiri
- MS: David Meshnick, Mingjian Lu, Zelin Li, Olatunde Akanbi, Harsha Madiraju, Leean Jo, Rounak Chawla, Andre Yost, Mirra Rasmussen, Scott Mauer, Dominique Yao

## Undergraduates

- Cora Lutes, Beck Pierce, Ravi Lin, Zhuldyz Ualikhankyzy, Vibha Mandayam, Jube Augustino, Nitin Chockalingam, Peter Schlueter, Andrew Villalobos, Kemal Ozdemirli, Christelle Yameogo, Jose Diego Zubieta Sempertegui, Gabriel Ponon, Lam Nguyen, Jonathan Libenson, Summer Sun, Mason Jester, Neha Panduri, Adam Goodman, Kevin Yin



### UL Solution

- Field Survey
- Retrieved Module analysis

#### Team members:

- Ruben Zabalza; Laing Ji; Kenneth P. Boyce; Colleen O'Brien



### National Renewable Energy Laboratory (NREL)

- Irradiance Simulation

#### Team members:

- Silvana Ayala; Matthew Brown; Michael D. Kempe

Department Of Energy (DOE)  
Solar Energy Technologies Office (SETO)  
DE-EE-0008748  
3 Years Project: A Data-driven Approach to  
Real-world Degradation of Backsheets

### National Institute of Standards and Technology (NIST)

- Field Survey
- Retrieved Module analysis
- ASTM

#### Team members:

- Stephanie L. Moffitt; Xiaohong Gu



### Du Pont De Nemours & Arkema

- Field Survey Protocol Feedback

#### Team members:

- Adam W. Hauser; Greg S. O'Brien; Jared Tracy; Kausik R. Choudhury; William J. Gambogi

### Case Western Reserve University (CWRU)

- Field Survey Protocol
- Retrieved Module Analysis
- Irradiance Simulation
- Spatiotemporal Model

#### Team members:

- Zelin Li; Raymond J. Wieser; Xuanji Yu; Laura S. Bruckman



# Commercial Power Plants: Field Surveys & Geospatial Modeling



**CWRU EMSE Graduate Students:  
Yu Wang (Avery Dennison) - initial  
Raymond Weiser (Current)**

**Zack Li (Current)**

**Xuanji Yu (Post Doc)**

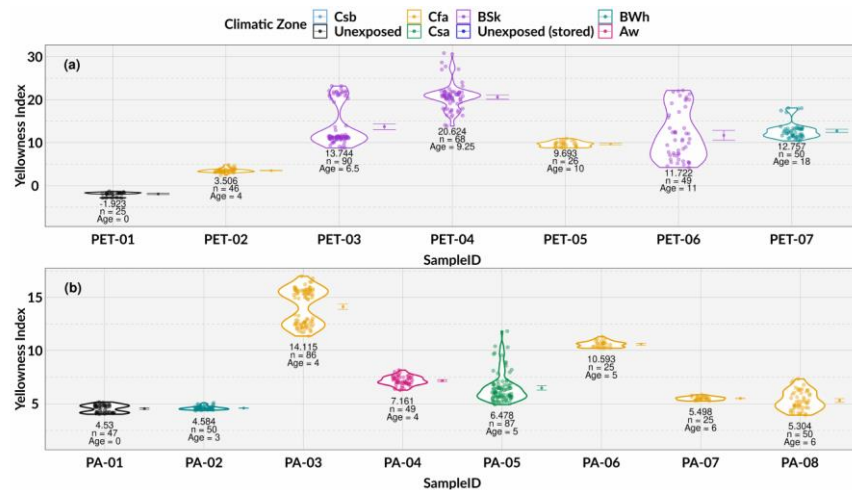
# Field Retrieved Modules

## Cross Sectional Retrieved Module Survey<sup>1</sup> :

- **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 BoM information



[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>.

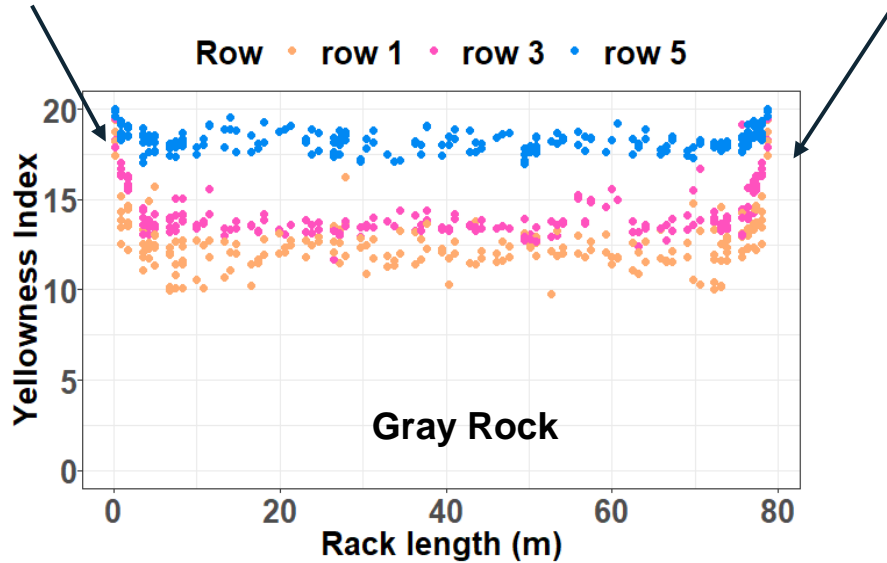


# Motivation: Initial Survey

## Is degradation uniform over a field?

- Are retrieved modules representative?

