PV Array Differential Backside Exposure Conditions: Backsheet Degradation and Site Design

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4th Atlas/NIST Workshop on Photovoltaic Materials Durability

December 5-6 2017

Gaithersburg, MD (USA)

National Institute of Standards and Technology
U.S. Department of Commerce

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Funded in part through DOE SunShot PREDICTS2: Backsheets (Award DE-EE-0007143)

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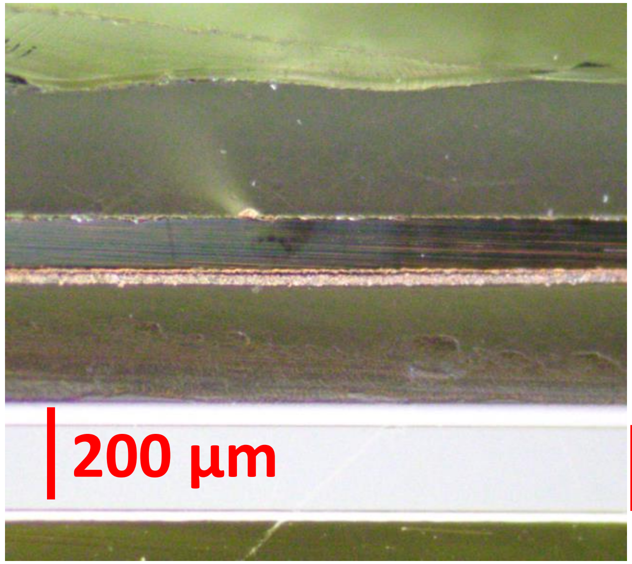
Case Western Reserve University – Yu Wang, Laura Bruckman, Roger French
Arkema – Sebastien Merzlic, Amy Lefebvre, Greg O'Brien
Northeastern University – Scott Julien, Kai-Tak Wan

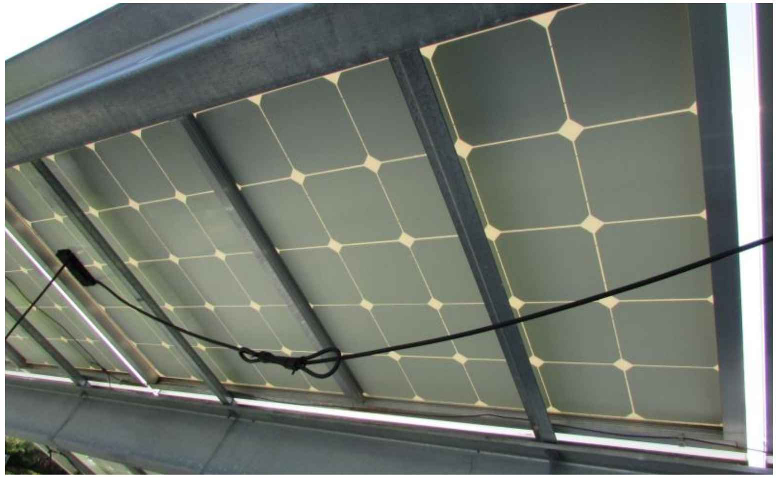
PV module construction: backsheets

PV backsheets are usually a polymer laminate:

- Inner layer: adhesion promotion
- Core layer: electrical insulation
- Outer layer: environmental protection
  - Good UV and hydrolysis resistance
  - Mechanical strength and flexibility

Structure of PV module





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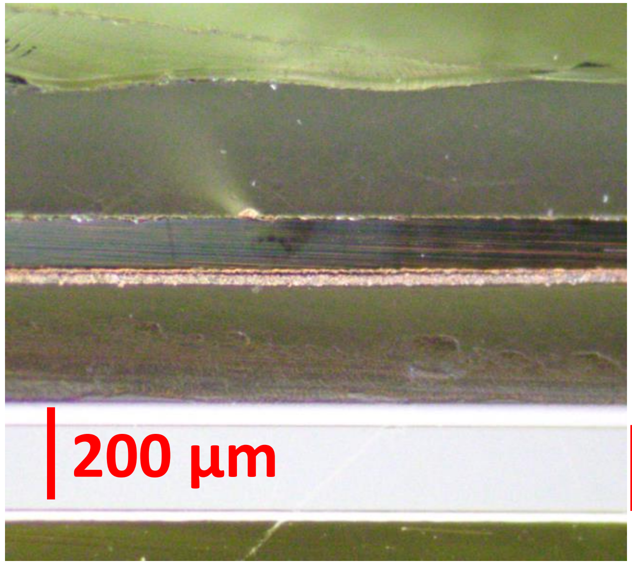
Backsheets approx. \$2 to \$7/m^2, 3% to 5% of total module cost:

- More expensive: **fluoropolymer**-based: PVF, PVDF, ETFE, THV, …
- Less expensive: **non-fluoropolymer**-based: PET, PEN, PP, PA, …

Structure of PV module



Fluoropolymer

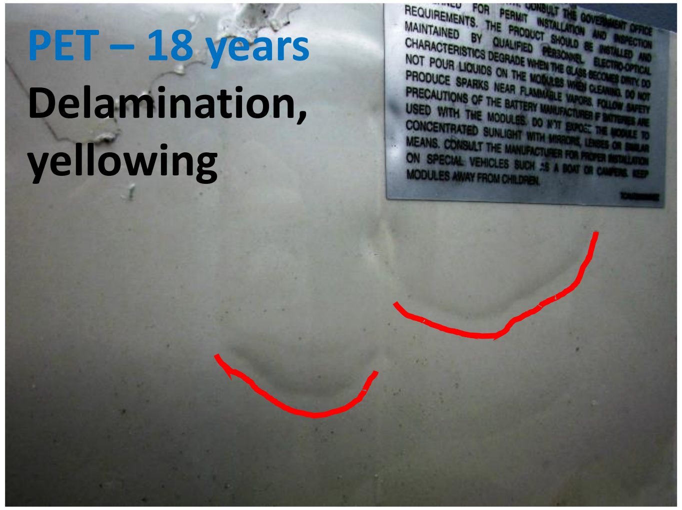
Fluoropolymer backsheets (PVF, PVDF, ETFE, THV, …) withstand weathering quite well, even after years

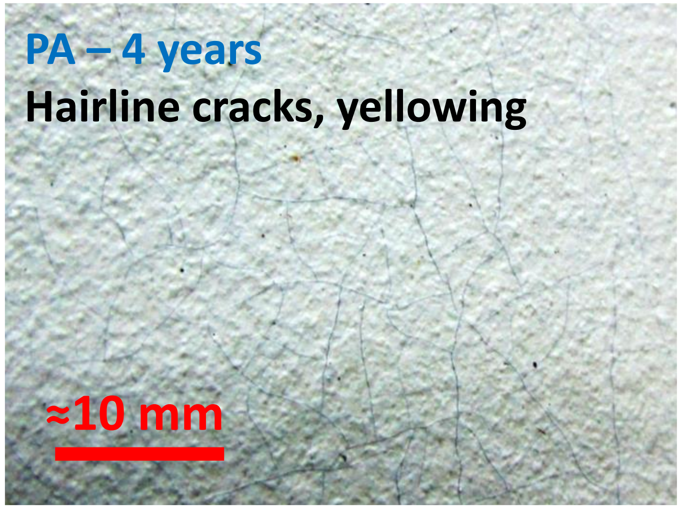
engineering

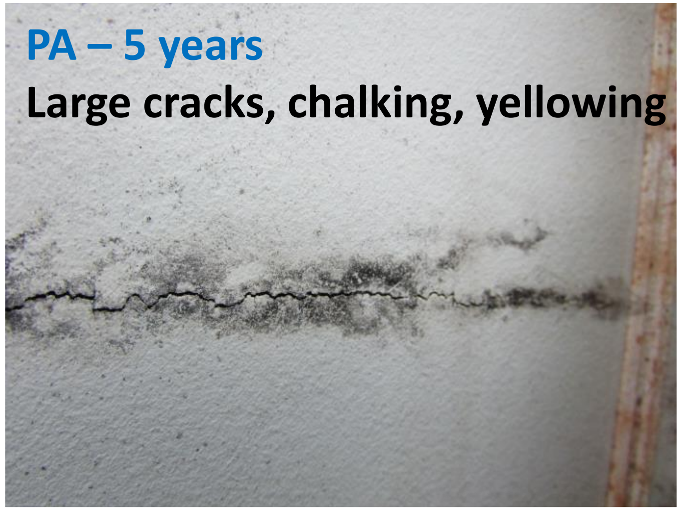
Fluoropolymer vs. non-fluoropolymer

Fluoropolymer backsheets (PVF, PVDF, ETFE, THV, …) withstand weathering quite well, even after years

Non-fluoropolymer backsheets (PET, PEN, PA, PP, …) tend to be more susceptible to environmental degradation



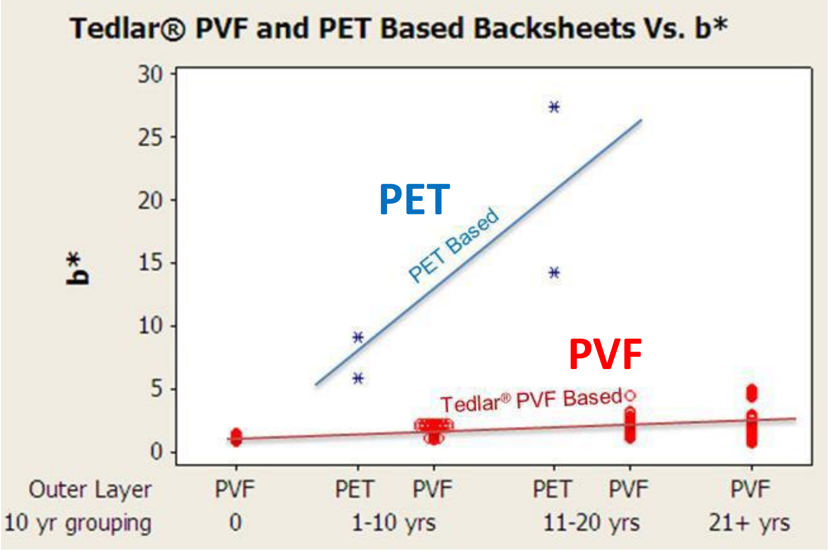




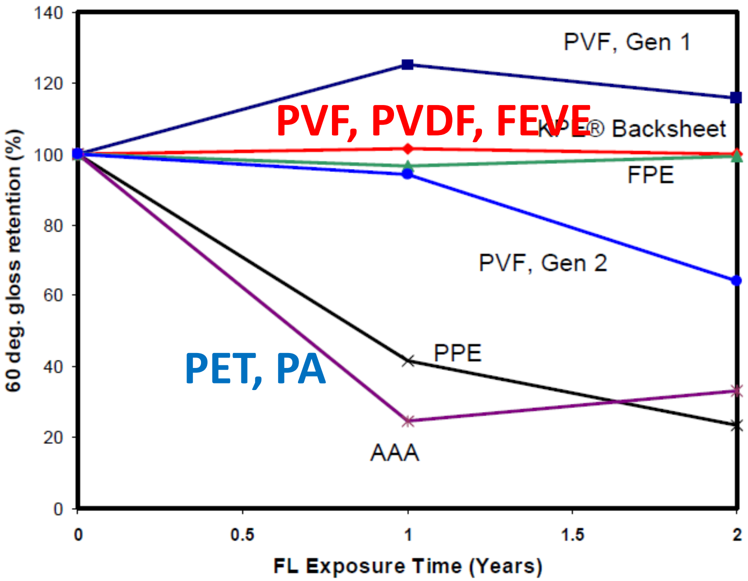
Fluoropolymer vs. non-fluoropolymer

Non-fluoropolymer backsheets tend to degrade more quickly, especially under UV

Yellowing over time



Gloss retention over time



Gambogi W, et al. Weathering and durability of PV backsheets and impact on PV module performance, Proc. of SPIE vol. 8825, **2013**

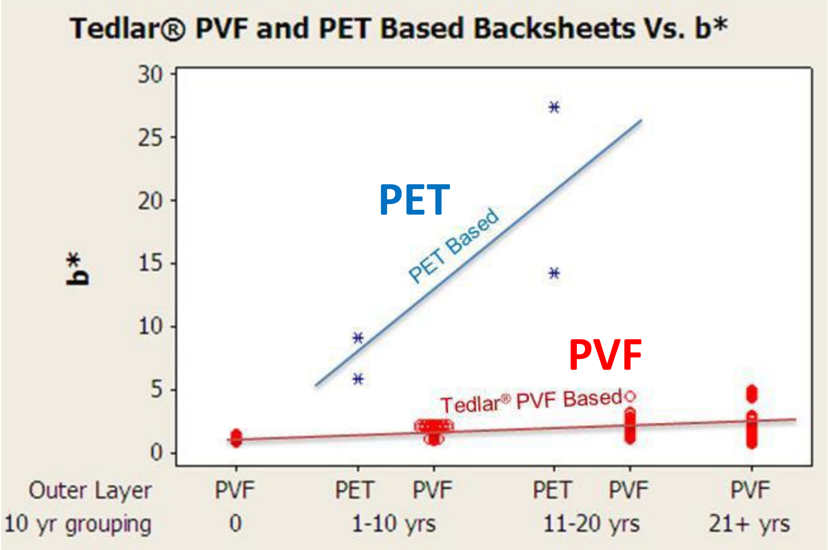
Lefebvre A, et al. Weathering performance of PV backsheets, NREL PV Module Reliability Workshop, **2012**

Fluoropolymer vs. non-fluoropolymer

Non-fluoropolymer backsheets tend to degrade more quickly, especially under UV, we must better understand how they degrade under real-use conditions

