Spatial-temporal Model of Backsheet Degradation and Soiling

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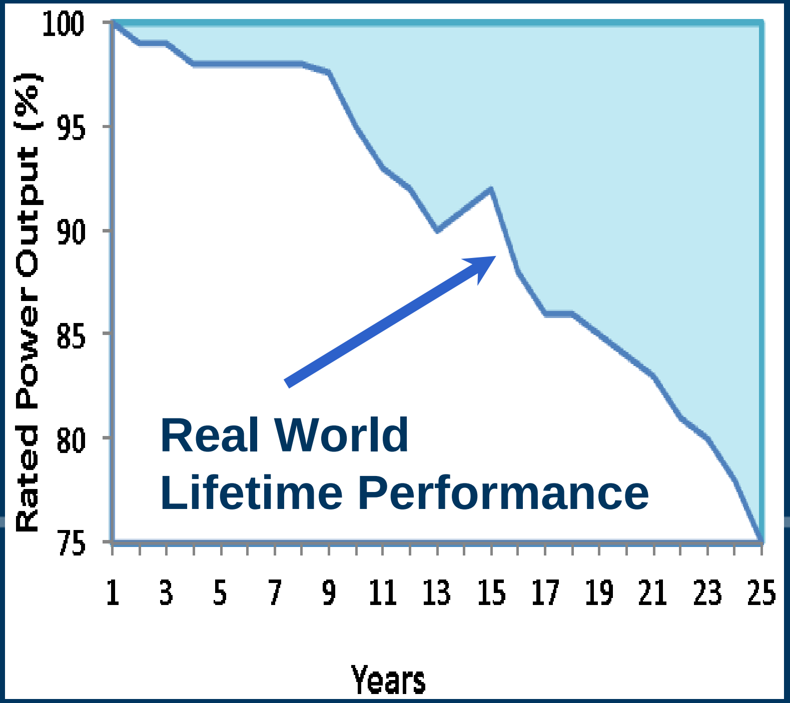

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Projects

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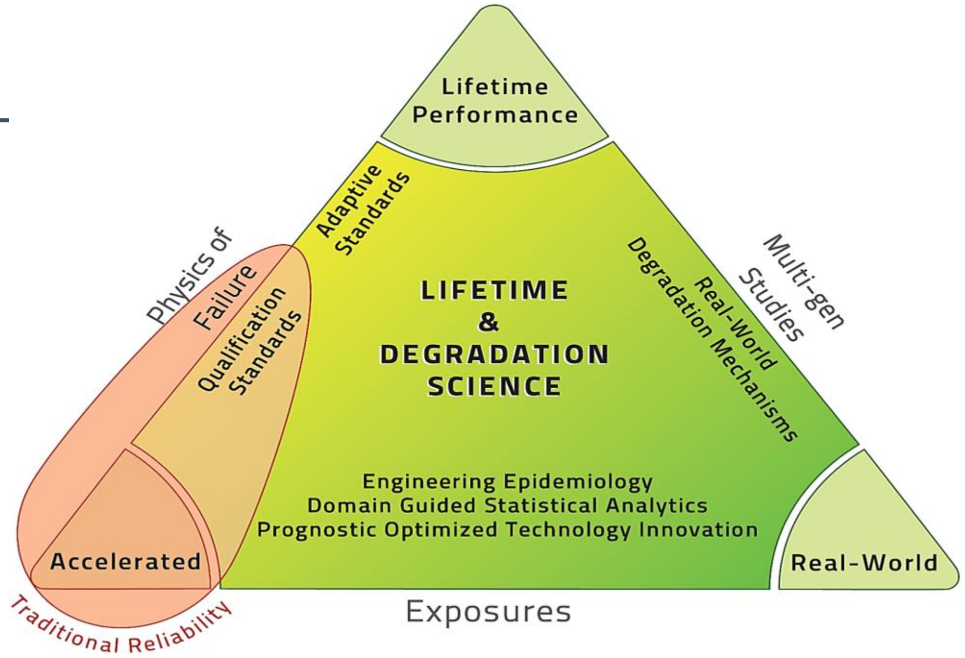
Outline

Data Science Approach to Lifetime and Degradation

Field Surveys of Real-World Power Plants

Spatial-Temporal Model Development

Degradation Science: Data Science & Analytics

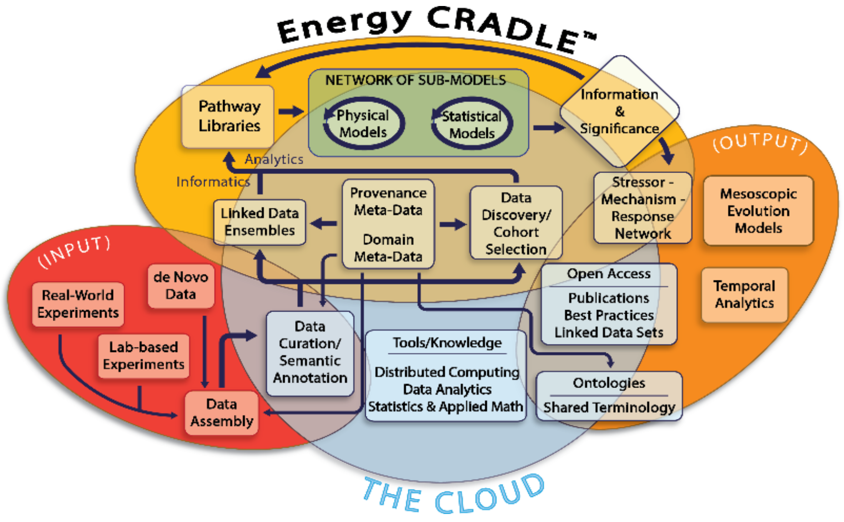


Long-lived, Real-world Systems

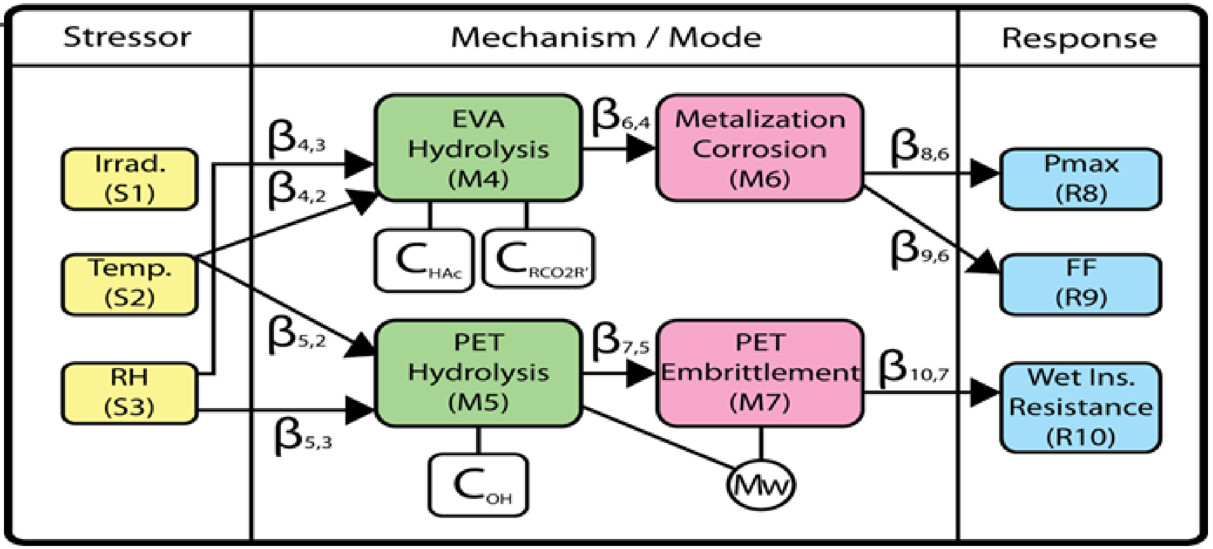
- Focus on Degradation Rates, not only Failures
  For Lifetime Performance
- Cross-correlate Mechanism & Rates
- Develop Mechanistic Network Models
- Cross-correlate
  - Real-World Exposed and Accelerated Exposures