## How do climate zones impact degradation?

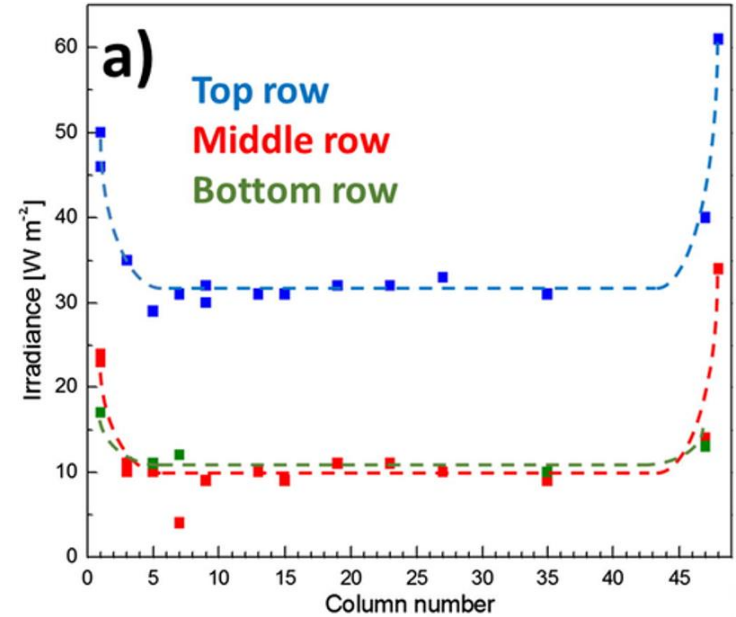
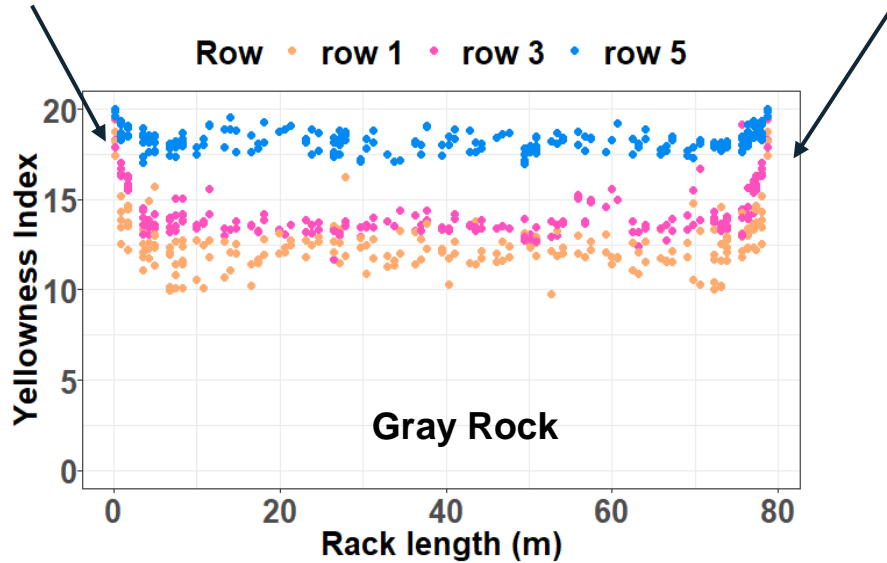


# Motivation: Initial Survey

## Is degradation uniform over a field?

- Are retrieved modules representative?

## How do climate zones impact degradation?



# Site Selection

## Sites with a wide variety of conditions

- Temperature Fluxuations
- Precipital Water
- Levels of Irradiance

## Climate Zone Classification

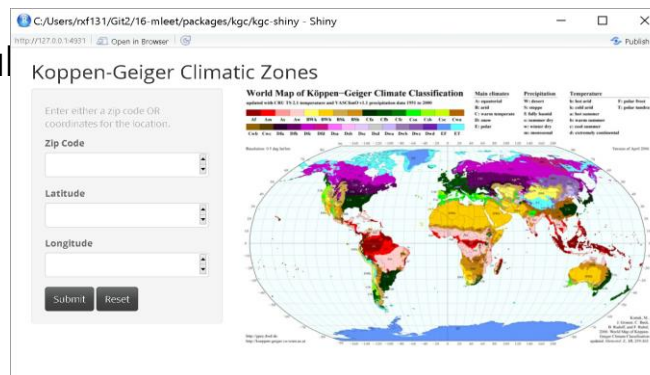
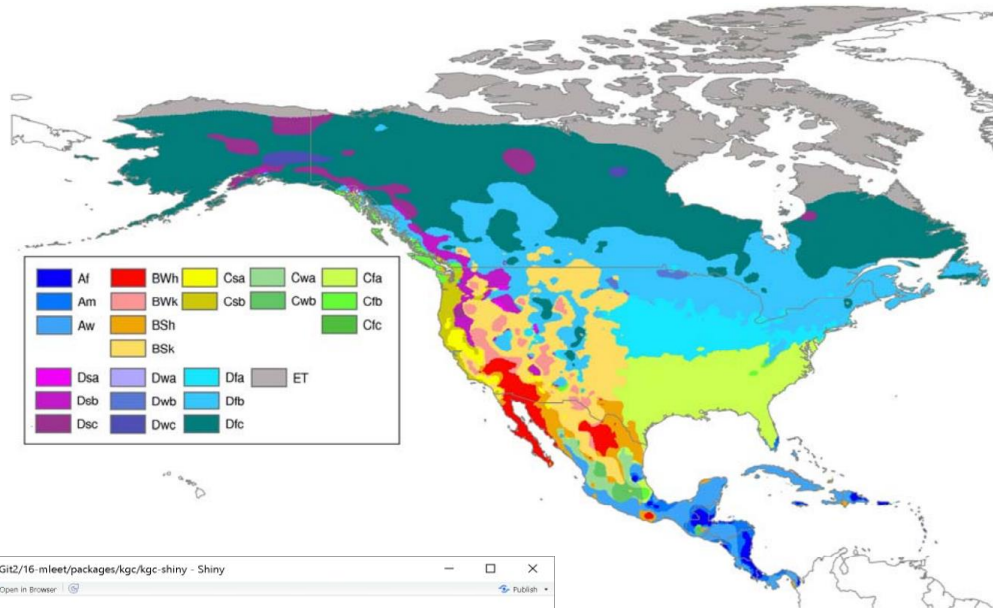
- Based on annual weather patterns
- Temperature, Precipitation, Irradiance, Windspeed, etc

## Köppen-Geiger

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

## Kgc on CRAN

- R Climate Zone Package



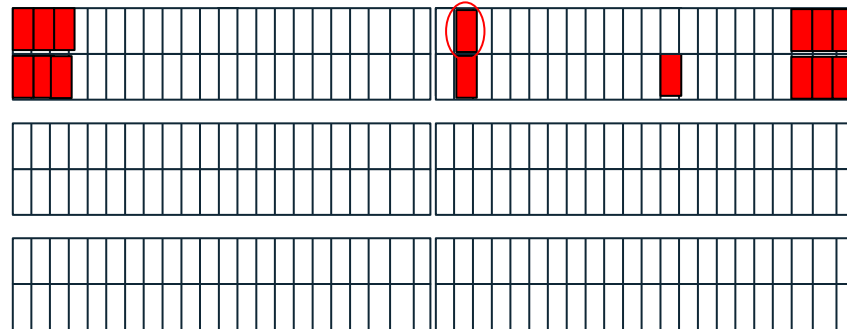
Köppen-Geiger<sup>6</sup>



# Field Study Protocol



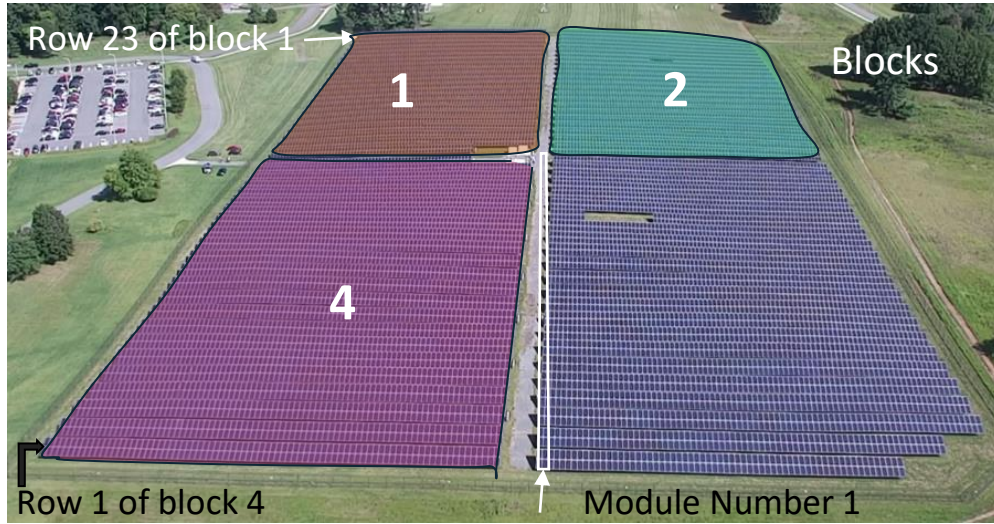
**Module Number:** Position of the module in the row (from the edge) i.e., Module 30