→ Survey array of modules with non-fluoropolymer backsheets

Yellowing over time



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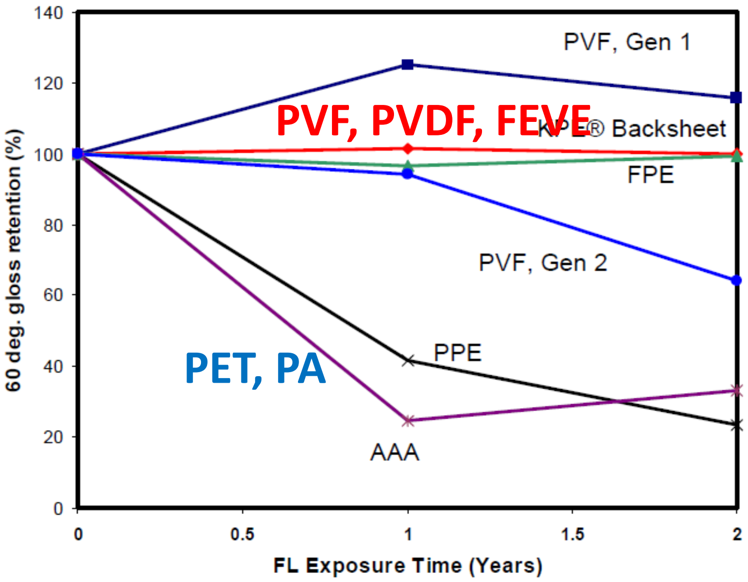

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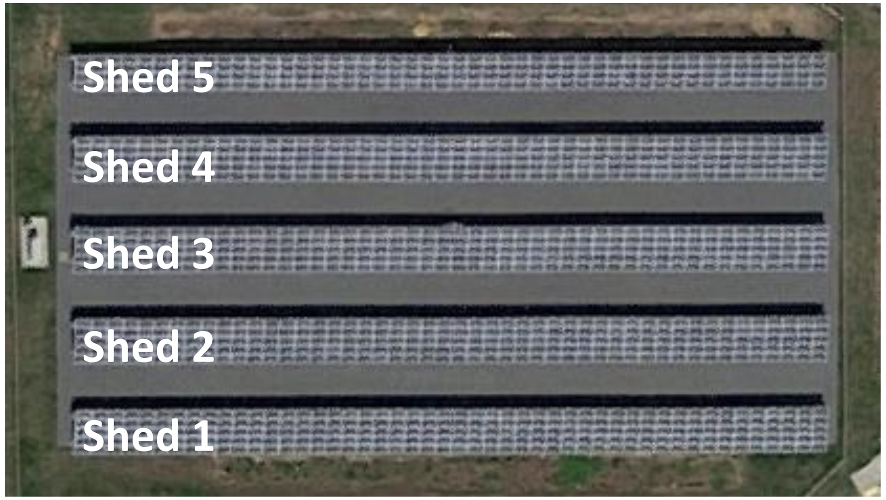
NIST CNST site overview

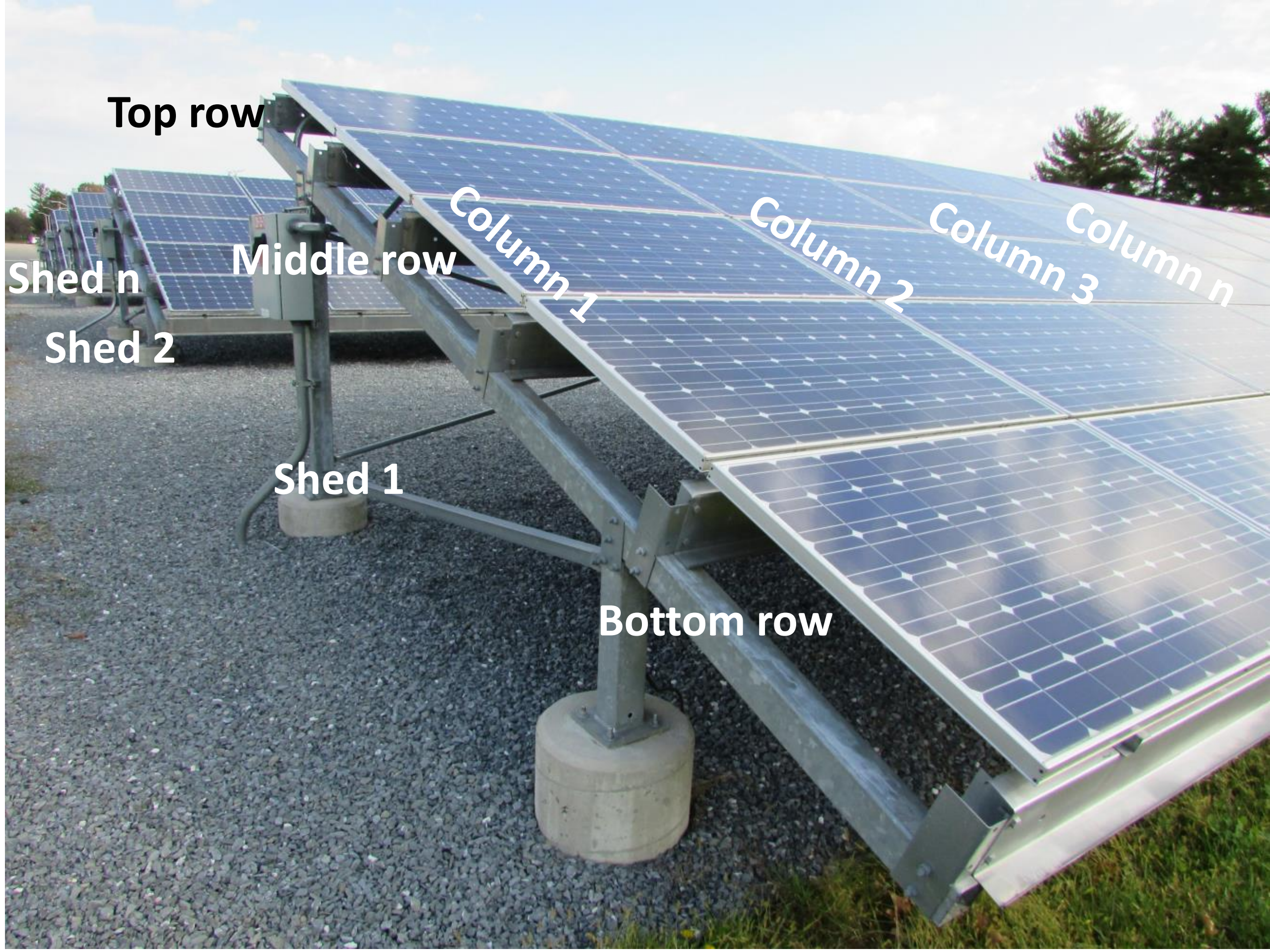
Array characteristics:

- In-service date: August 2012
- Rated production: 271 kW (1152 modules)
- Layout: 5 sheds with 48 columns, 5 modules per column, 20° mount

Module characteristics:

- Cell type: monocrystalline Si
- **Backsheet material: PEN-based**

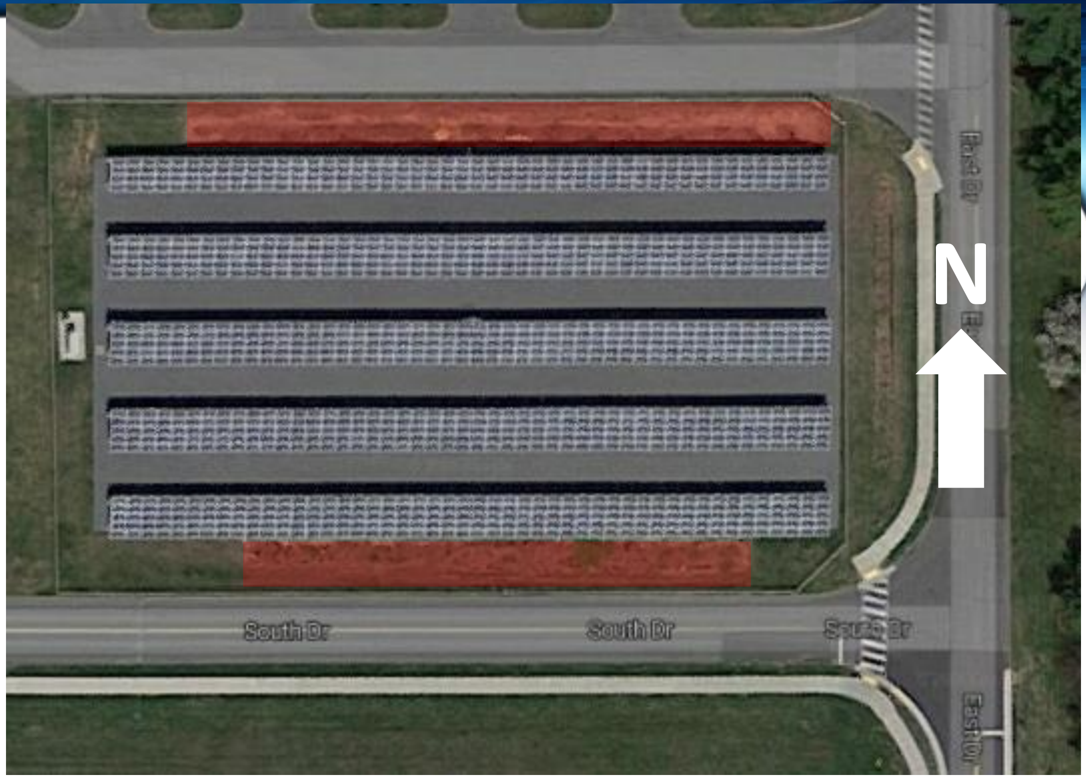




NIST CNST site overview

Site characteristics:

- Location: Gaithersburg, Maryland (USA)
- Elevation: 136 m
- Climate: Dfa (hot humid continental)
- Surroundings:
  - Situated on grayish rock (2-4 cm diameter)
  - Bordered by grass, and ditches on the front and backside