Data Science Approach

- Distributed Computing: Hadoop/Hbase/Spark
- High Performance Computing
- Energy-CRADLE
- Open and Reproducible tools



Degradation Science: Data Science & Analytics



Develop Population-based Studies

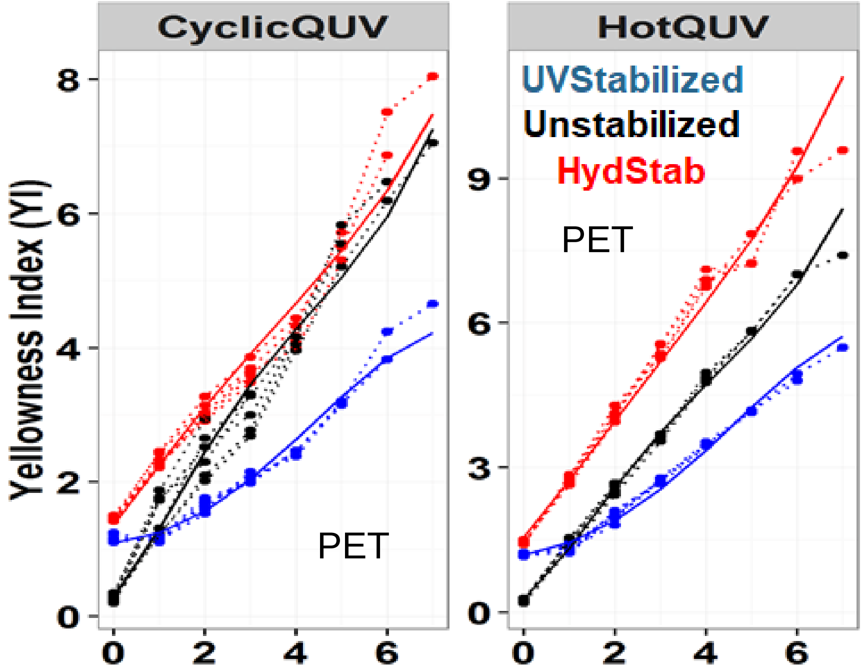
- Engineering Epidemiology of
  - Real-world Power Plants
  - Accelerated Laboratory Exposures

Data Science Approach Using

- Data-driven, Unbiased Analysis
- With Mechanistic Chemistry & Physics
- Inferential Statistics
- Statistical & Machine Learning

Develop Domain Science Guided, Network Models

- Integrated Real-world and Lab-based studies
- netSEM: Integrated Physical & Statistical sub-models
- Across Populations and Through Time



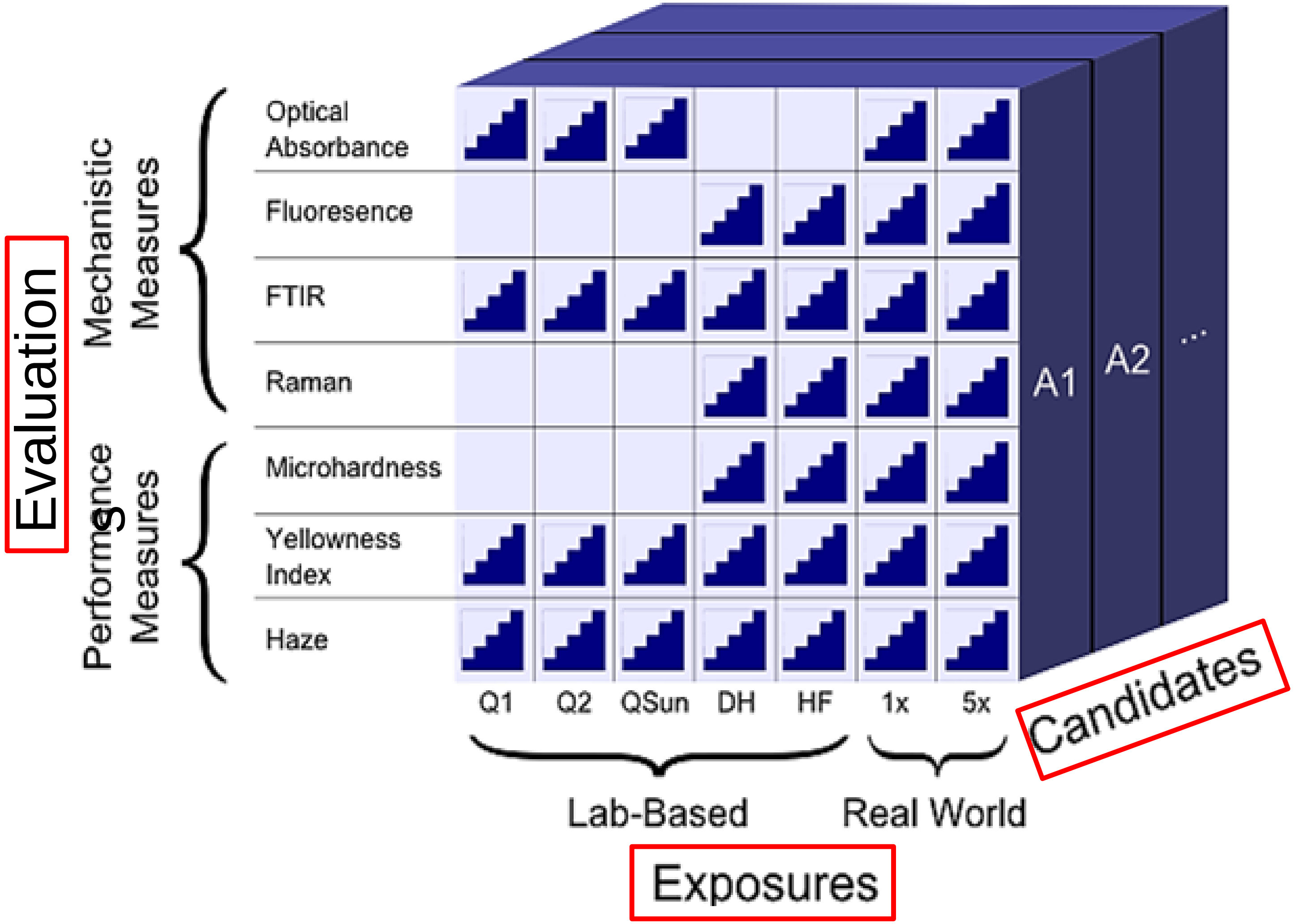
Degradation Science “Data Block” For Statistical Analytics

Using a < Stress | Mechanism | Response > Framework

Multiple Datatypes
- “Point” values
- Spectra
- Images
- Hyper-spectral Images

Basis in Physics and Chemistry
- Stressors: Heat, Moisture, Irradiance, etc.
- Responses: Yellowness Index, Gloss, Haze, etc.