**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...

# Field Survey Protocol: Nomenclature (Real Examples)

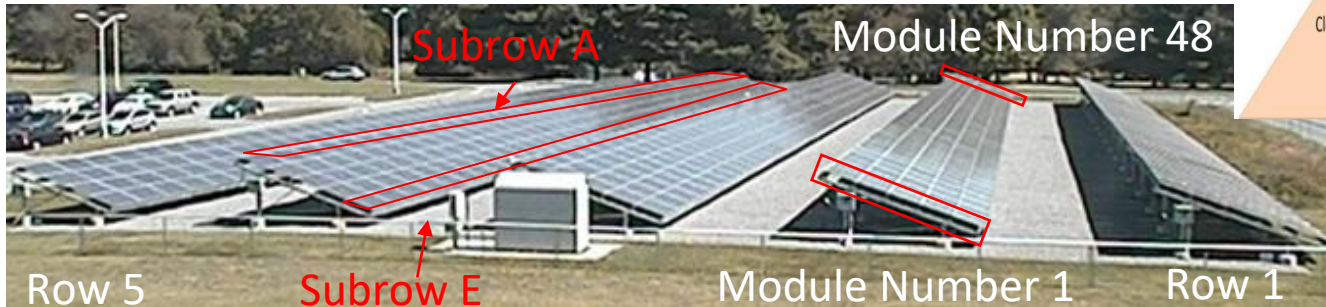
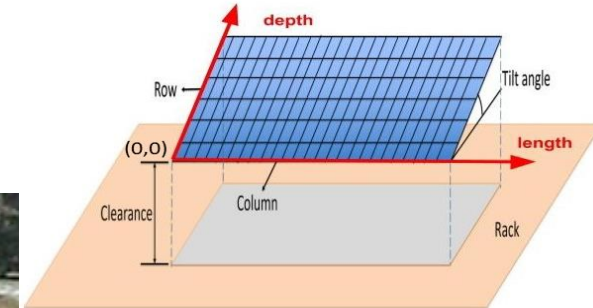


## Frontside unshaded

- Row 1 of Block 4
- Row 1

## Rearside unshaded

- Row 23 of Block 1
- Row 5

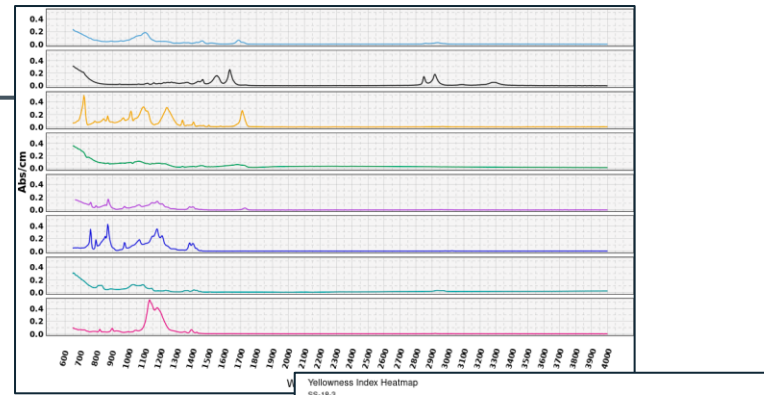


# Materials Characterization

## Attenuated Total Reflection

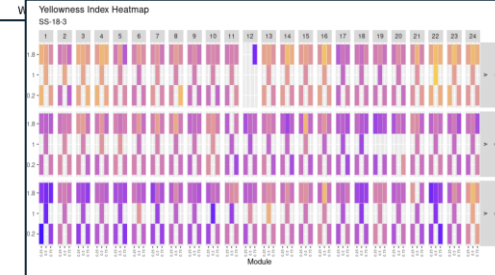
### Fourier Transform Infrared (ATR-FTIR)

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



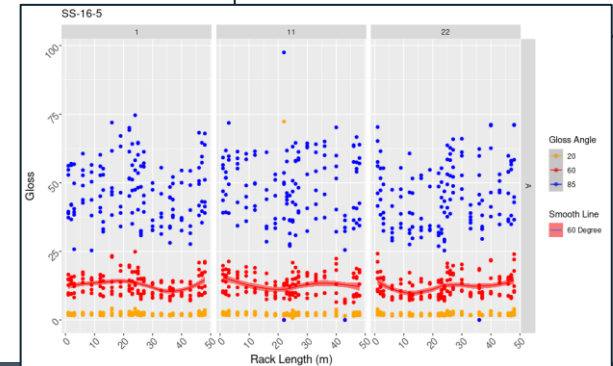
## Yellowness Index

- 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





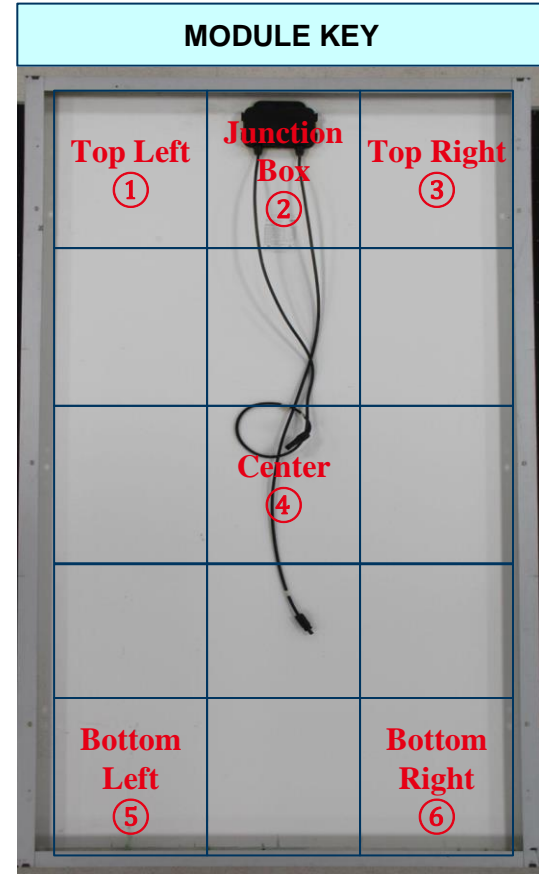
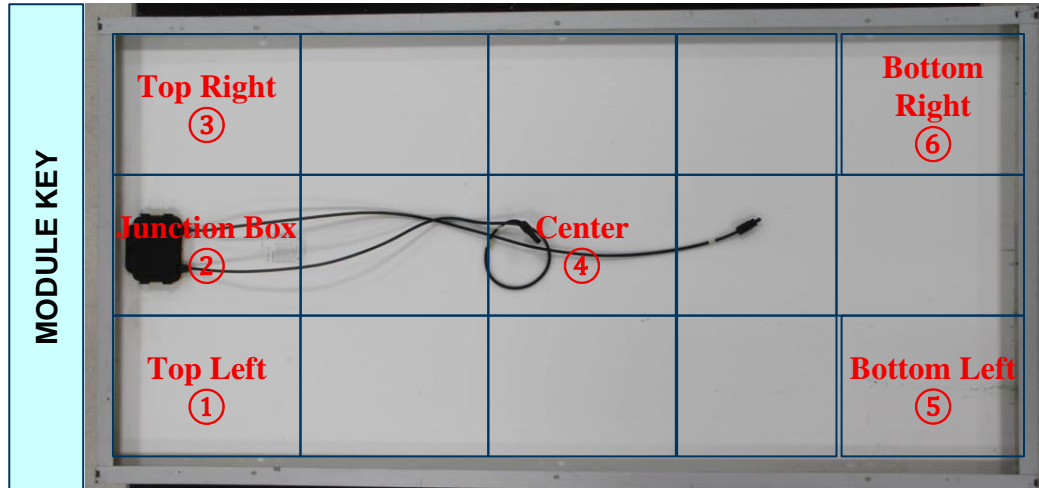
# Field Survey Protocol: Measurement Positions