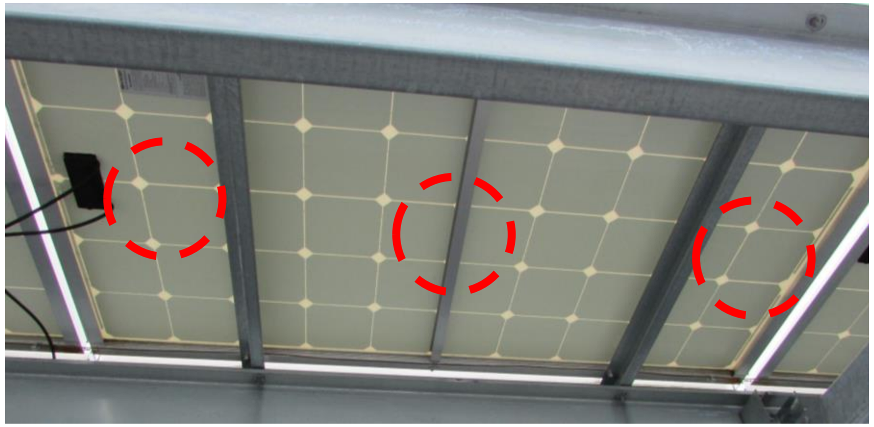
Survey methodology

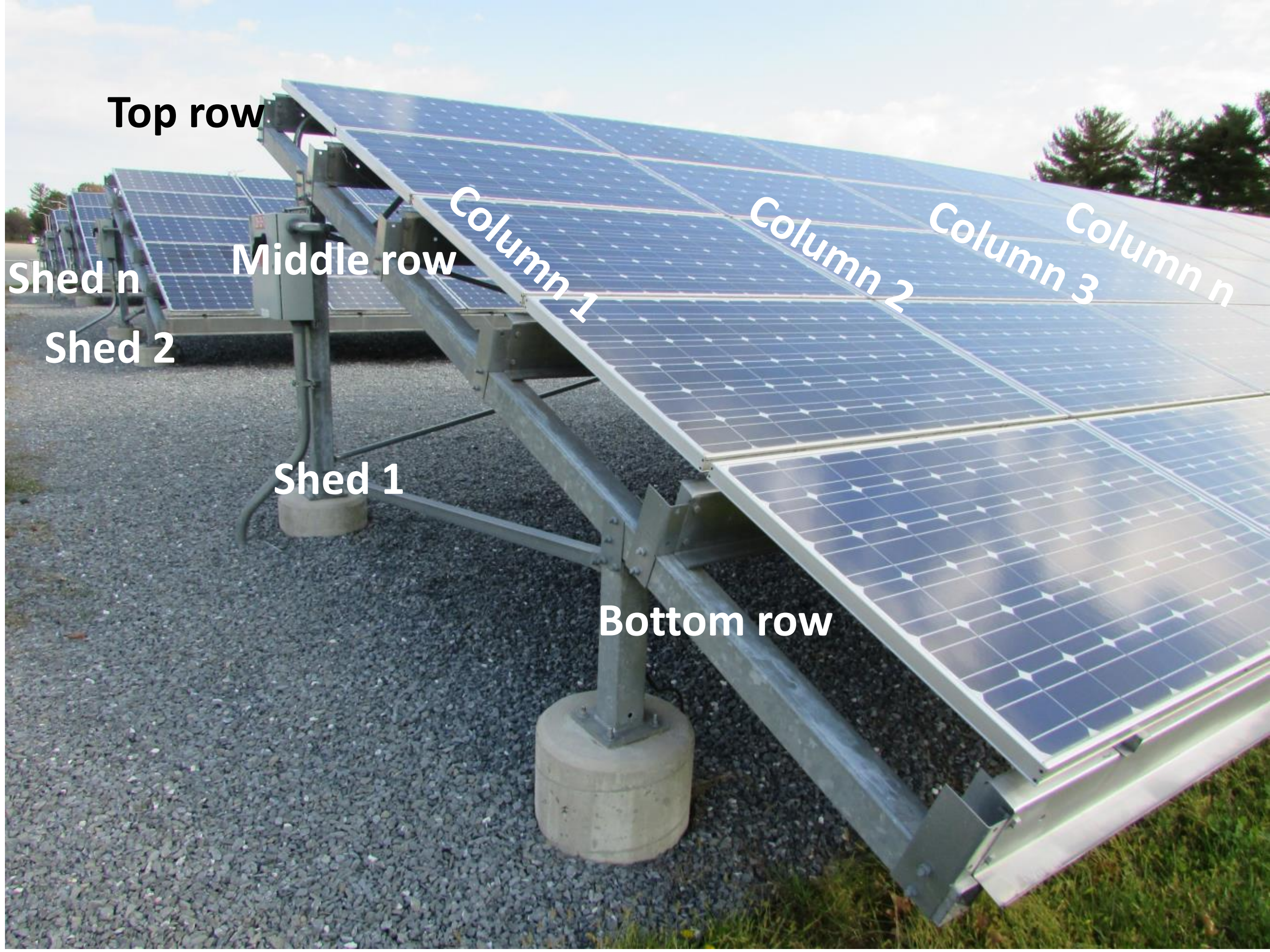
Visual inspection: all 1152 modules

Color and gloss: ~240 modules, three points on each module

FTIR: ~40 modules

Dates of inspection: 24 October and 18 November 2016

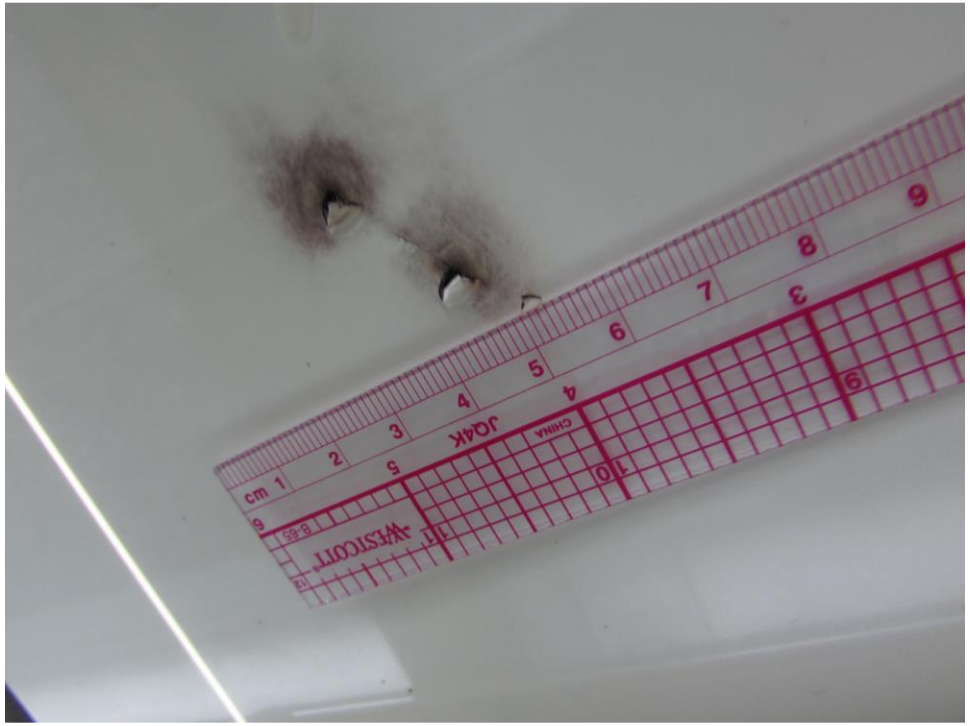




Visual inspection

Two major backsheet defects observed:

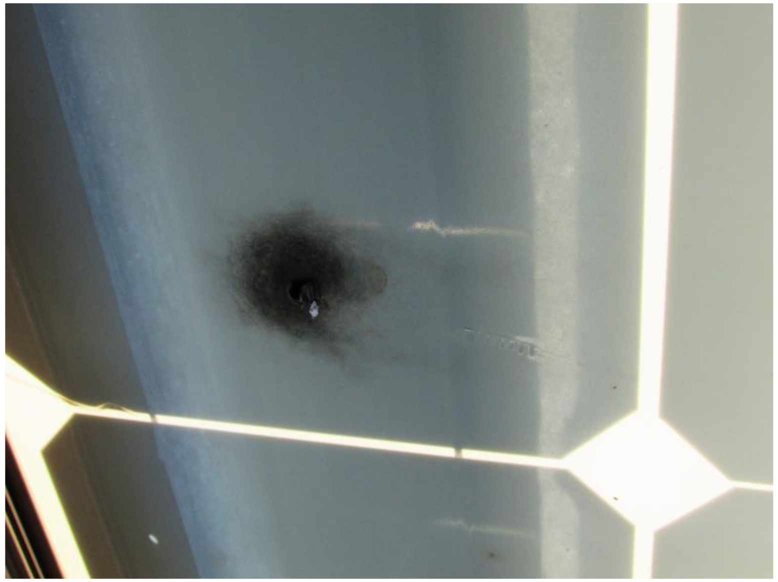
1) Burn-throughs
2) Busbar bumps

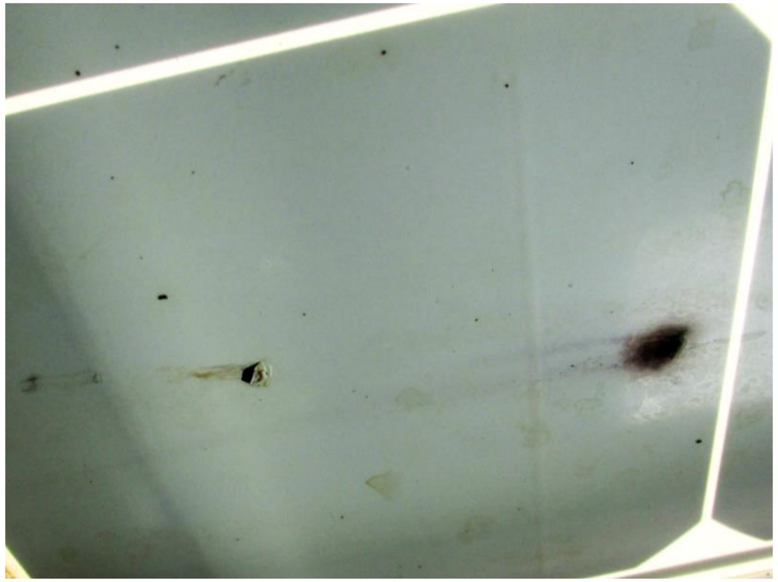


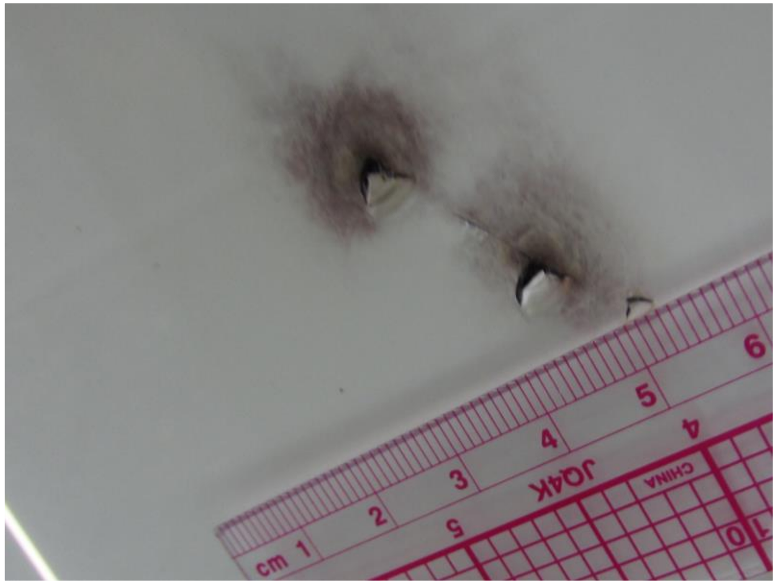
Visual inspection

1) Burn-throughs

- Observed in ~3% of modules, less common on bottom row
- Affected modules typically have 1-2 marks







Visual inspection

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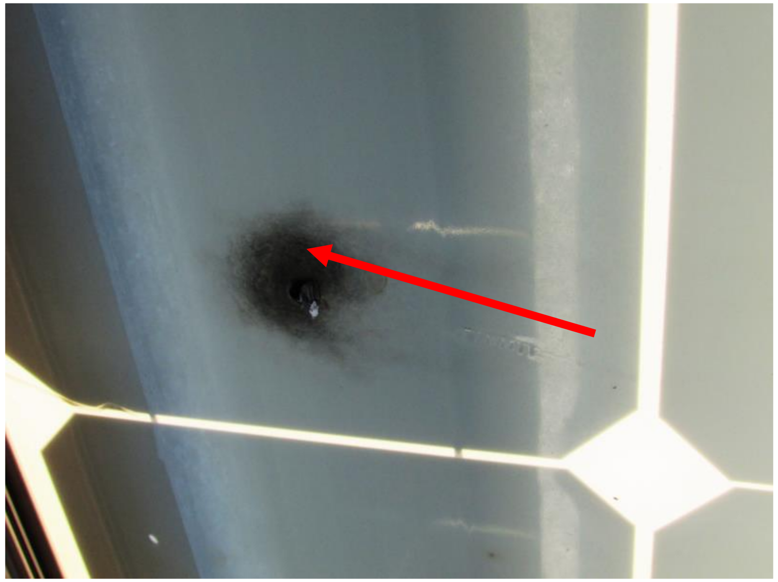
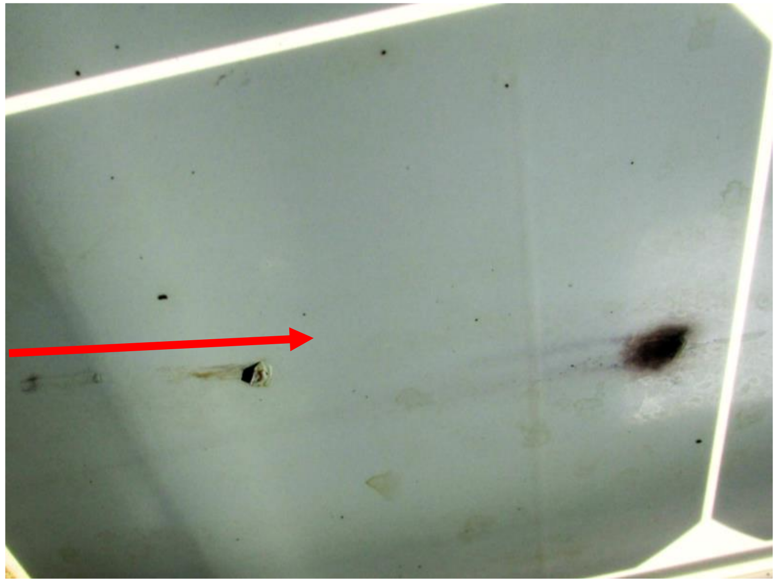
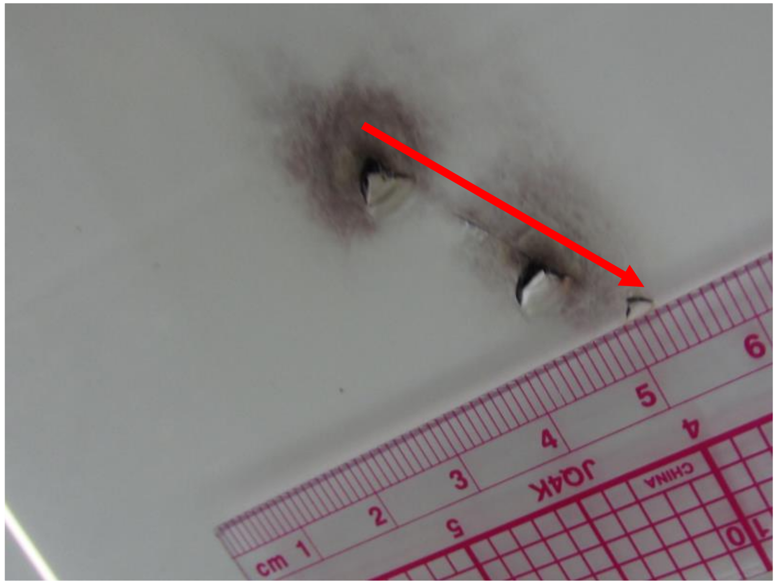
- Affected modules typically have 1-2 marks
- Many occur near physical damage due to handling (red arrows)