Statistically Informed Study
- Large Volume of Samples
- Diverse Exposures
  - Real-world & Lab Base
  - Accelerated & Real-time
- Many Evaluations
  - Mechanistic & Performance



Backsheet Degradation Field Surveys

Introduction of Field Survey

Field Survey:

- **Study the Degradation of PV Panel Backsheet in Real-World**
- **Degradation changes over time**
- **Degradation changes over space**
    - install location in the rack
    - ground cover
- **Degradation changes over space**
    - Different backsheet materials
    - Different climate zones
- **Influence the rear-side irradiance and temperature near backsheet**

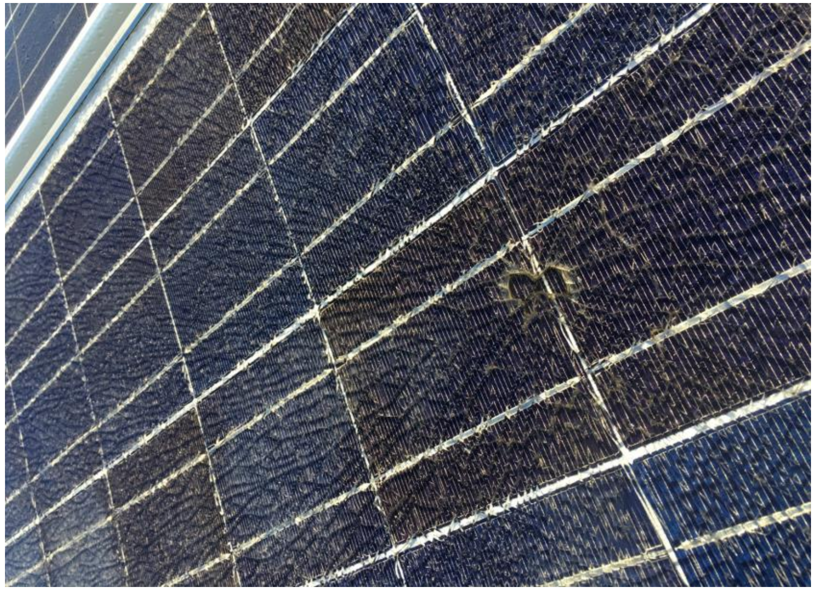
Field Survey Procedure

Site Metadata (Stress)

- climatic zone, module brand/model (backsheet type), mounting configuration
- Ground cover, weather data

Visual Inspection of Modules

- according to IEA PVPS Task 13 guidelines
- crack of front glass, snail trail and so on



Backsheet Survey (Response)

- Color (yellowness index)
- Gloss
- FTIR
- Multiple Locations on backsheet
- Sample size calculations
- Future field surveys (albedo and temperature)

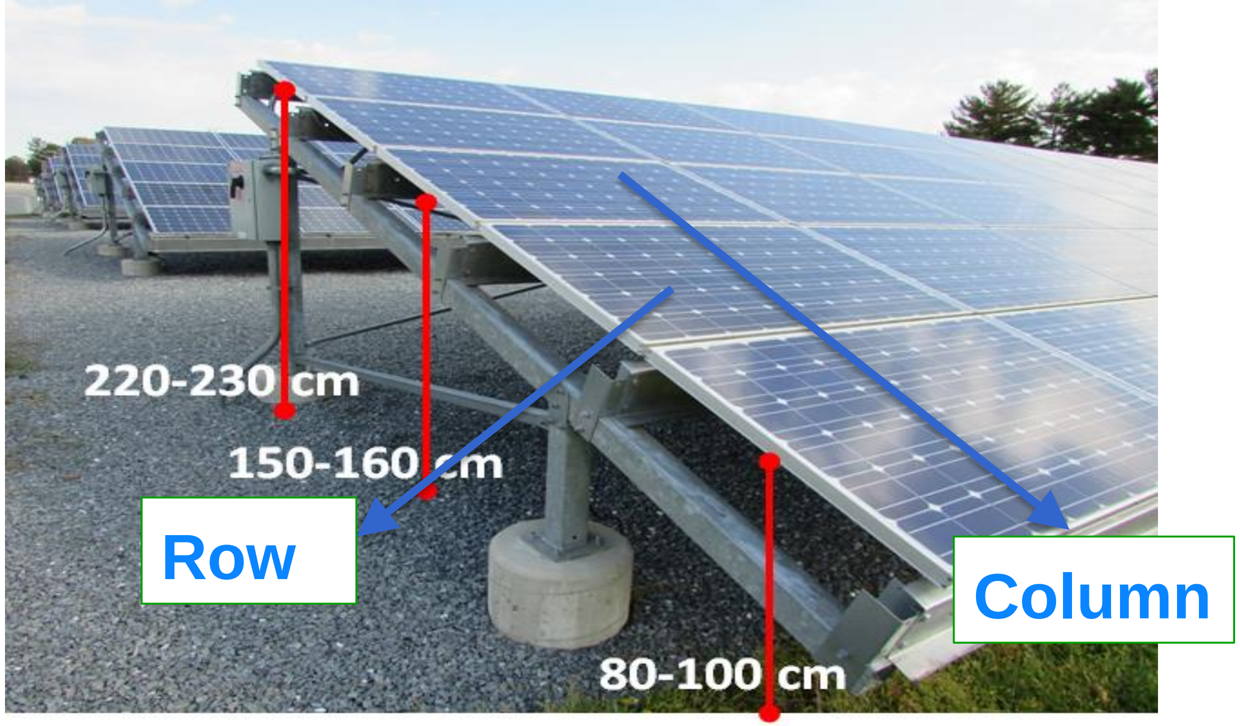
Field Module Metadata

Rack: a cluster of PV modules in the field

Row: modules with same heights in the same rack

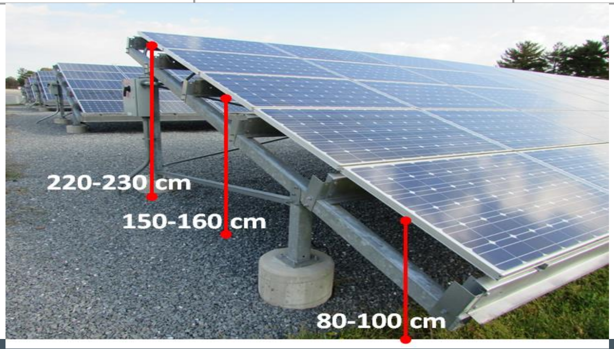
Column: module location in the rack (from left to right, on the back side)

Tile angle: angle of the rack to the ground



PV Module Field Survey

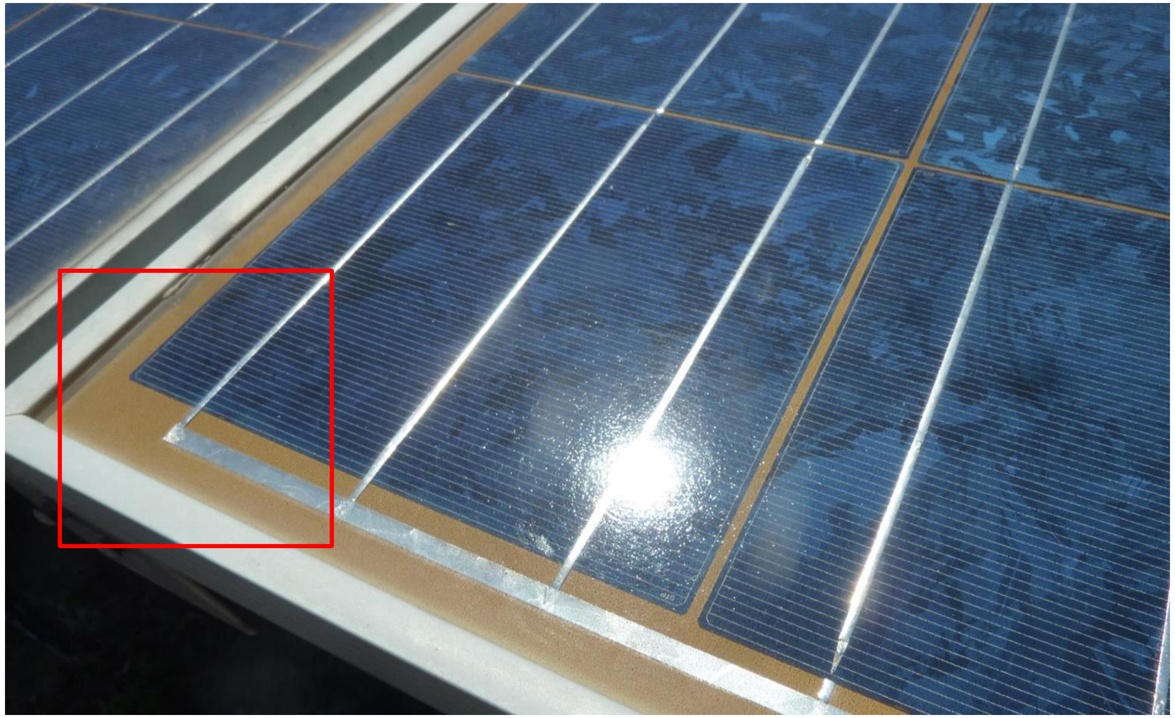
Site Location	Climatic Zone	Backsheet Material	Ground Cover	Install Configuration	Rack Length	Rack Height	Note
North America 1	**Dfb**	PVDF; PA	Grass	Landscape	80; 82	4; 5	
North America 2	**Cfa**	PET	Grass	Portrait	24, 36, 78	2	
North America 3	**Dfb**	PET	Roof	Portrait	3 - 28	1	Low angle, backsheet is covered
North America 4	**Dfa**	PEN	Rock	Landscape	48	4,5	
China	**Cwb**	PVDF, PVF, PET	Concrete and grass	Landscape			