Multiple measurements done for each module

Not every site has same positions measured

- Due to mounting constraints

Recommended locations



# Data Cleaning & Storage

## FAIRification of data

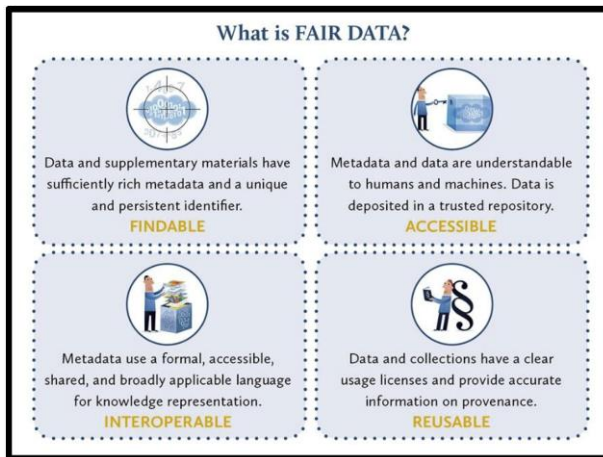
- Findable
- Accessible
- Interoperable
- Reusable

## Data storage

- Hadoop/Hbase
- Stored as JSON-LD

## Data Analysis

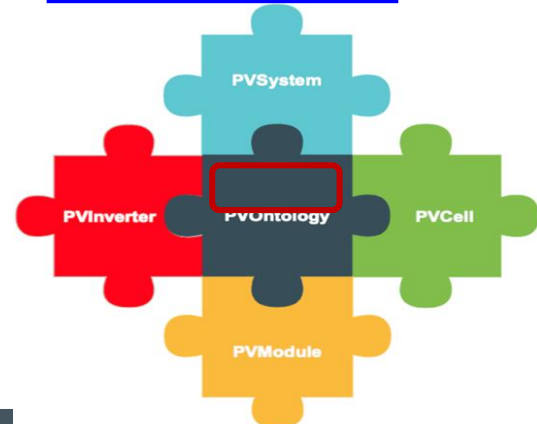
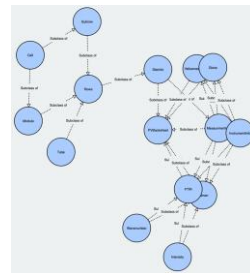
- High-performance computing (HPC) cluster



## FAIRMaterials

- Python and R Packages
  - FAIR Ontology
  - JSON-LD Metadata, Data
- [Read The Docs](#)
  - Documentation
  - Code Examples
  - JSON-LD Playground
  - WebVOWL

## [OSF Open Data](#)





# Field Survey Observations



# Overview of Completed Surveys

## 41 sites surveyed

- 7 Climatic zones
- 8 Material types
  - 7 polymers
  - 1 glass

**3,467 modules**

- **17,684 measurements**

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

# Revisited Sites: Temporal Information

## NIST Small Site (Example)

- SS-16-0 : 09/01/2016 (4 years)
- SS-16-1 : 10/27/2020 (8 years)
- SS-16-8 : 09/15/2022 (10 years)

## NIST Large Site

- SS-16-2 : 10/28/2020 (2 years)
- SS-16-7 : 09/14/2022 (4 years)

## Mcco Site

- SS-17-1 : 07/06/2019 (5 years)
- SS-17-3 : 08/12/2022 (8 years)

## UL Ground Site

- SS-18-2 : 01/21/2021 (10 years)
- SS-18-3 : 01/10/2023 (12 years)