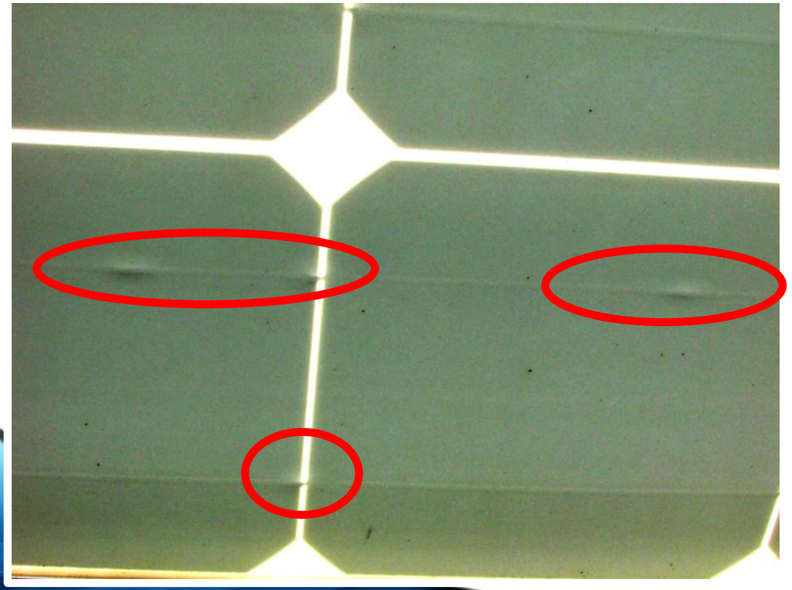


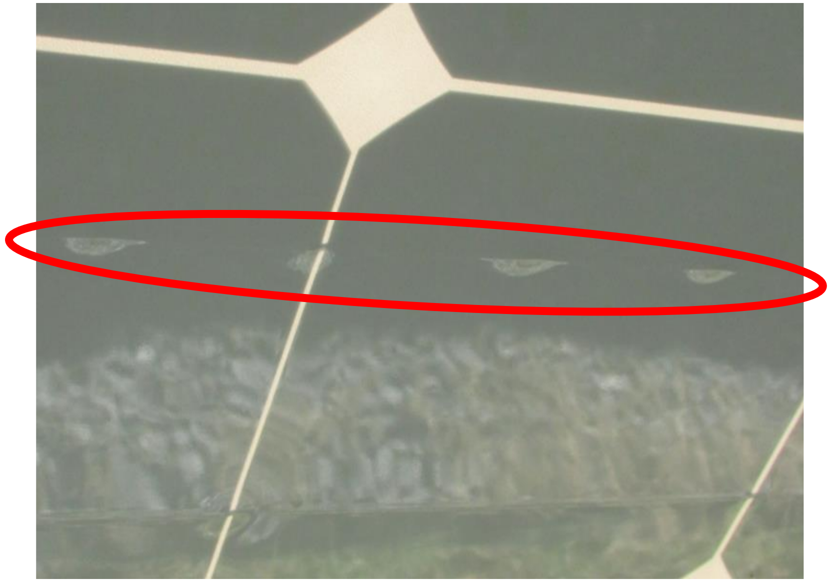


Visual inspection

2) Busbar bumps

- Observed in 5-10% of modules, more common on bottom rows
- Affected modules typically have multiple bumps
- Occur along busbars and at interconnects

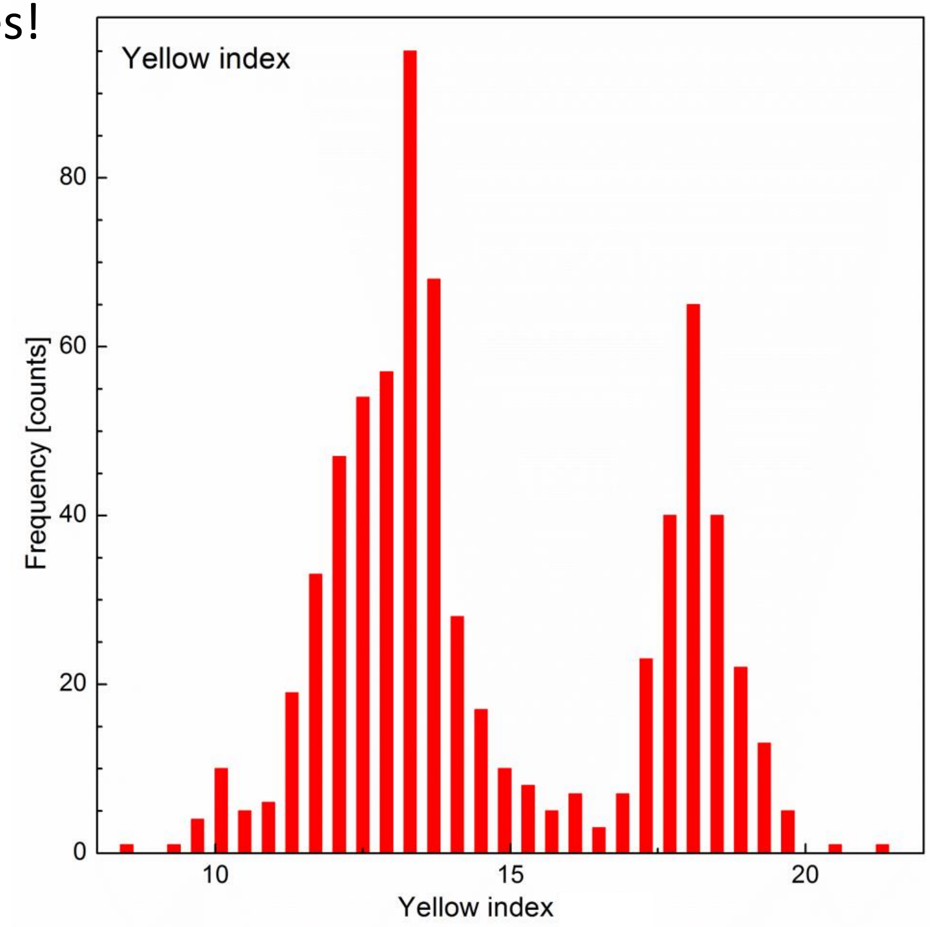


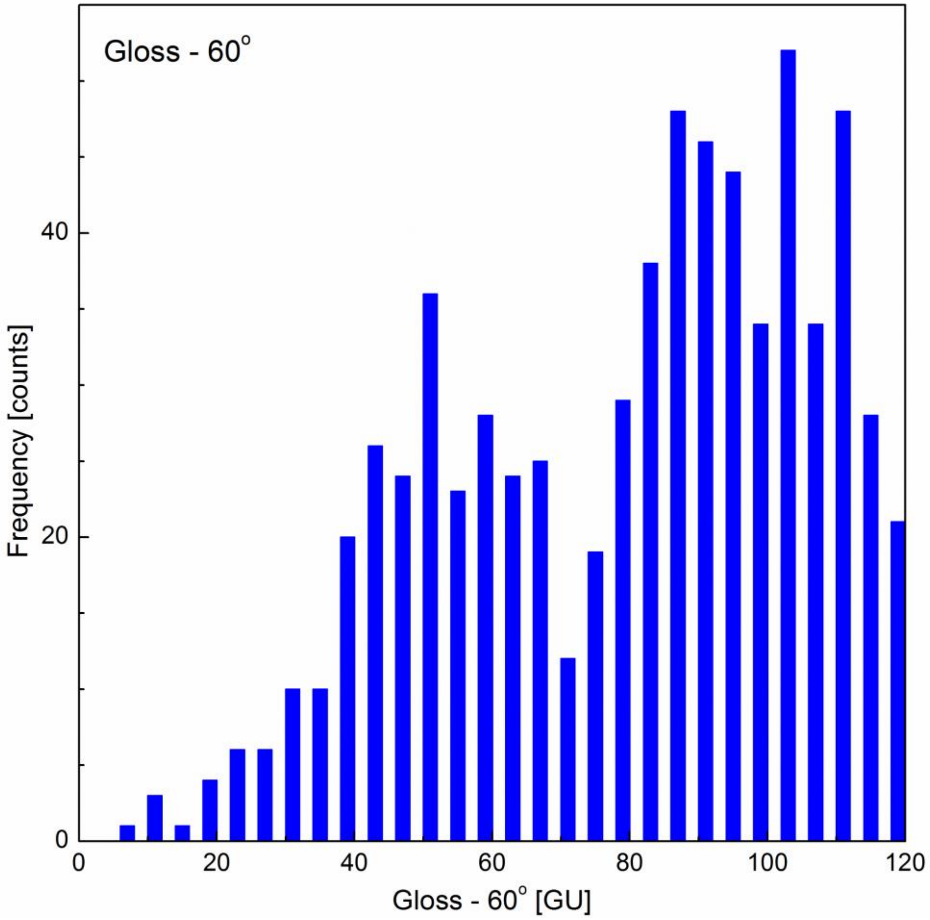


Yellow index and gloss

Huge range of yellow index and gloss values!

Array should be divided into sub-sections to identify yellowing and gloss trends



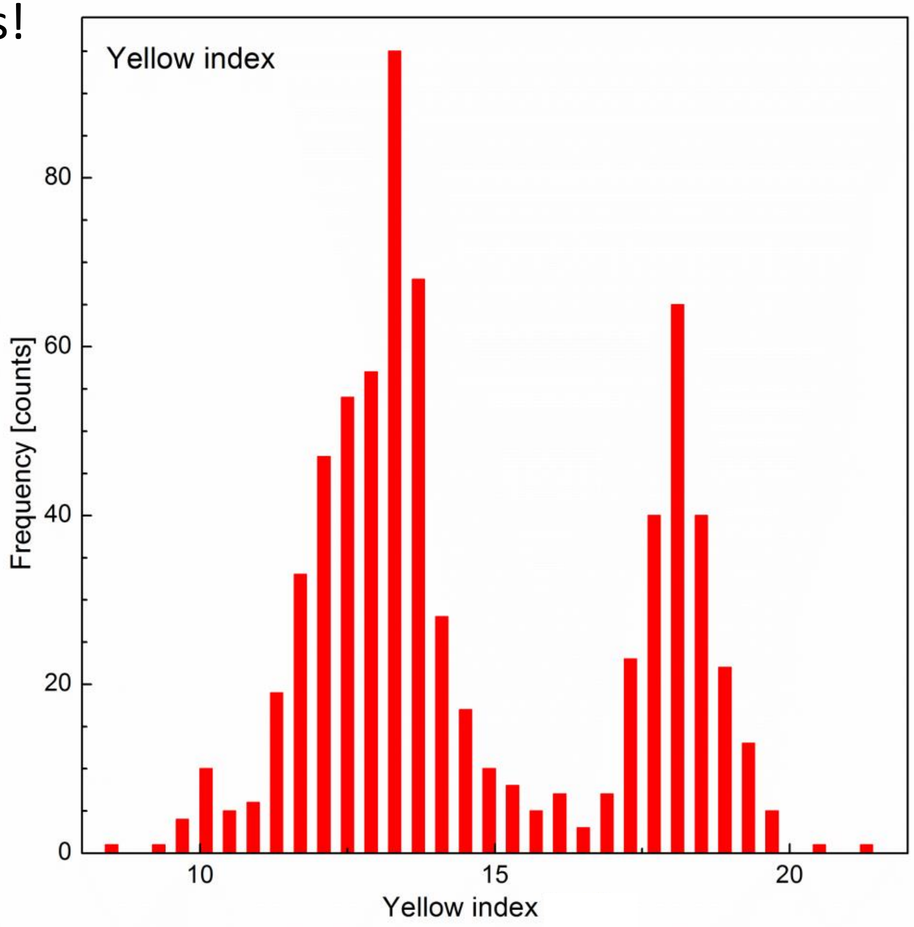


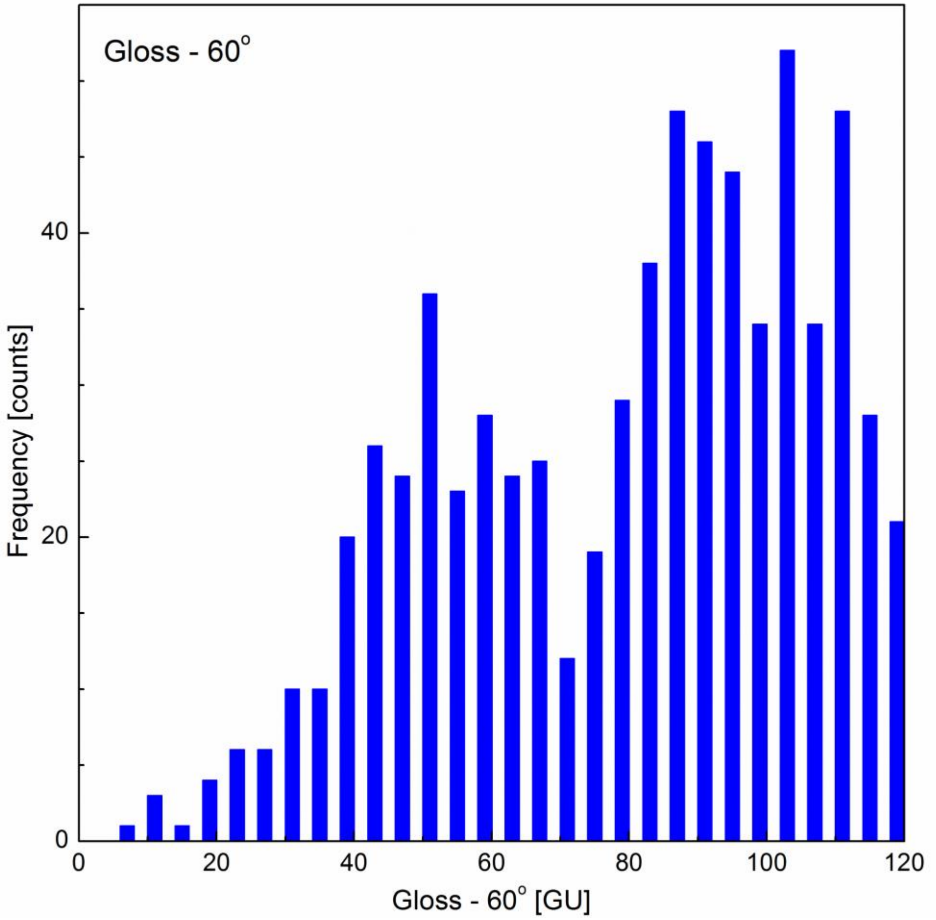
Yellow index and gloss

Huge range of yellow index and gloss values!