Observed Failure Modes in Fields

Discoloration

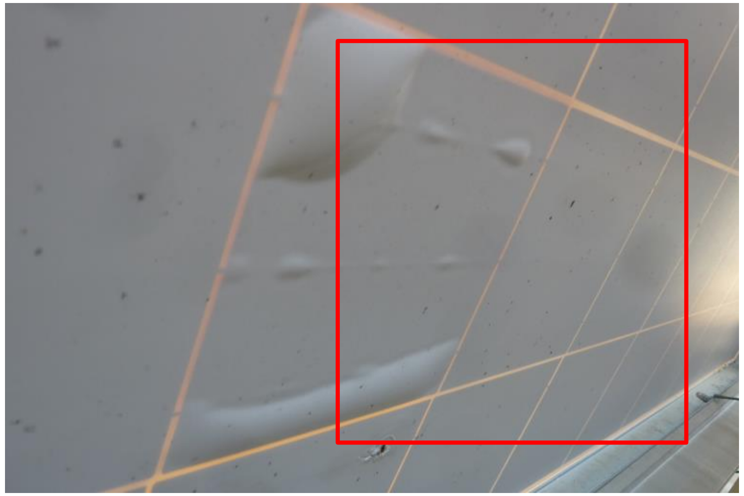
- Yellowing of inner layer of backsheet



China

Delamination

North America 4



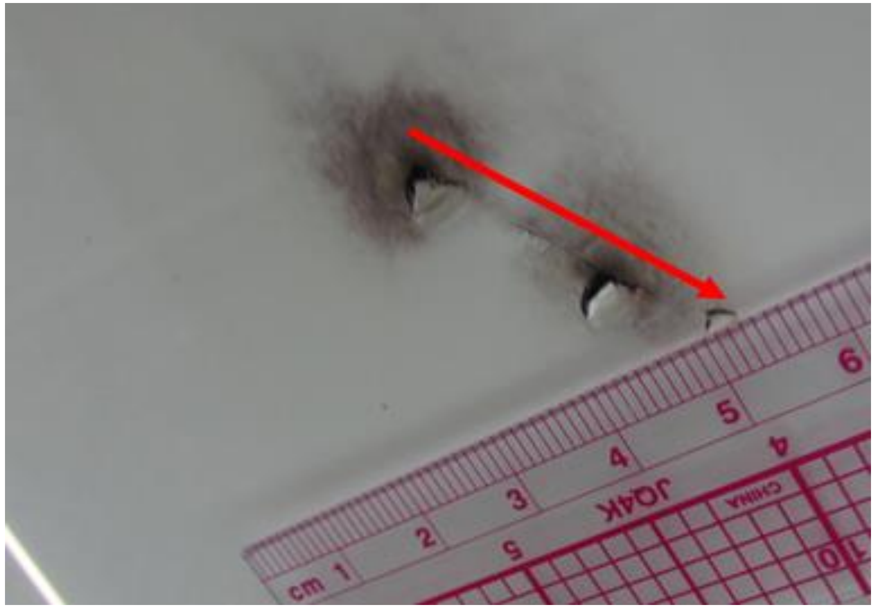
China

Observed Failure Modes in Fields

Hot Spot and Burn Marks

China

China



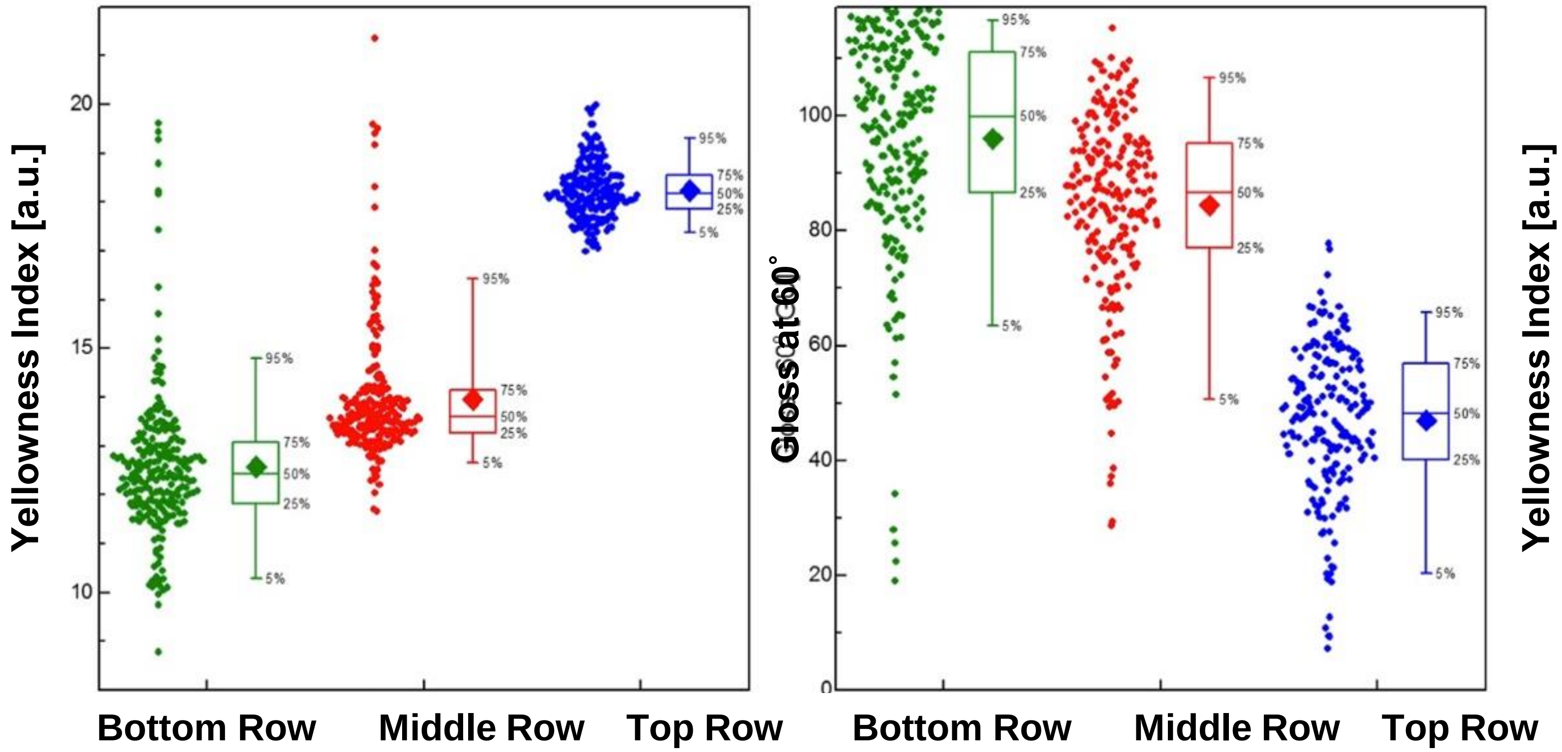
North America
4

Scatter Plot of Measured Data Observations

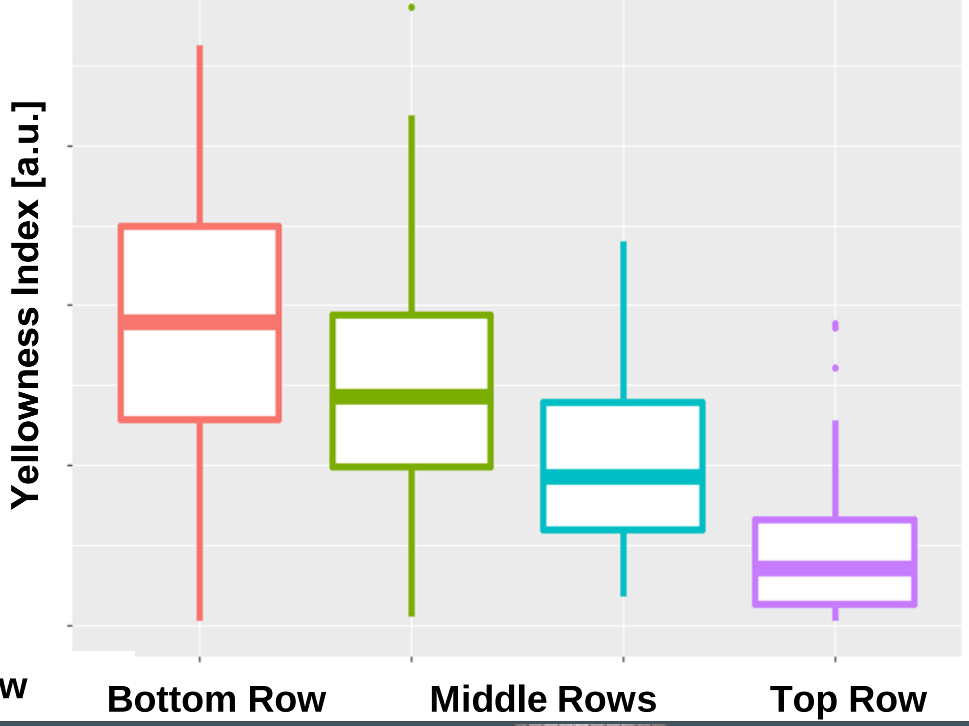
Height Effect (module height):

- **Greatest effect on backsheet degradation**
- **Influences the rear-side irradiance distribution**
  - Differences of albedo
  - Range of yellowing of PVDF backsheet in North America 1

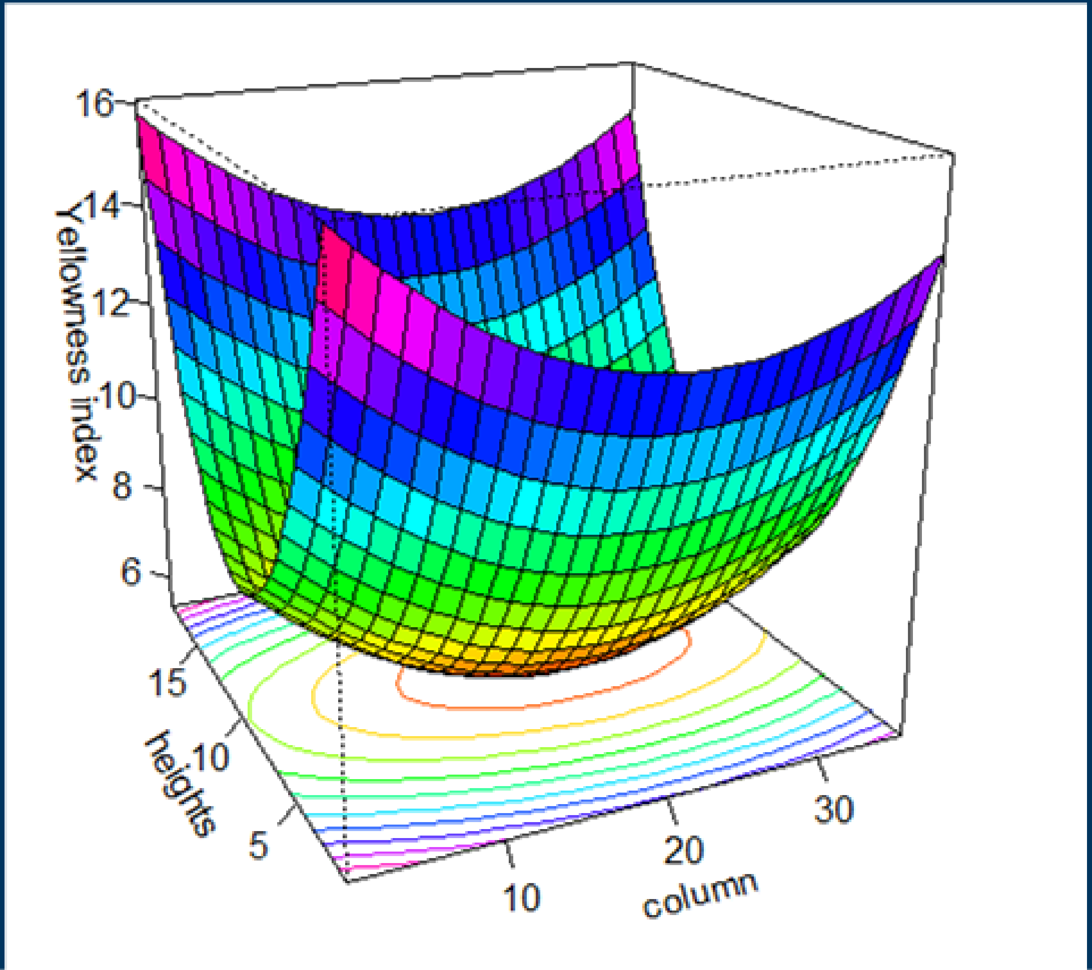
Field Survey in North America 4



Field Survey in North America 1



Temporal-Spatial Model Development



Temporal Spatial Model Introduction

- Study the effect of where the module is installed on the degradation of backsheet
- Model how this degradation space changes over time.
- Data-driven model with real-world degradation data
  - Represent the effect of weathering factors, ground cover, soiling, and backsheet material