MCCo



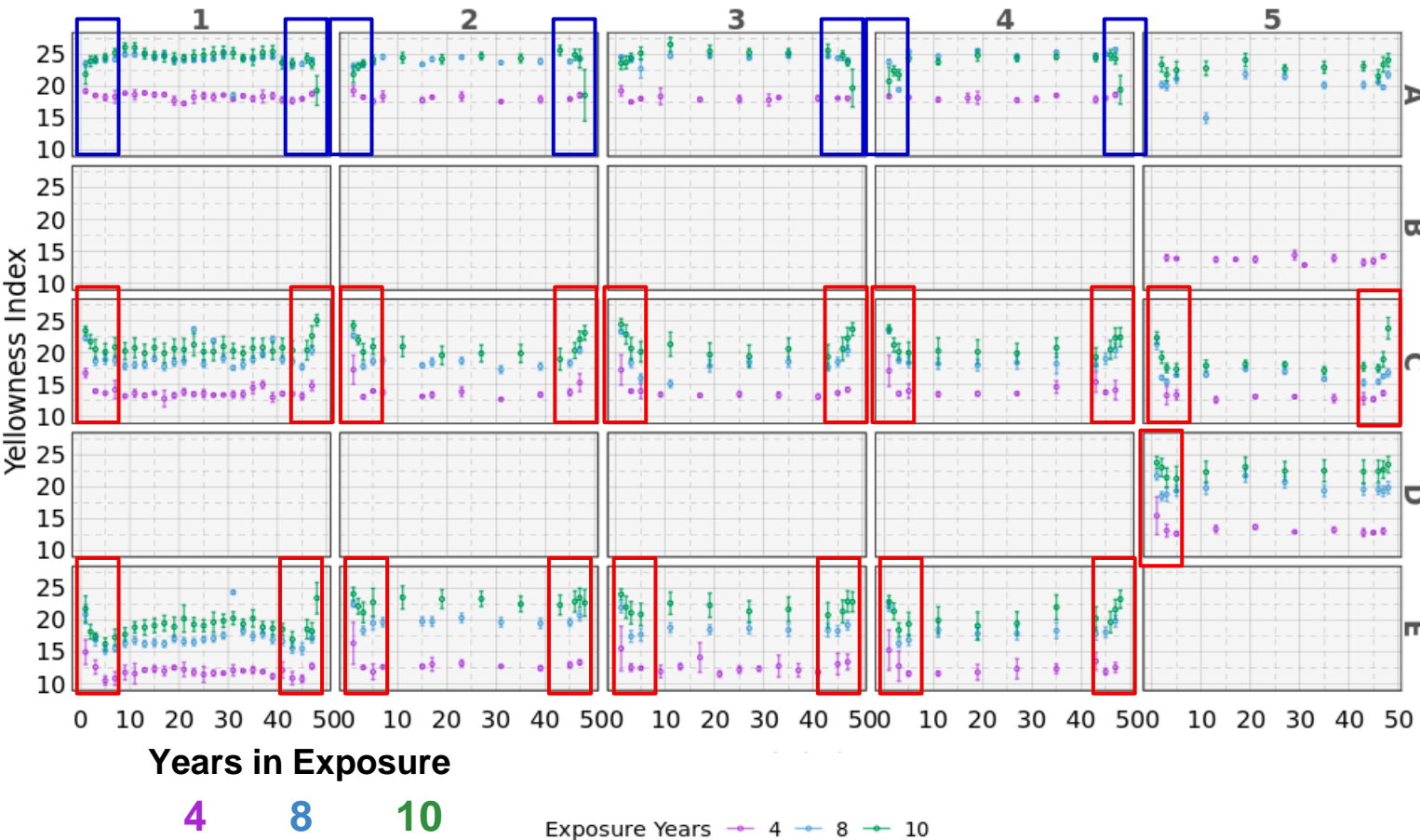
NIST Large

NIST Small

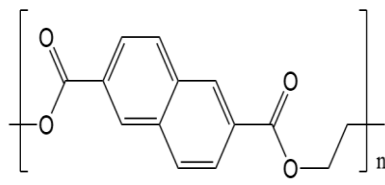
UL Ground



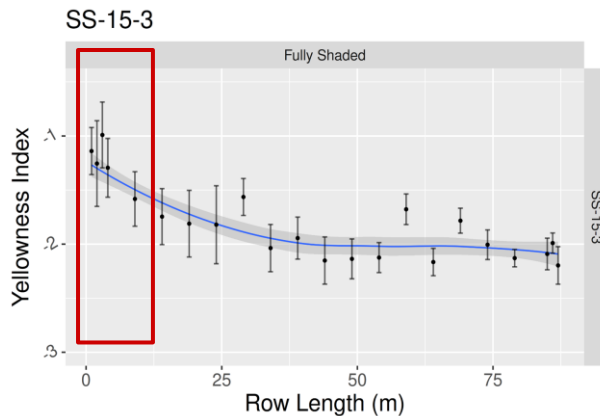
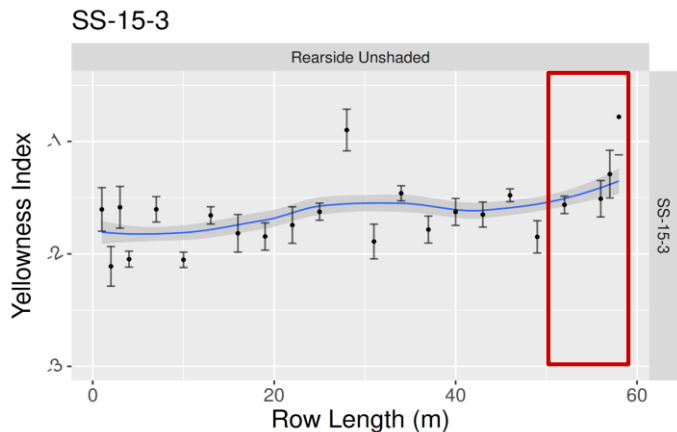
# Field Survey Observation: Spatiotemporal Degradation



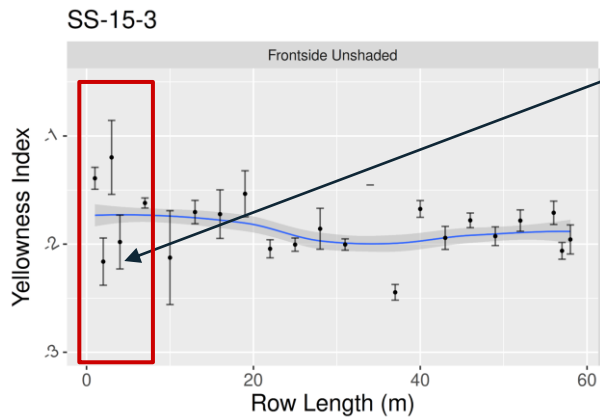
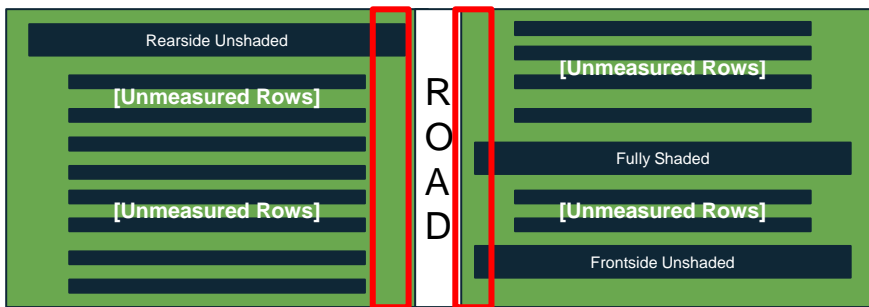
Polyethylene naphthalate (PEN)