Array should be divided into sub-sections to identify yellowing and gloss trends:

- Row (height)
- Column (edge proximity)
- Shed (various ground covers)





Height effect: rows

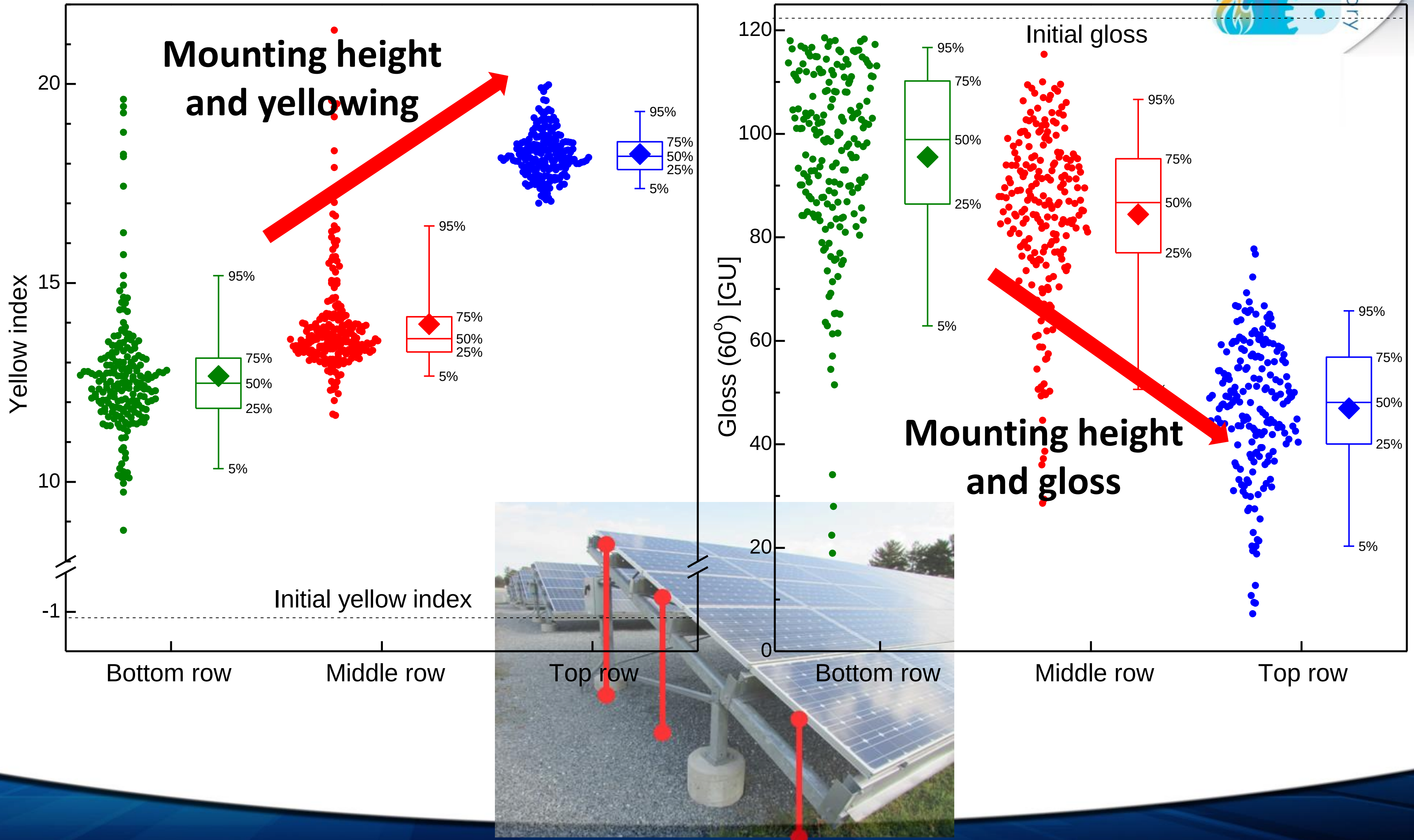
YI and gloss depend on module height

Bottom row → top

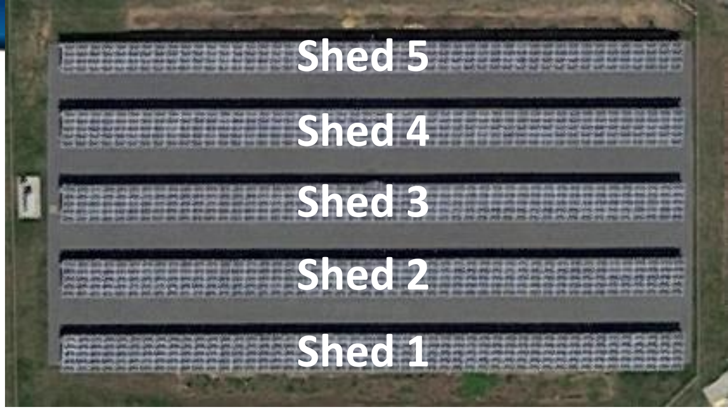
YI: 12.6 → 18.1

Gloss: 91 → 50

A wide tail exists: positive skew for yellowness, negative skew for gloss



Edge effect: columns



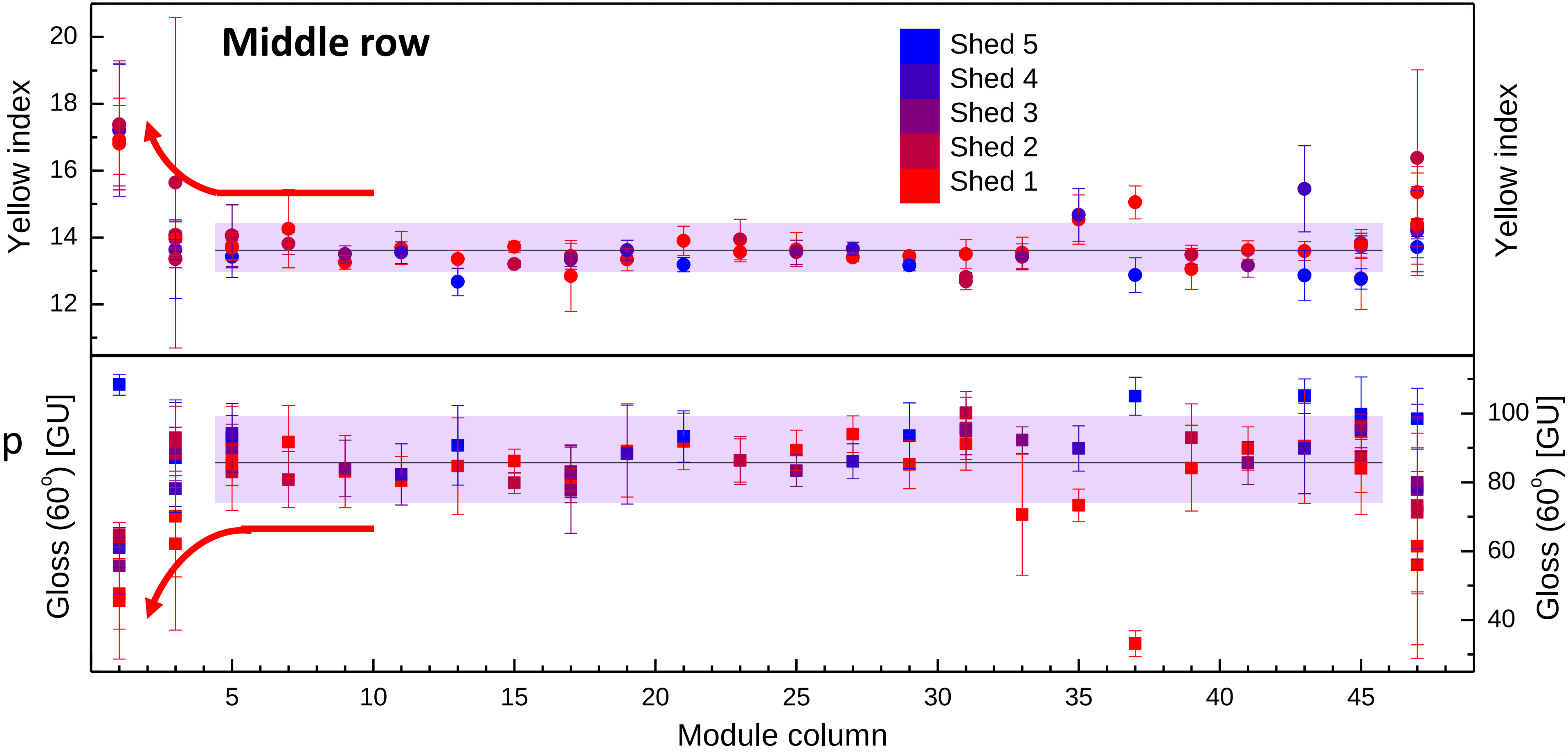
Proximity to array edge (<6 m) also influences YI and gloss

Center col. → edge

YI: 13.6 → 19.6

Gloss: 87 → 28

Effect is weaker in top row



Ground albedo effect: sheds

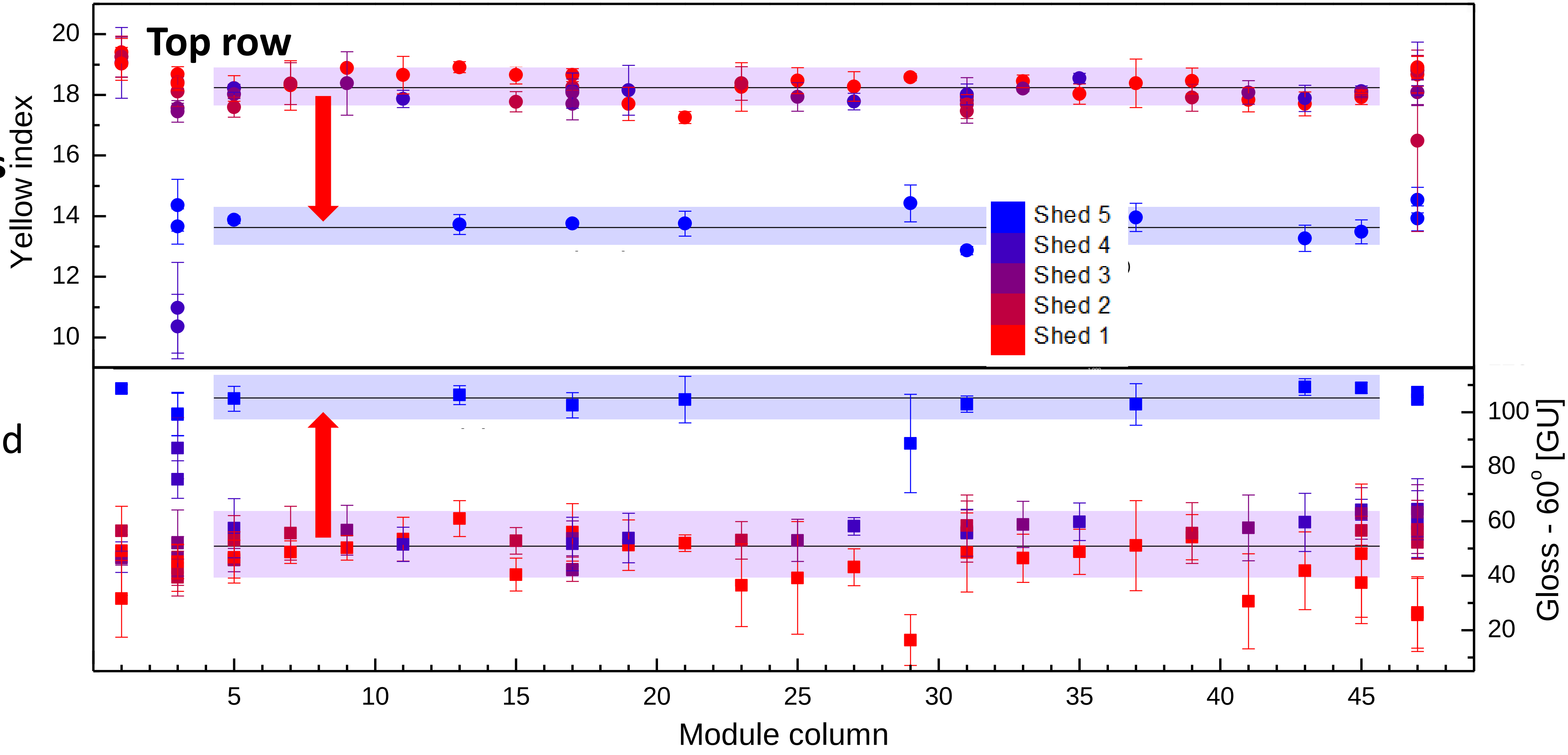
Ground albedo (rock v. grass) influences YI and gloss