- Difference of degradation behavior of modules exposed to same location
    - More obvious of long time exposure
    - Compromise the lifetime of backsheet
- The rear-side irradiance also influences the efficiency of bifacial PV module
- Soling adds uncertainty into models of time

Temporal Spatial Model Development

- Response Surface Method
  - Mathematical and statistical techniques based on the fit of a polynomial equation to the experimental data
  - Examine the “surface” or the relationship between the response and the factors affecting the response
    - Over a certain region of interest
    - Determine the setting for these factors that result in the optimum value of the response
    - Identify factors that affect the response
  - Intend to be used in experiment designation
  - Used to find the suitable approximation to the true relationship between module installation factors with degradation
    - with a sequence of experiment data

- Model pattern
  - First order
    - Steep Ascent Model

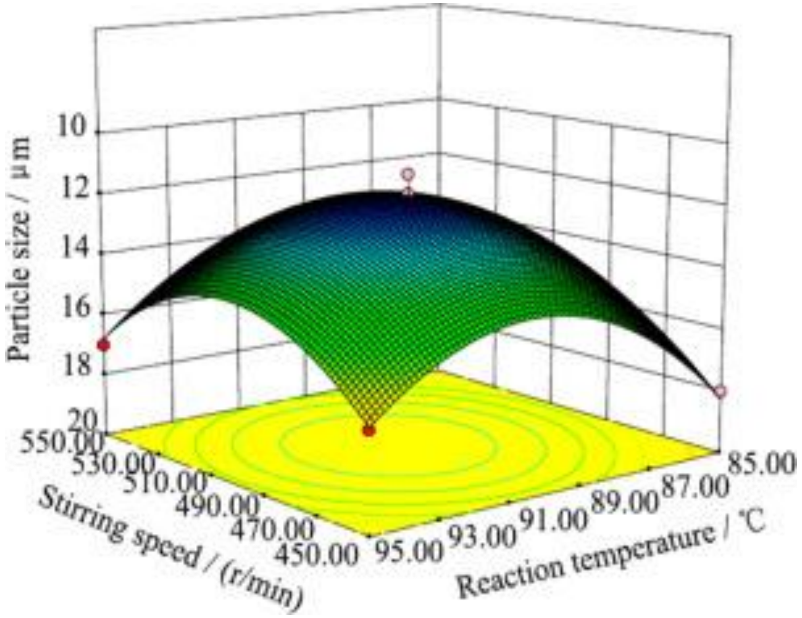
$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \varepsilon$$