# Non-uniformity: Irradiance Exposure due to Road



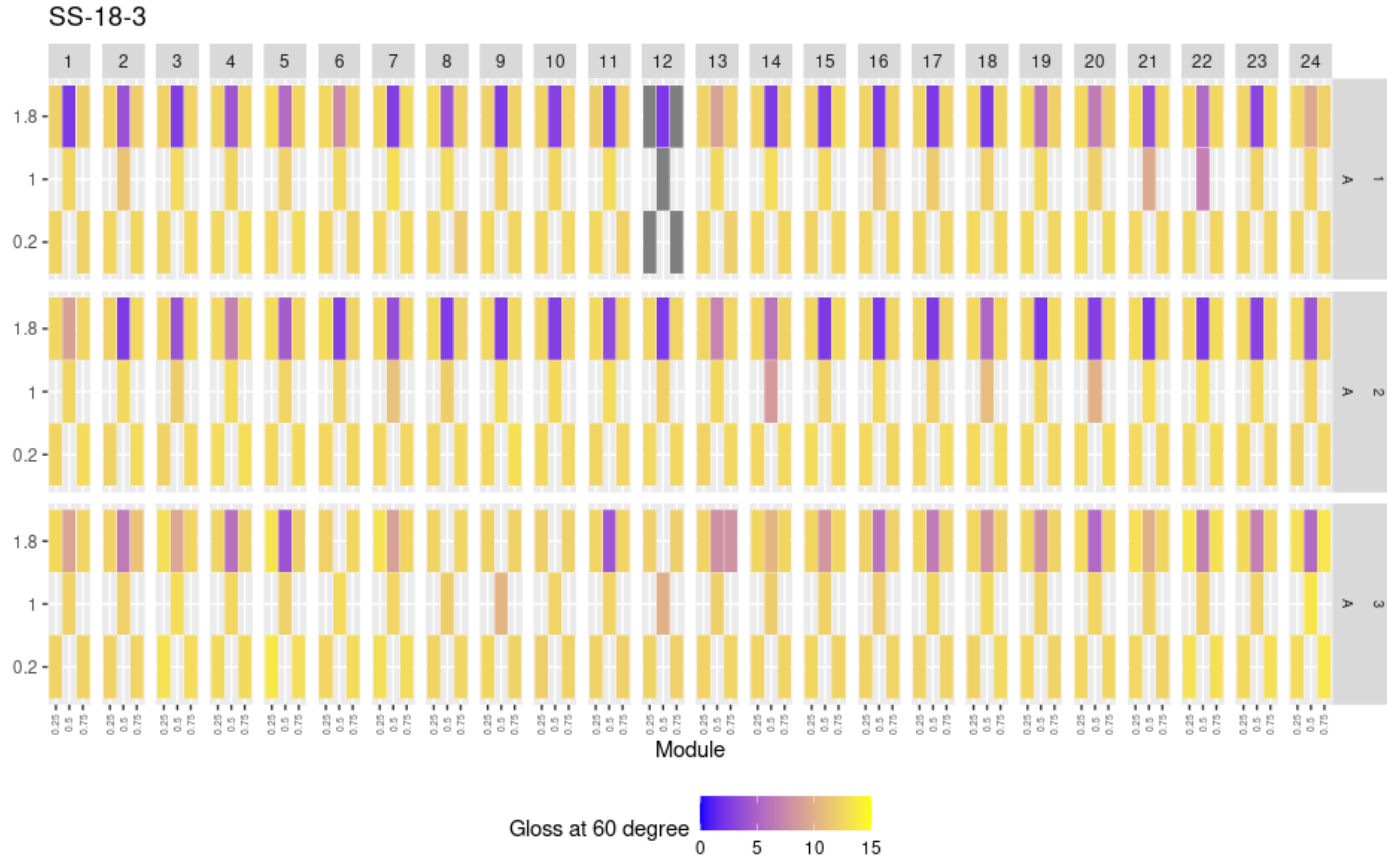
Inference by eye:  
83.4 % CIs



Module  
Replacement



# Gloss Measurements for Junction Boxes

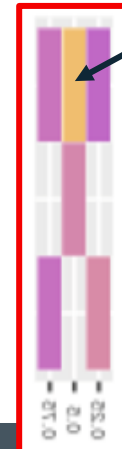


## Gloss heatmap

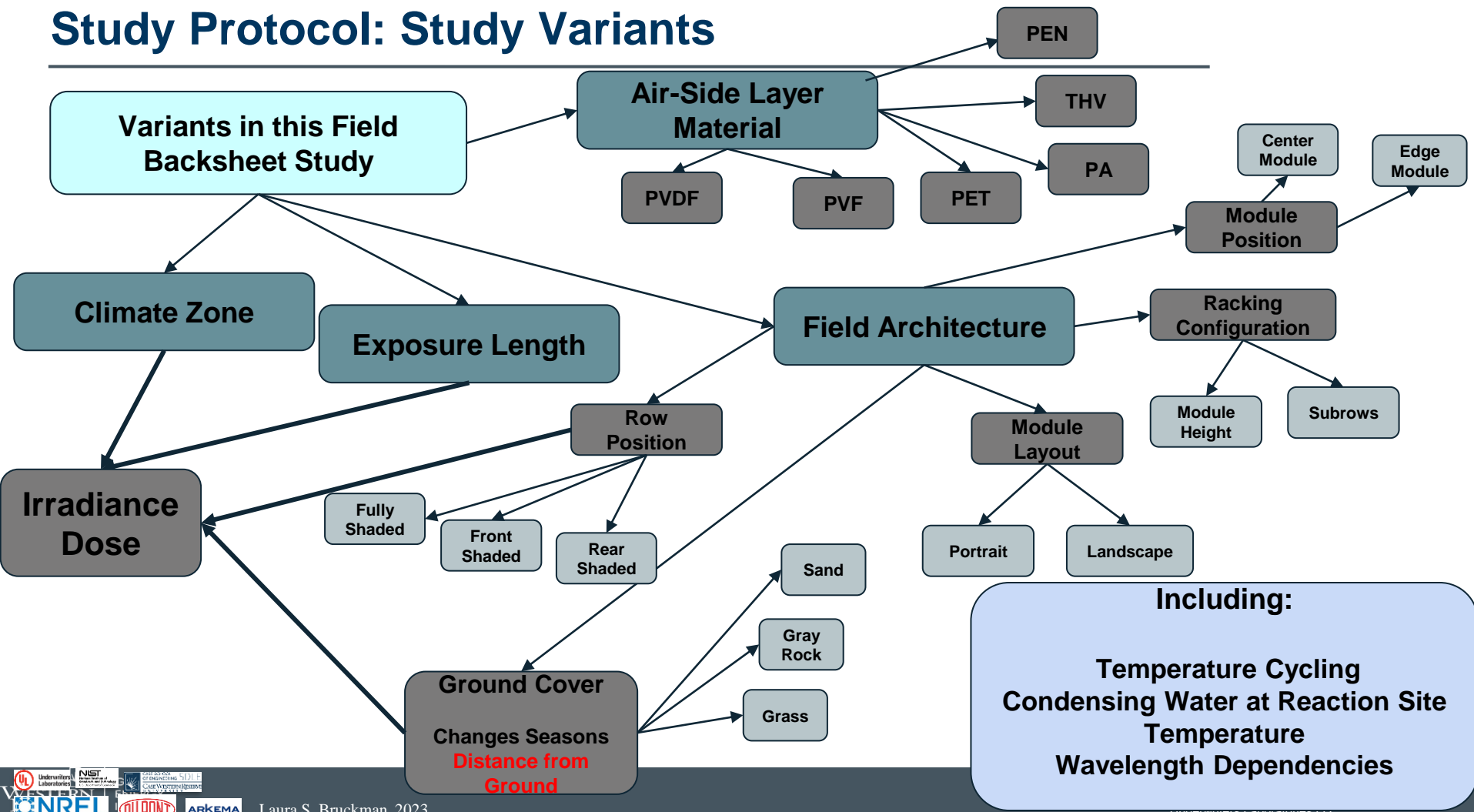
- Has the same trends as YI

Significant & clear trends

Junction box



# Study Protocol: Study Variants

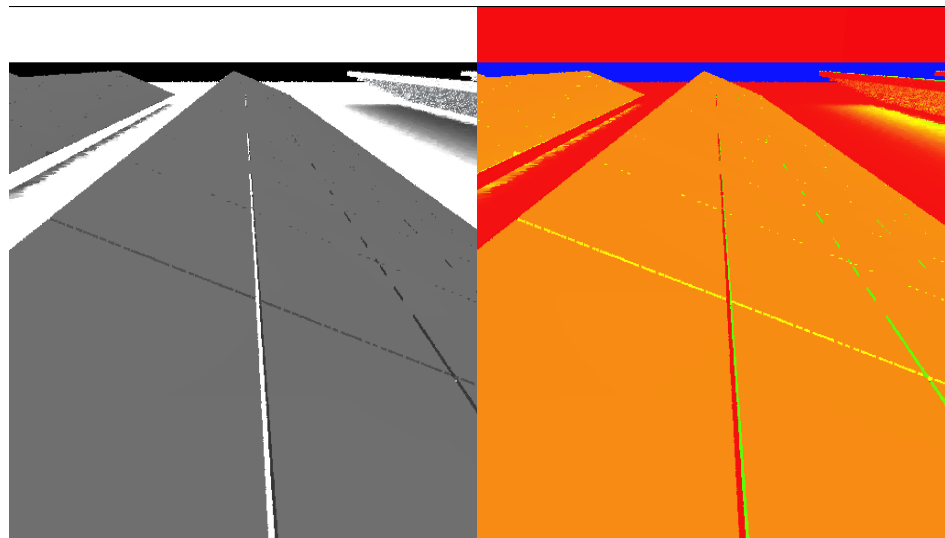