Rock shed → grass

YI: 18.1 → 13.7

Gloss: 50 → 103

Also observed in shed 1 bottom row



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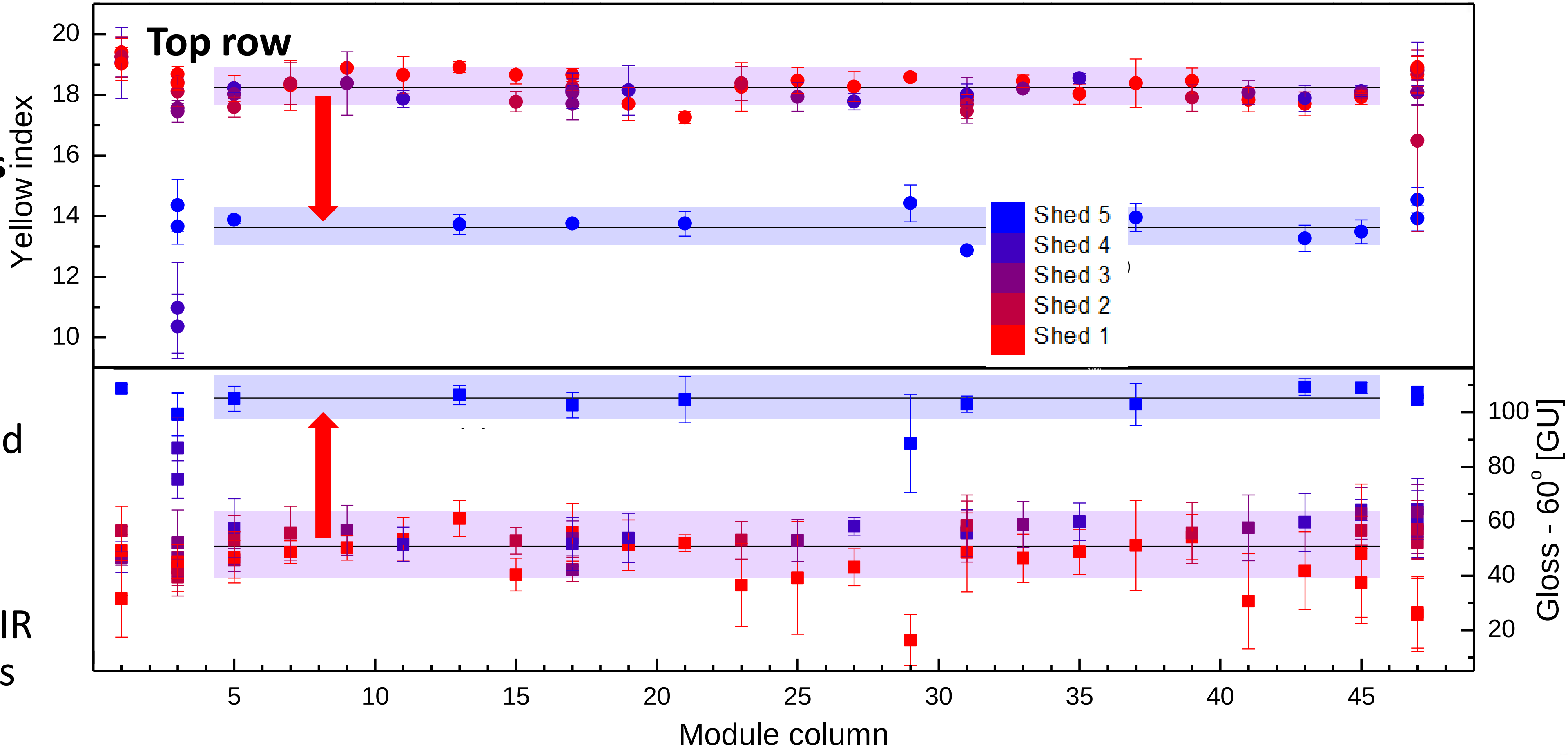


Also observed in shed 1 bottom row

Oxidation peak in FTIR follows similar trends for the height, edge, and albedo effects

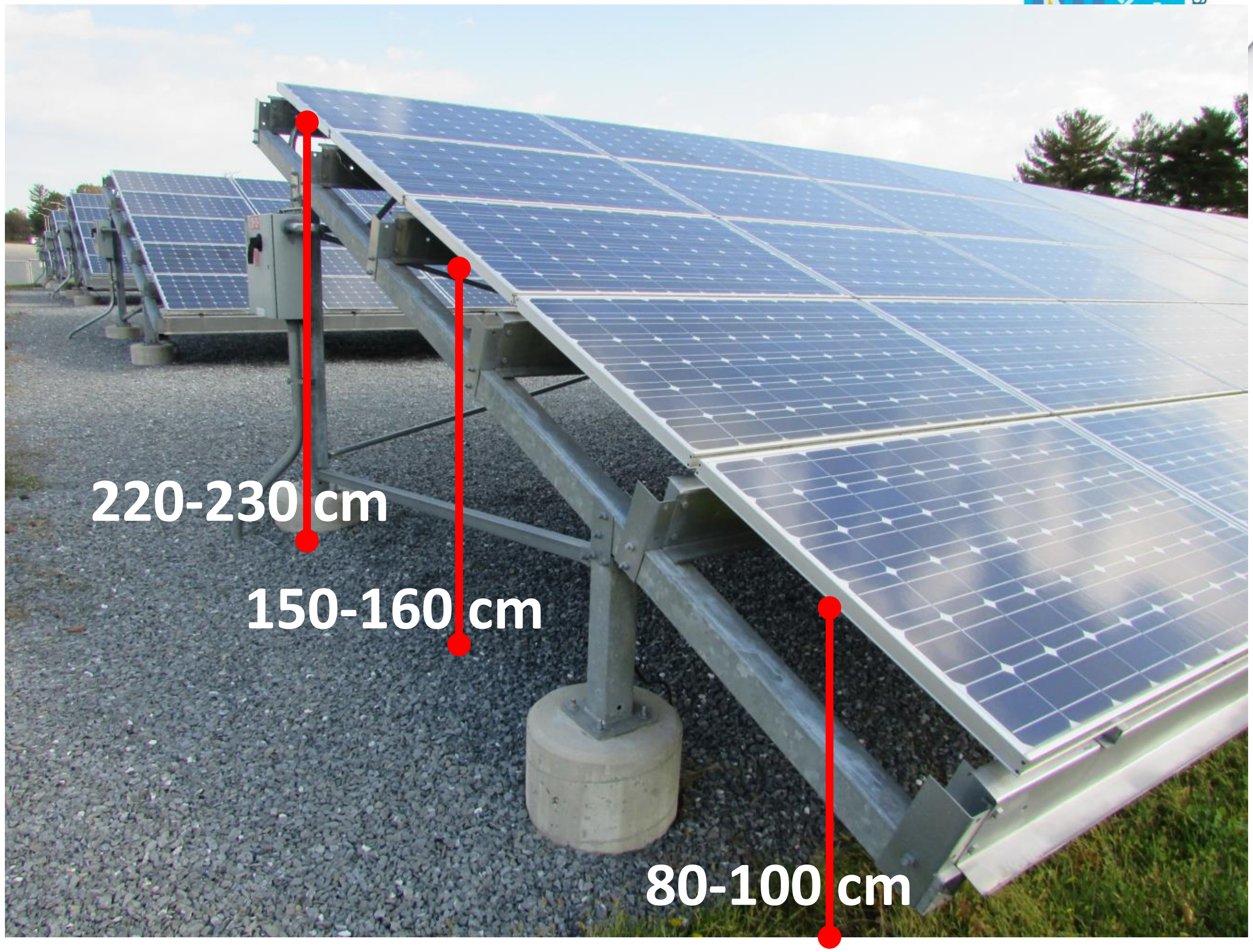
Exposure conditions

Module position clearly influences backsheet degradation, why?

Differential exposure conditions of

- Irradiance
- Temperature
- Humidity
- Wind, precipitation, etc.

Structural and environmental factors are at play



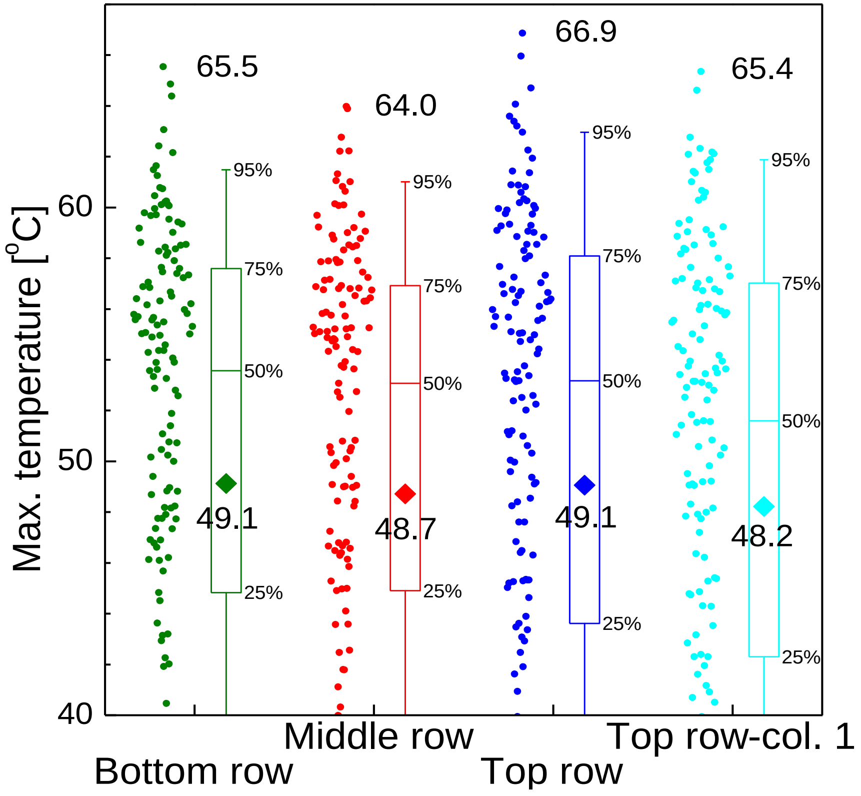
Backside temperature

No significant differences in average, max., or min. temperatures and module row throughout the year

- Median summer time max. mid 50's °C
- Edge module slightly cooler (1-2 °C)
- Similar temperature profiles throughout day

- **Not likely to have caused the broad range of properties observed in the array**

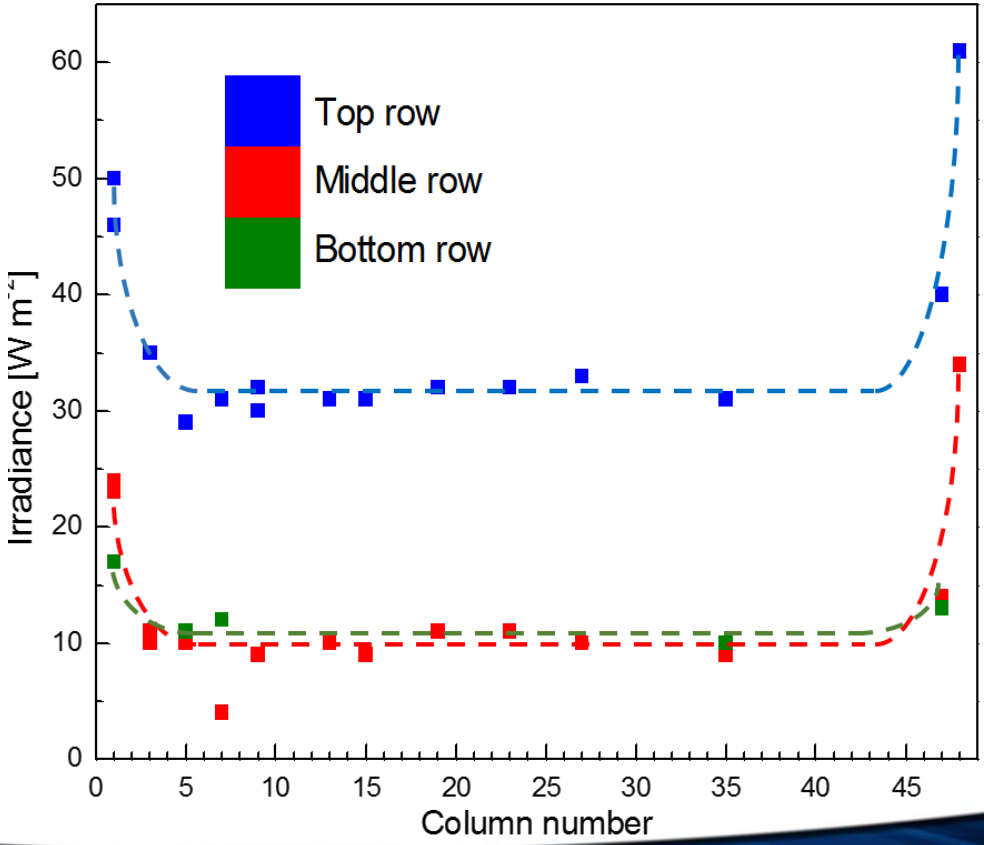
Daily max temps. May-August 2016



Backside irradiance

Total and spectral measurements in April 2017 showed significant differences depending on module position