    - Screening Response Model

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \varepsilon$$

    - Second order
      - improve the optimization process
      - include the quadratic and interaction terms

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon$$



E.g.: **Response surface methodology (RSM) application to optimize the preparation of the Zn-Sm antibacterial white carbon black.** [1]

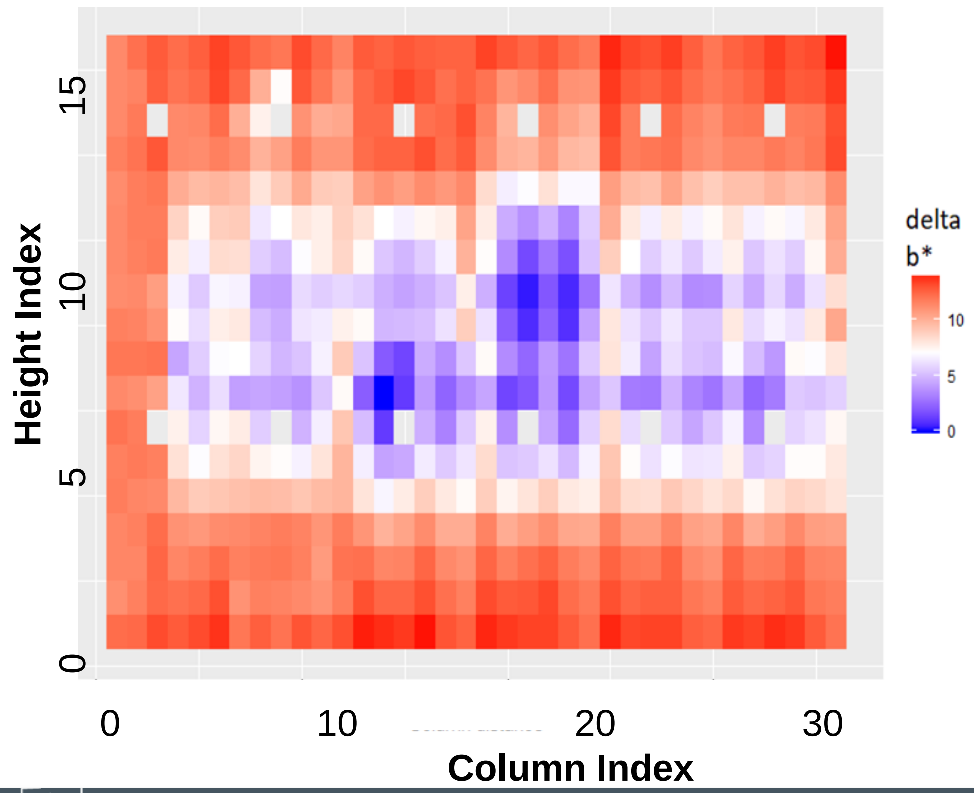
[1] Cuiping MAO, Bin ZHANG, Xiaoning TANG, Huan LI, Suqiong HE, Optimized preparation of zinc-inorganic antibacterial material containing samarium using response surface methodology, In Journal of Rare Earths, Volume 32, Issue 9, 2014, Pages 900-906, ISSN 1002-0721, https://doi.org/10.1016/S1002-0721(14)60161-7. (http://www.sciencedirect.com/science/article/pii/S1002072114601617) Keywords: response surface; inorganic antibacterial material; zinc ion; samarium; rare earths

Temporal Spatial Models Evaluation on Published Data

DuPont Field Survey presentation[1]

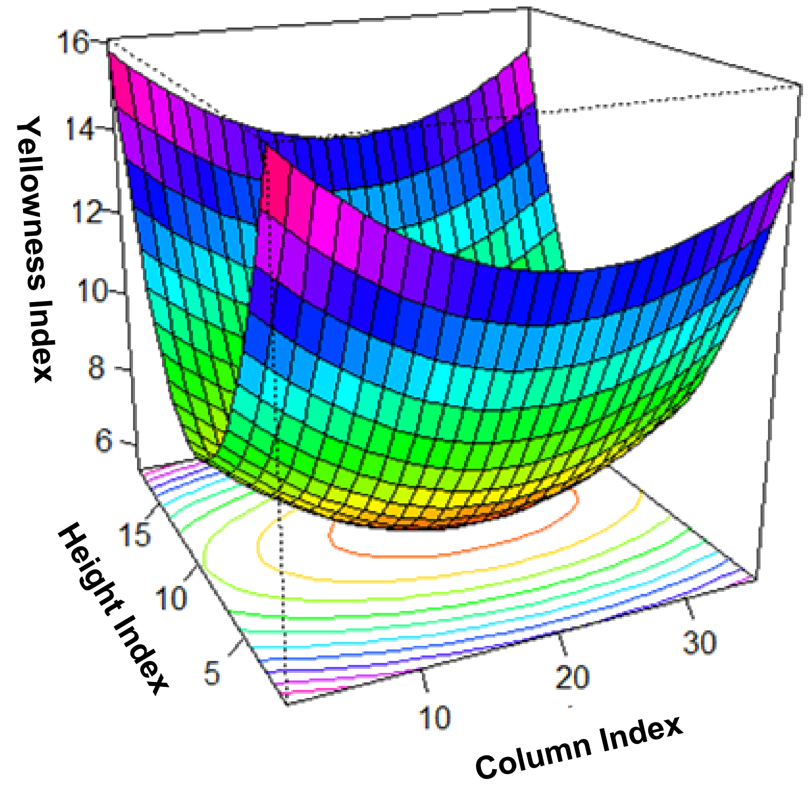
- Roof mounted: 6 modules
  - 15 years
- PET outer layer
- ~150 mm from corrugation

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon$$



Evaluation

- Use second order surface response model
- **Adjusted R^2 = 0. 6962**
- Significant p-value of each predictors
- Second order response surface model



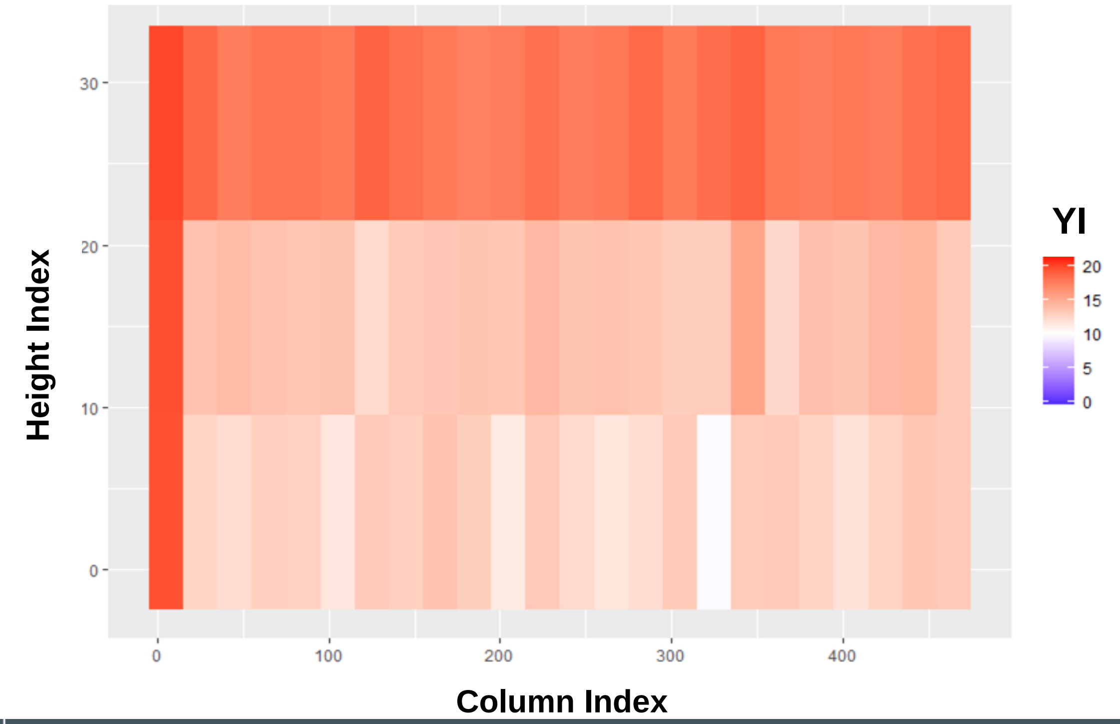
[1]W. Gambogi, J. Kopchick, T. Felder, S. MacMaster, A. Bradley, B. Hamzavytehrany, C.-F. Wang, H. Hu, Y. Heta, Lucie Garreau-Iles and T. J. Trout, “Sequential and Weathering Module Testing and Comparison to Fielded Modules ”, NREL PV Module Reliability Workshop 2015, https://www.nrel.gov/pv/assets/pdfs/2015_pvmrw_65_gambogi.pdf