# Rear-side Irradiance Simulation

# 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

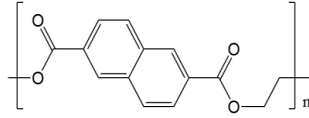
Weather data source

- Typical Meteorological Year (TMY)

# Leveraging Anisotropic Exposure

## Field in Maryland

- Built in 2012
- Backsheet material: PEN
- Climate Zone: Cfa
- DC-output: 271kw (360V, 753A)



SS-16-0

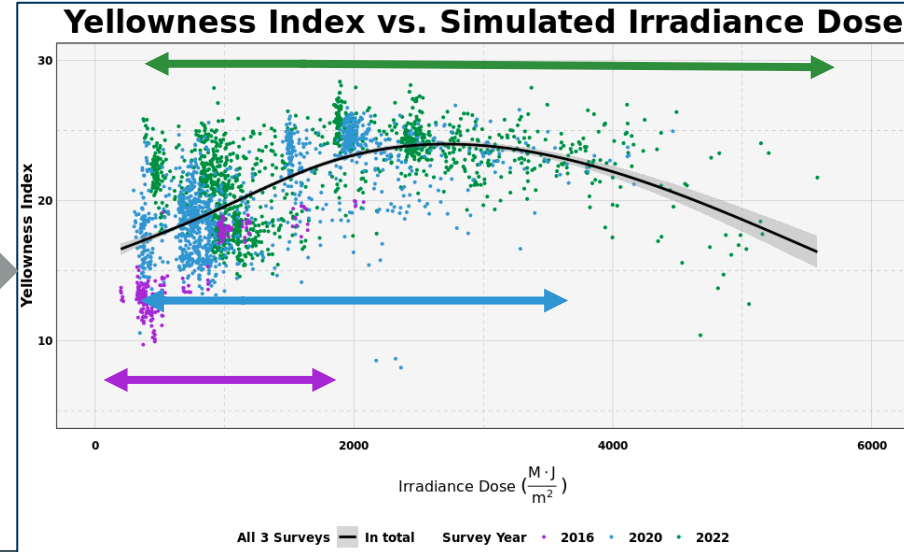
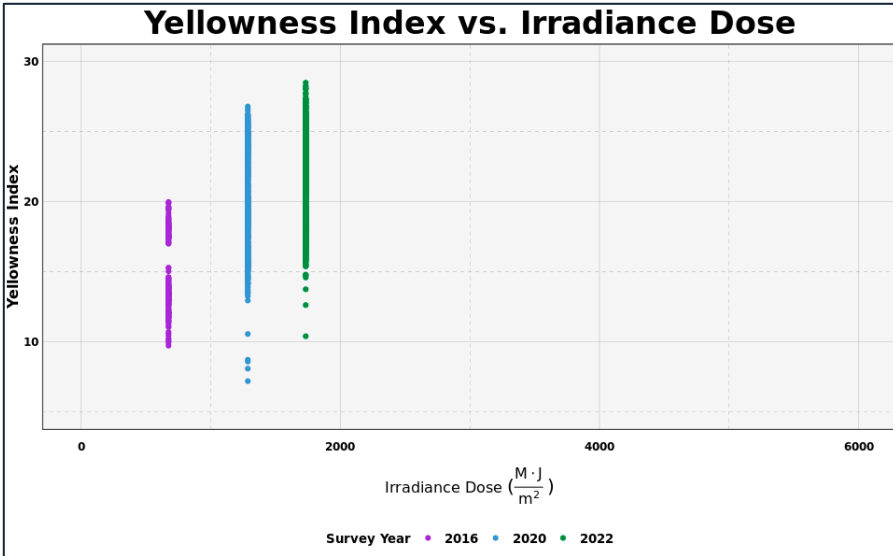
- 4 years