Backside irradiance noon 28 April 2017

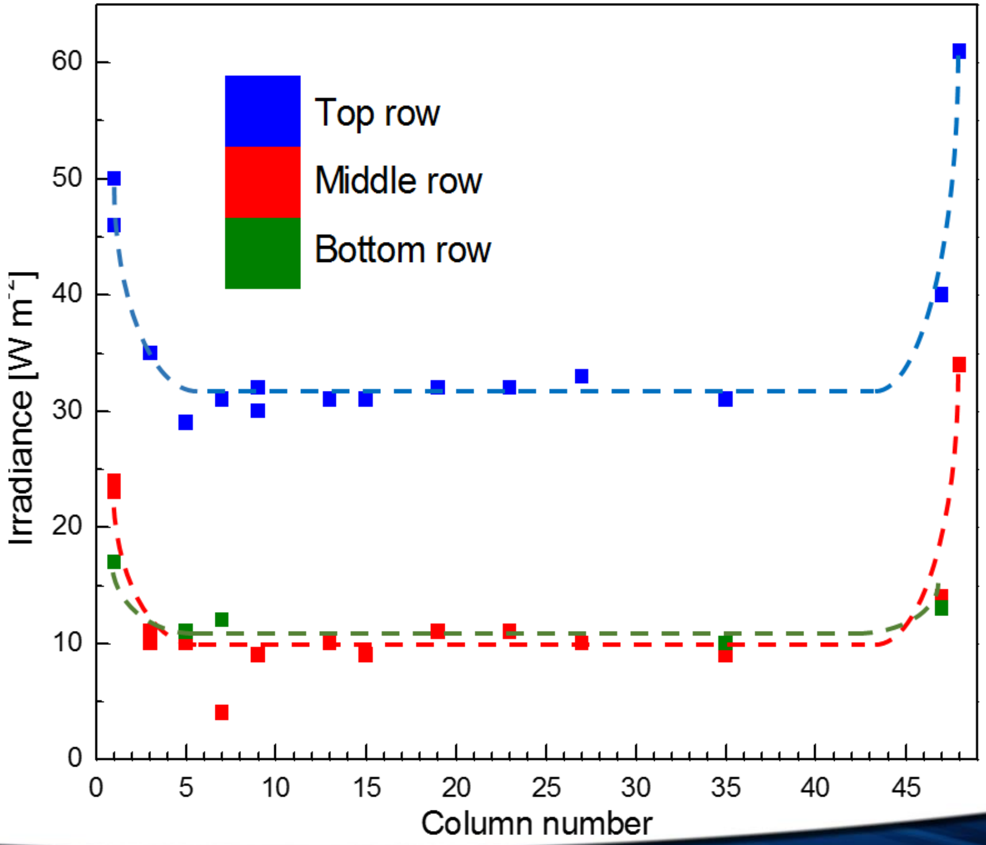


Backside irradiance

Total and spectral measurements in April 2017 showed significant differences depending on module position, due to two factors:

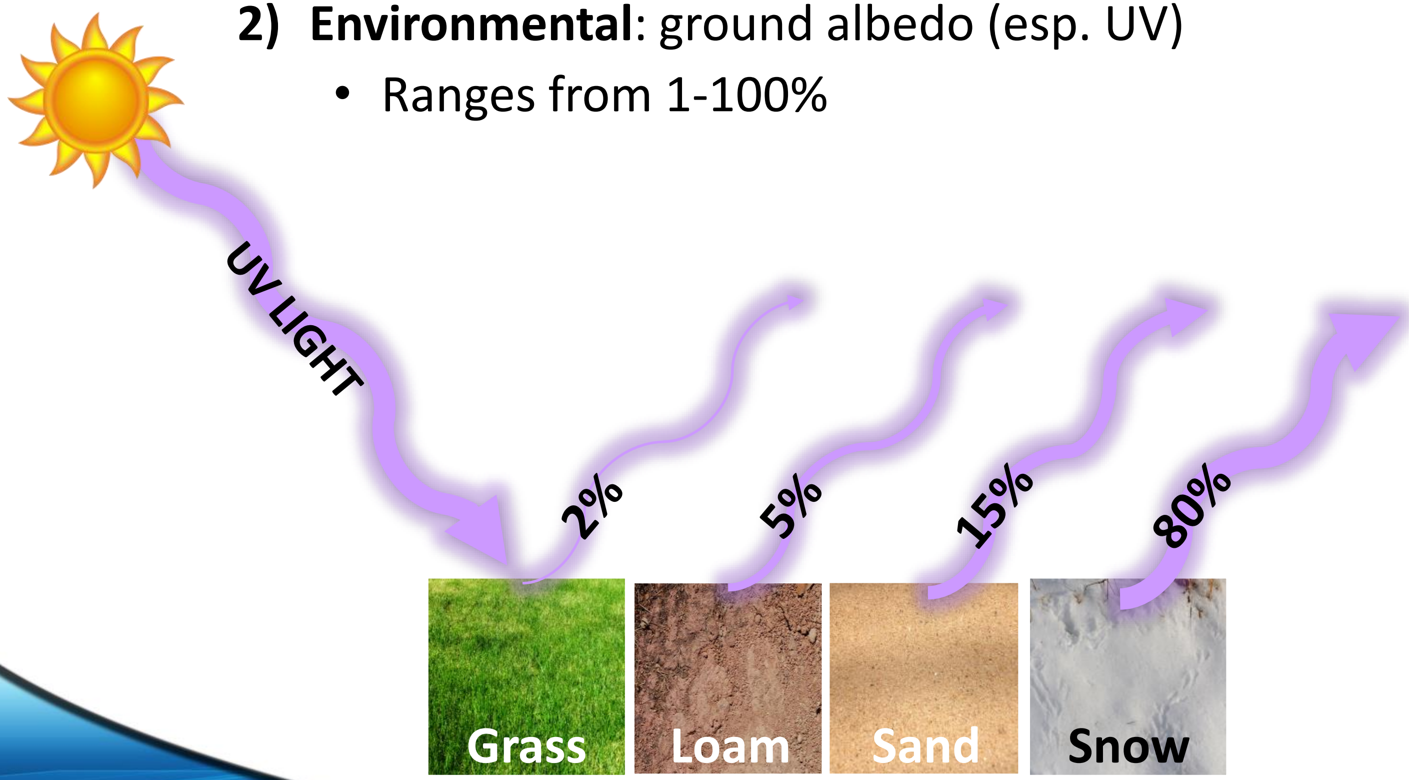
1) **Structural**: light blocking structures
2) **Environmental**: ground albedo

Backside irradiance noon 28 April 2017

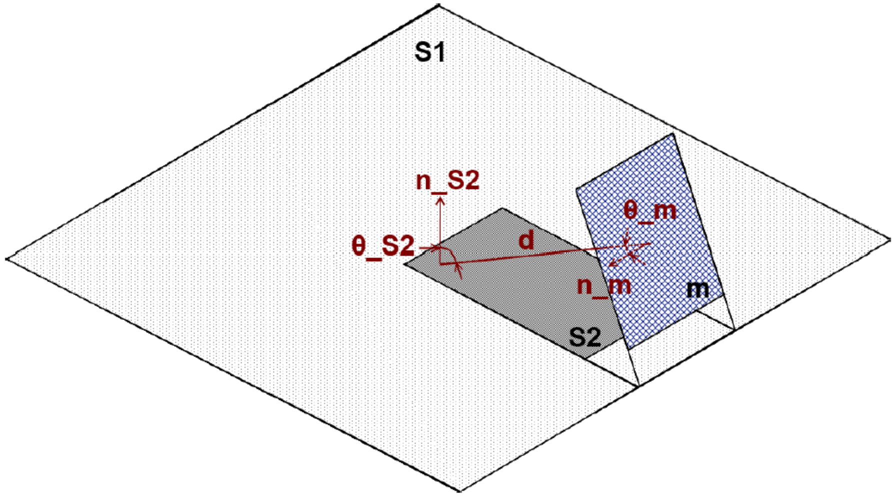


Backside irradiance

1) **Structural**: light blocking structures
   - At solar noon, up to 80% of the ground “seen” by backside of a stand alone module is shaded, and potentially even more for an array of modules
2) **Environmental**: ground albedo (esp. UV)
   - Ranges from 1-100%



Backside view factor calculation



Dupeyrat P, et al. Investigations on albedo dependcy of bifacial PV yield, 29th EUPVSEC, **2014**

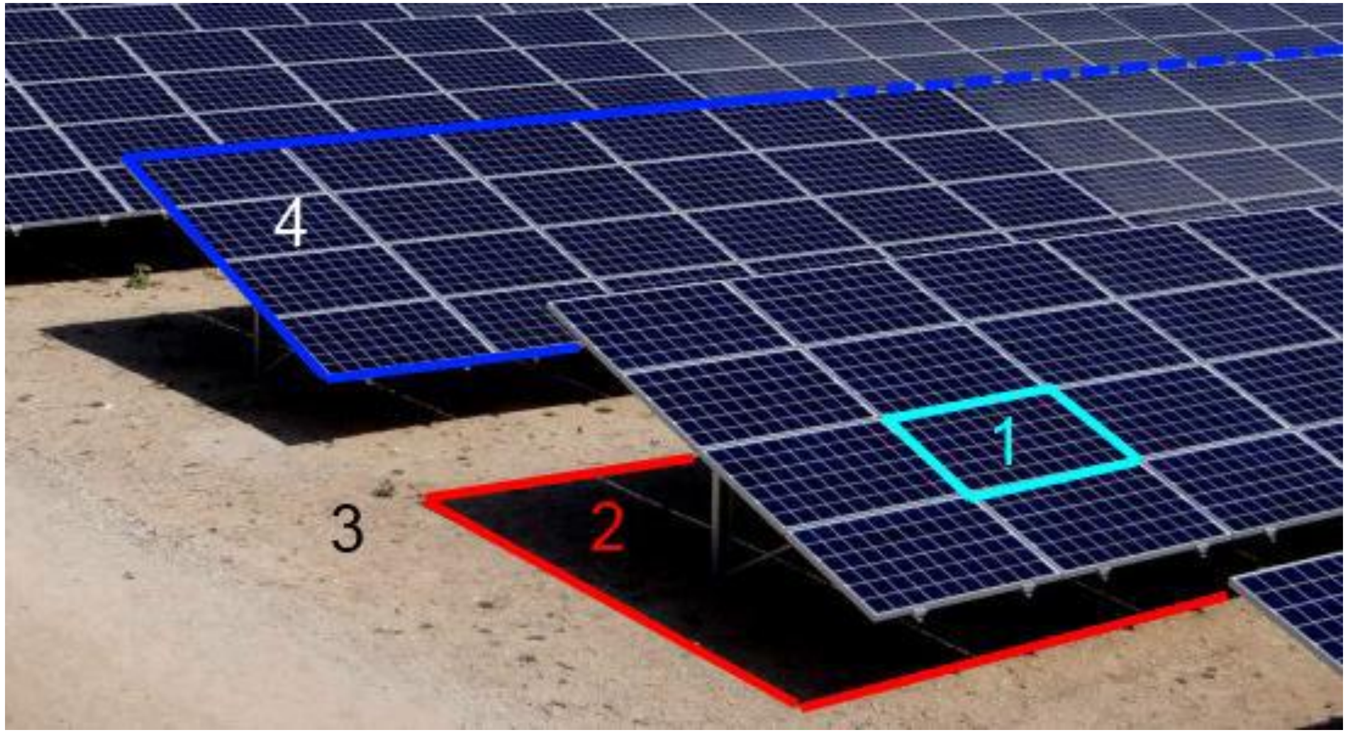
Irradiance modelling: view factor

For the backside of a given **module (1)** there is a finite amount of albedo light received from:

- **shaded ground (2)**
- **illuminated ground (3)**
- **neighboring structures (4)**

This will change depending on:

- Module position
- Ground albedo
- Time of day and year
- Weather



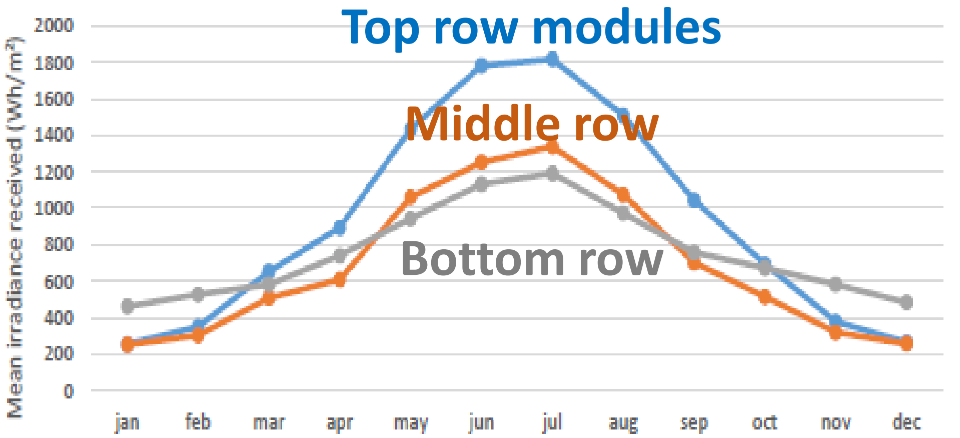
Chiodetti M, et al. Bifacial PV plants: performance model development and optimization of their configuration, KTH Masters thesis **2015**

Irradiance modelling: view factor

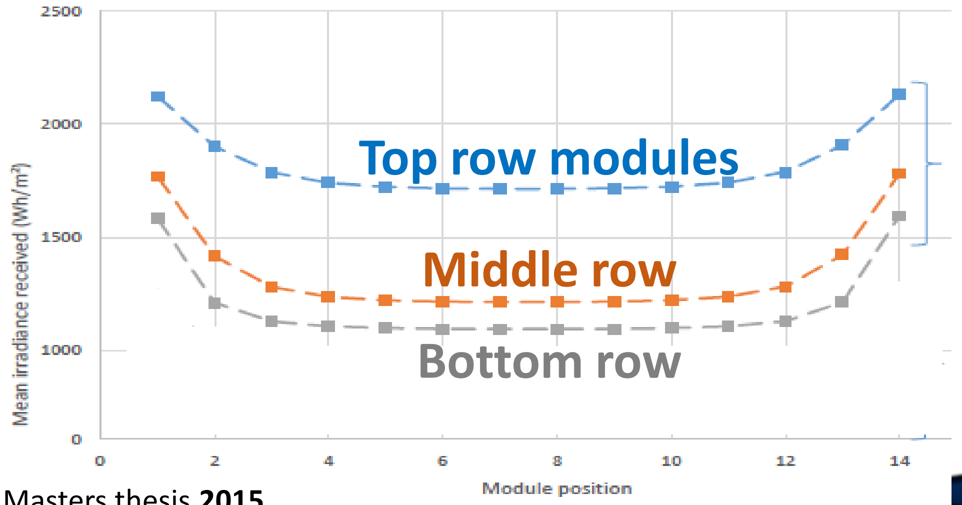
Irradiance may be higher for the lower modules during winter