Temporal Spatial Model – North America 4 (PEN)

Yellowness Index Data

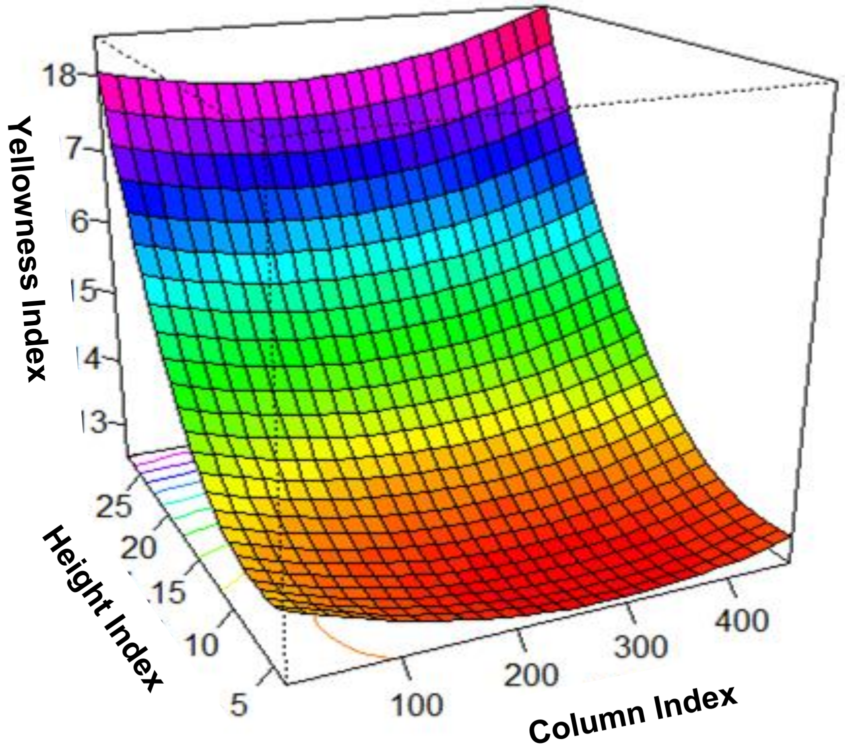
- Strong edge effect
- Significant effect of height
- Edge effect decrease with increase of height
- Did not measure the edge on one side
- Ground cover is white rock

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 + \varepsilon$$



Second Order Response Surface Model

- **Adjusted R^2 = 0.6819**
- Capture the feature of data:
  - Height effect
  - Edge effect
  - Greater curvature surface of lower height
    - strong edge effect

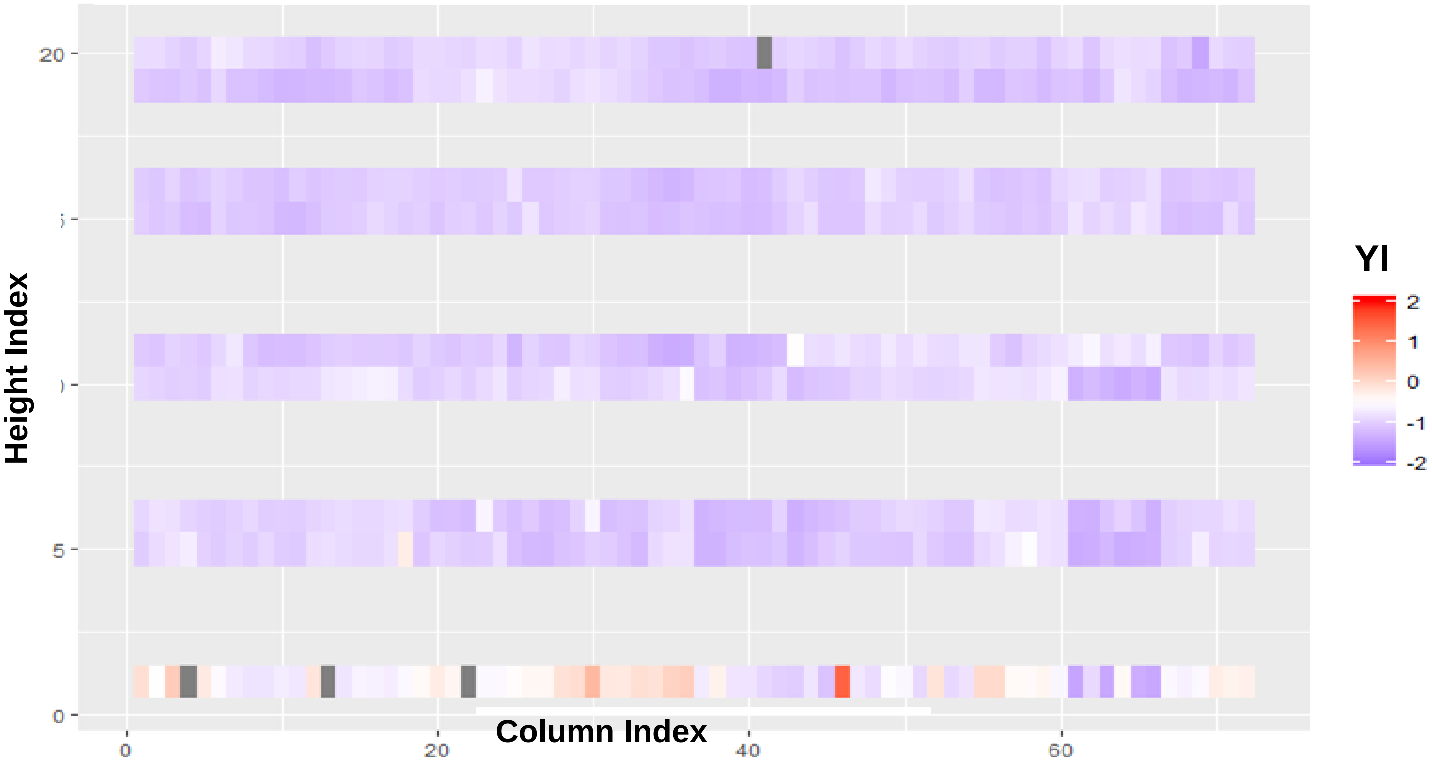


Temporal Spatial Models – North America 2 (PET)