SS-16-1

- 8 years

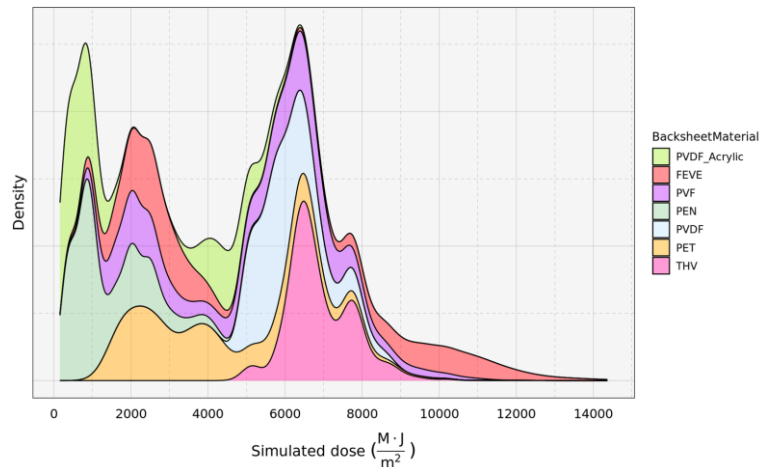
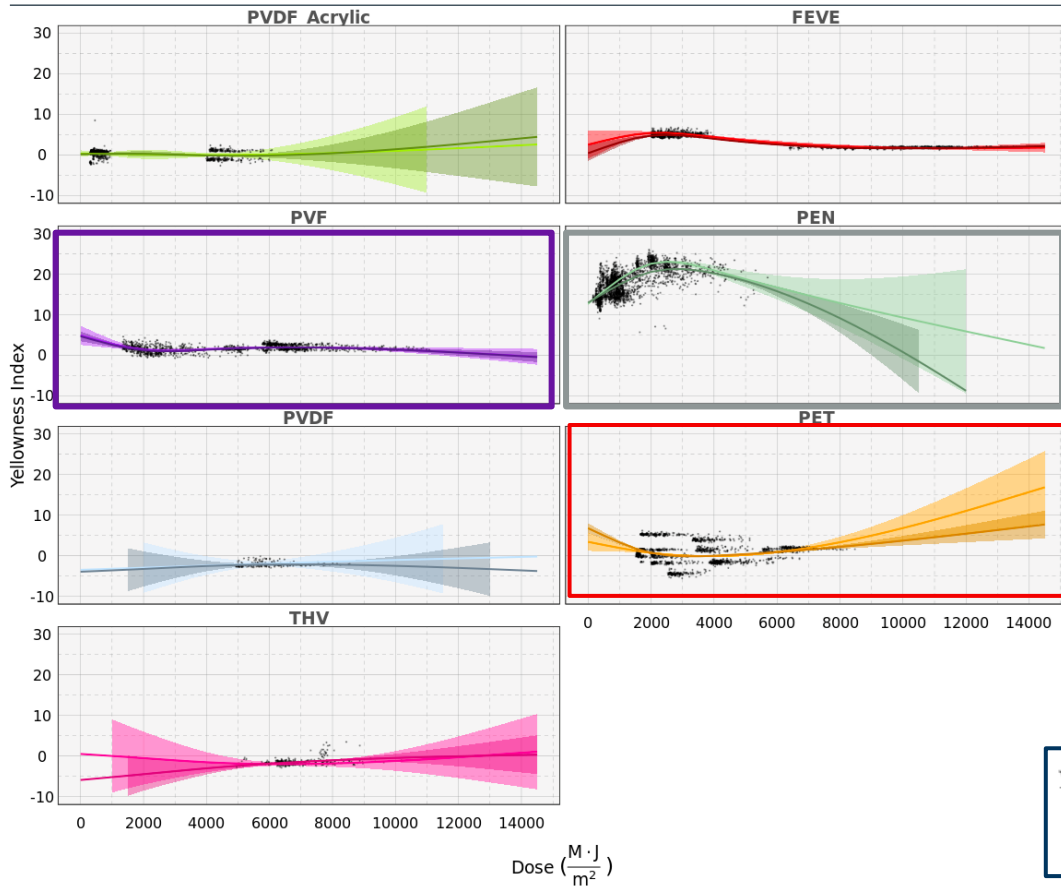
SS-16-8

- 10 years





# YI Versus 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<sub>Dose</sub>:** Sum of simulation irradiance for the exposure time in each field (MJ/m<sup>2</sup>)

**M<sub>i</sub>:** Type of Material

**JB<sub>i</sub>:** 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<sup>2</sup>: 96.2%

Training RMSE: 1.78

Testing RMSE: 1.80

# Capturing Temporal Distribution

PEN

1

2

3

4

5

A

B

C

D

E

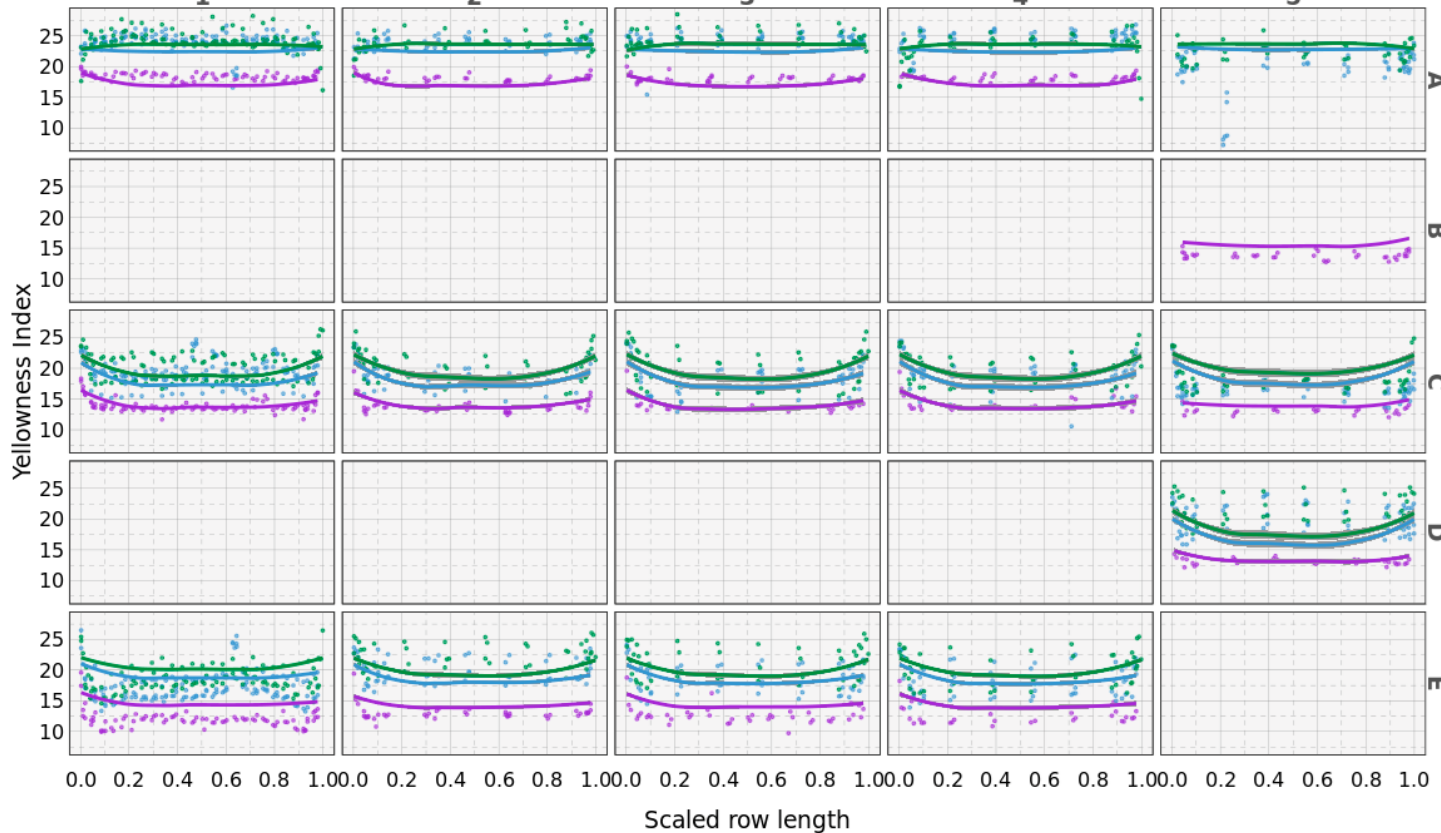
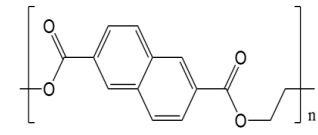
Years in Exposure

4

8

10

Polyethylene naphthalate (PEN)



**Thank you!**

**Questions?**

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