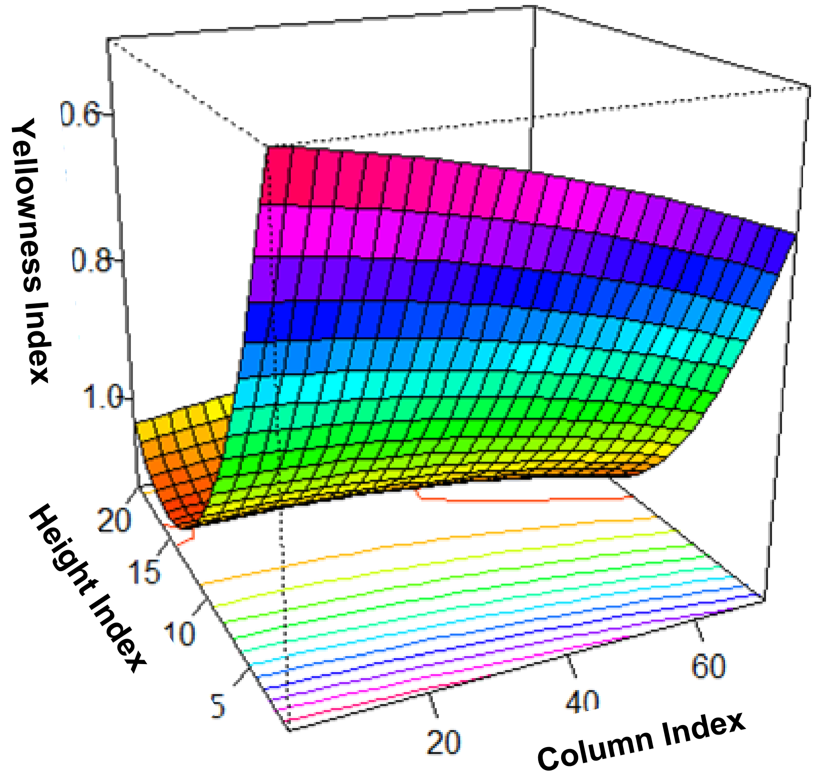
Yellowness Index Data: (the right end of data represent the center of the row in the field)

- Weak height effect
  - Similar YI of backsheet with different height
  - Short exposure time & small albedo of grass
- Highest YI of backsheet at lowest height

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon$$



- **Low adjusted $R^2 = 0.0582$**
  - Small variance with column and height
    - Short exposure years
    - Low albedo of ground cover (grass)
    - Minimal backsheet degradation (PET)

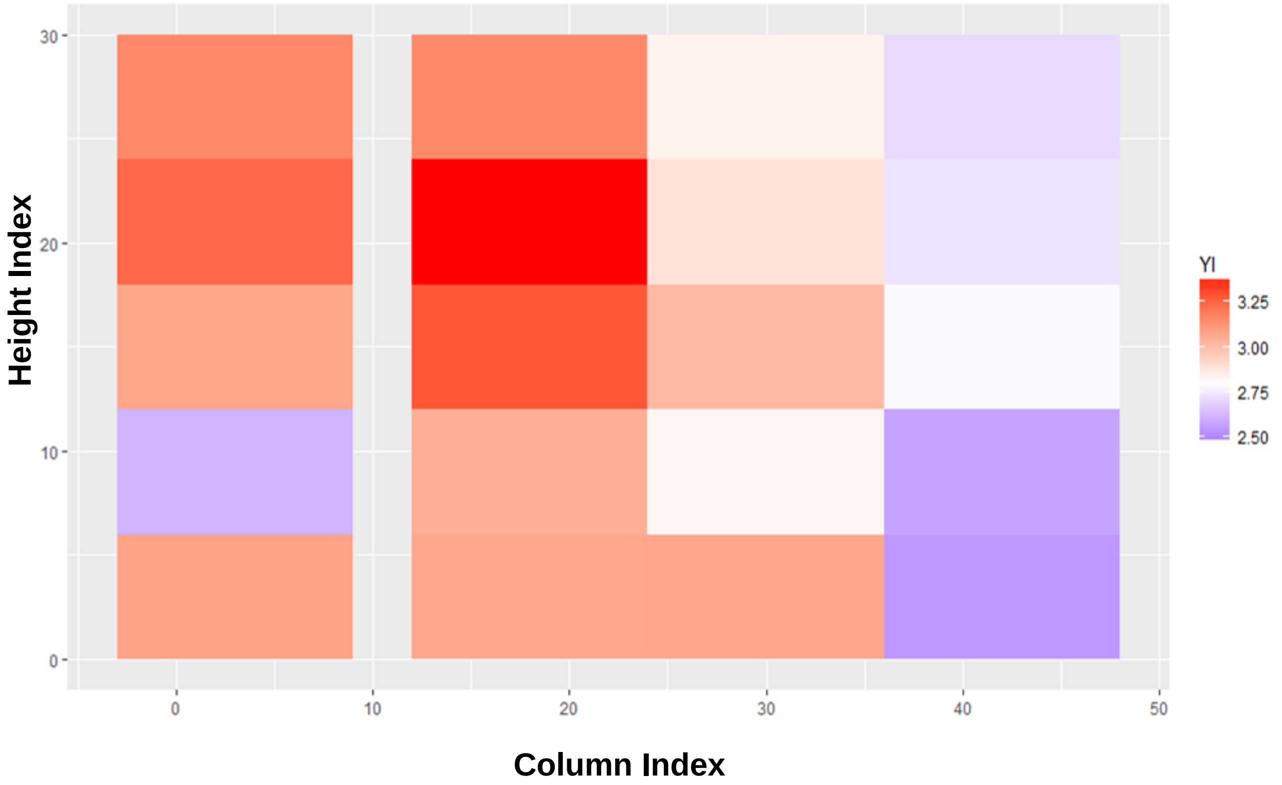


Temporal Spatial Model – North America 1 (Polyamide)

Yellowness Index Data: (the right end of data represent the center of the row in the field)

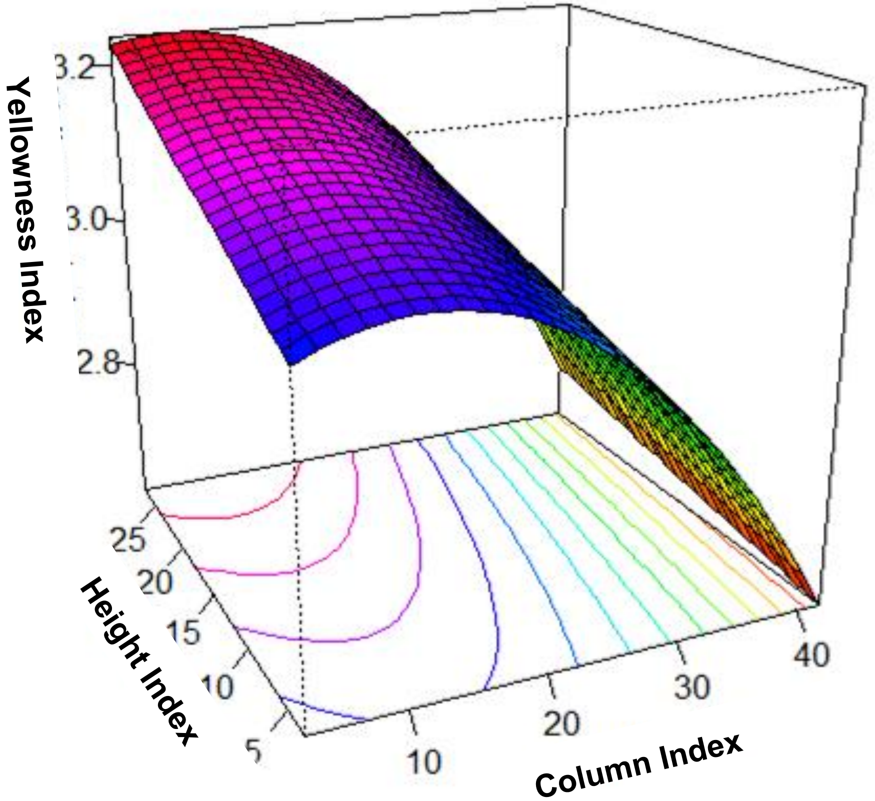
- edge effect observed
- low albedo of grass ground cover

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \varepsilon$$



- **Adjusted R^2 = 0.6014**
- Capture the feature of data:
  - edge effect, lower yellowness index at lower backsheet
-

YI



Spatial-Temporal Model Conclusions

Develop models to predict the backsheet degradation of modules over space

Module location in a rack relates to the rear side irradiance distribution

- Edge effect

Module height and elevation height affect the rear side irradiance

- Non-uniform rear-side irradiance

Albedo of ground cover impacts degradation

UV-resistance of backsheet material is important in slowing of degradation

- Excellent UV-resistance of fluoropolymers

Incorporate multiple different responses beyond color

Soiling impacts the development of these models

- Soiling will change over time

Thank you!

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