An edge effect is expected

Irradiance and time of year (view factor)



Irradiance and module column



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Lindsay A, et al. Enhancing bifacial PV modelling with ray-tracing, 6th PV PMC Workshop, **2016**

Irradiance modelling: view factor and ray tracing

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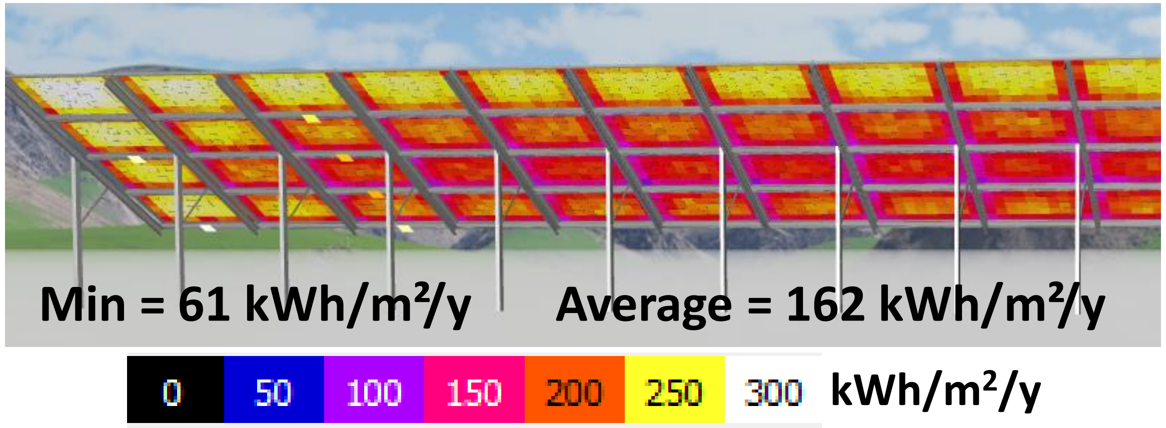
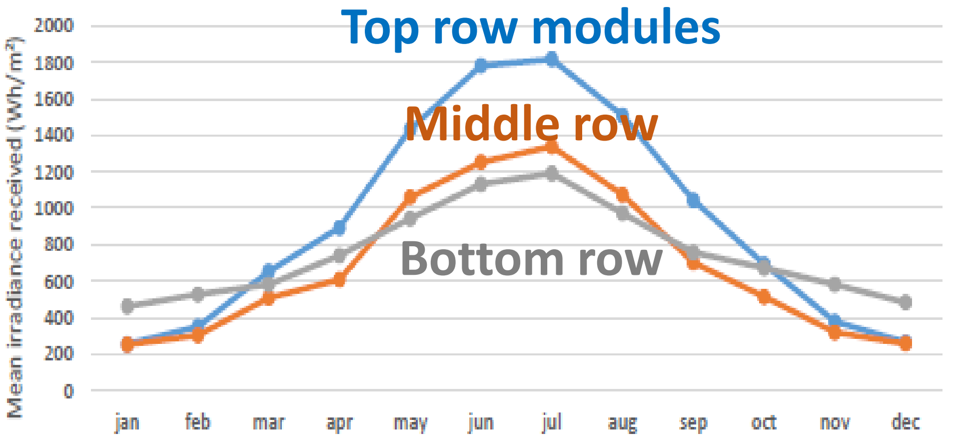
Annual backside irradiance (ray trace)



Irradiance and time of year (view factor)



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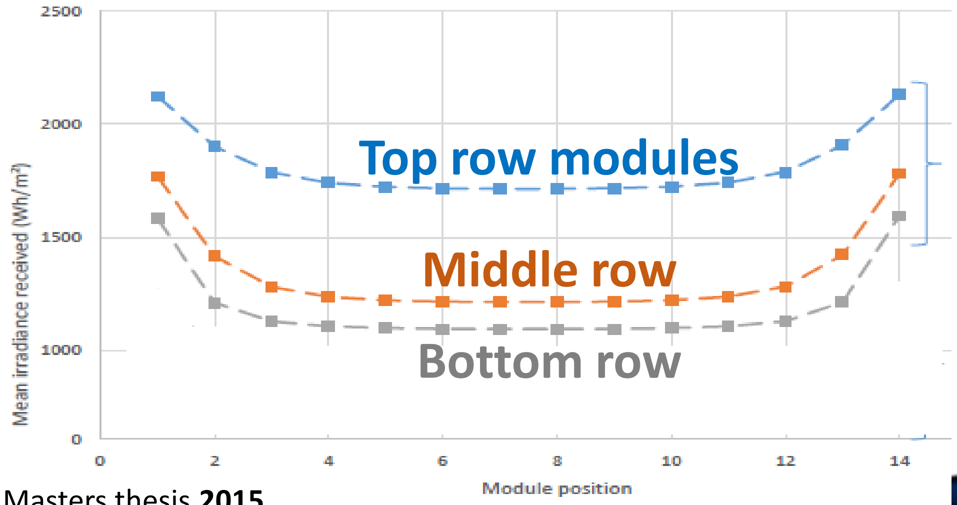

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Degradation, safety

Safety: to date, no modules have been removed due to backsheet degradation, though the burn-throughs may be a concern

Degradation, safety, and performance

Safety: to date, no modules have been removed due to backsheet degradation, though the burn-throughs may be a concern

Performance: 96 (out of 1152) modules have I-V tracers

First comparisons of output (power) and module position do not show a significant correlation after 4 years in the field

Too soon? Backsheet degradation is cumulative, and effects may become more apparent at mid- to end-of-life

Summary

- Structural and environmental factors significantly influence backside exposure conditions, esp. to light:
  - Height effect: top row modules experience more weathering
  - Edge effect: columns within ~6 m from edge undergo greater weathering
  - Ground albedo effect: high UV albedo surfaces accelerate degradation

Summary

- Structural and environmental factors significantly influence backside exposure conditions, esp. to light:
  - Height effect: top row modules experience more weathering
  - Edge effect: columns within ~6 m from edge undergo greater weathering
  - Ground albedo effect: high UV albedo surfaces accelerate degradation

- UV is more damaging to non-fluoropolymer backsheets, so:

- Can array design can be improved to limit UV exposure

- What level is realistic for material testing?

Same module, other sites

Exposure for 3 summer months in Albuquerque, NM, field-mounted

Whitest region:
YI = -1.1
Gloss (60°) = 122 GU

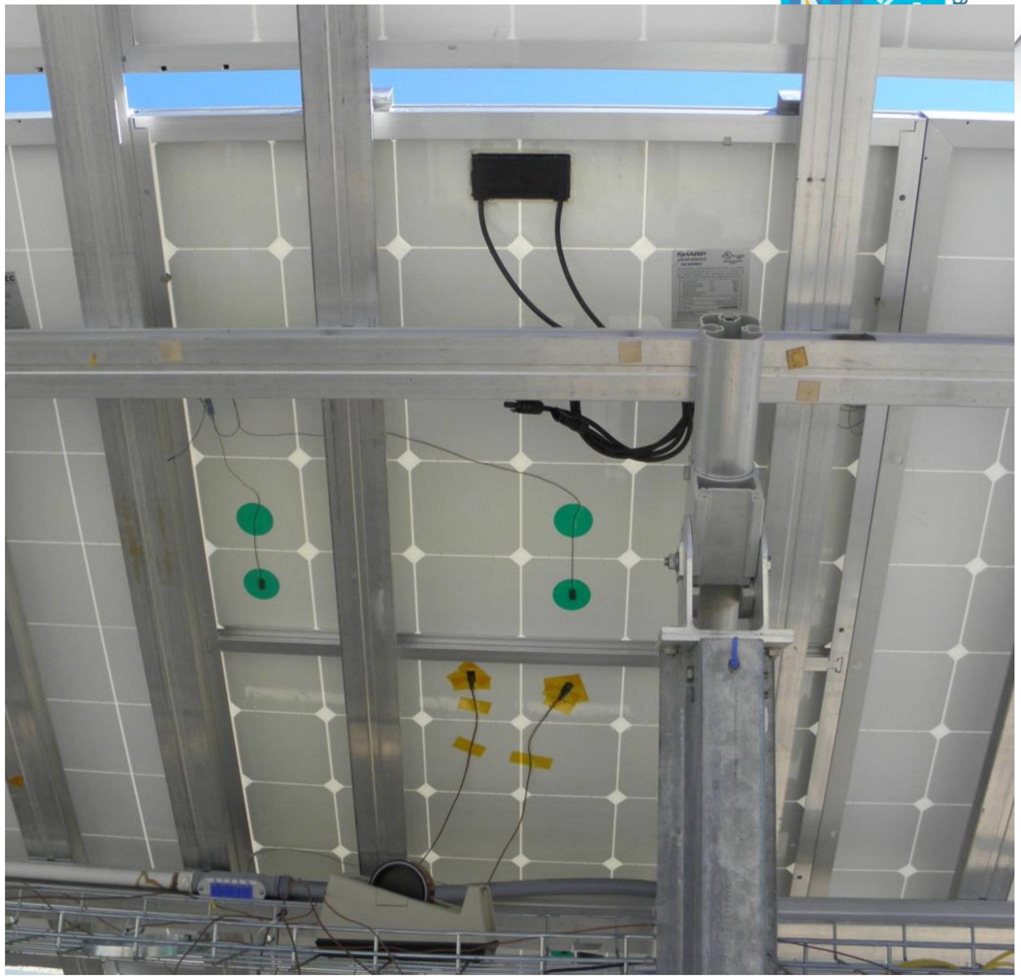
Non-uniform yellowing and gloss-loss (typ. >100 GU)

Yellowing as advanced as NIST field array modules:

- Sandy vs rocky ground cover (higher UV albedo)
- Higher ambient temp. and global irradiance

Yellow index

12.6	J-box **9.9**	**12.7**
8.5	**8.6**	**11.4**
13.8	**14.0**	**16.9**



Same module, other sites

Exposure for 4.5 years in Gaithersburg, MD, roof-mounted

Also exhibits non-uniform yellowing and gloss-loss (typ. >110 GU)

Yellowing is less advanced than NIST field array modules:

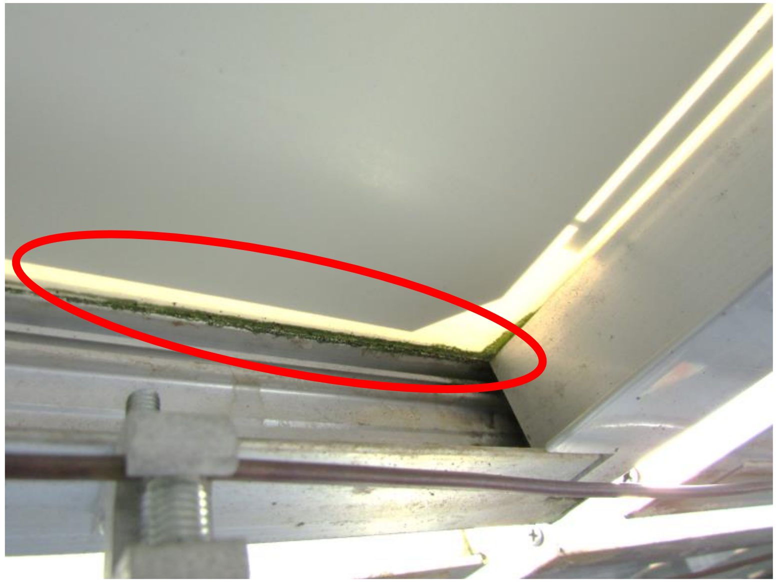
- Much less light hitting the back
- Higher summer time max temperatures (high 60’s vs low 50’s)

Yellow index

Whitest region:
YI = -0.2
Gloss (60°) = 131 GU

Visual inspection

3) Miscellaneous:
   - Junction boxes appear okay, some have dirt buildup
   - Organic growth on frame (bottom) and backsheet near frame
   - Birds, wasps…
   - Dirt, scratches, tape, epoxy, etc…



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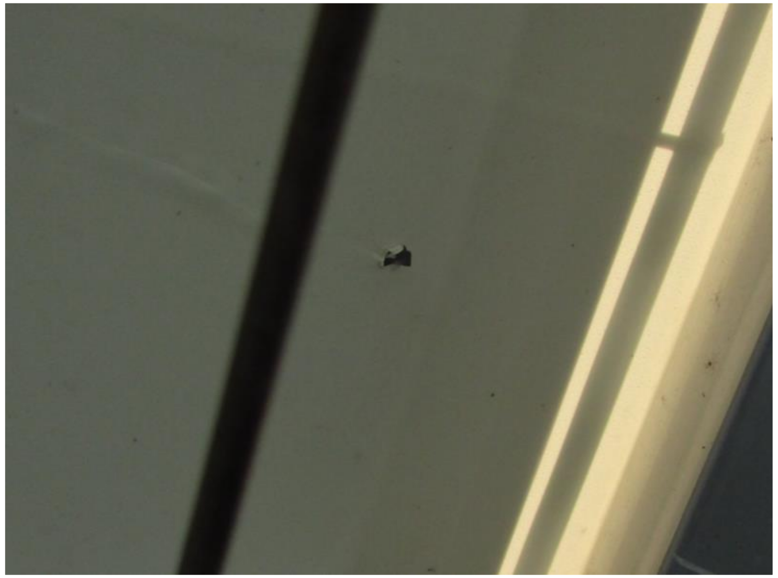
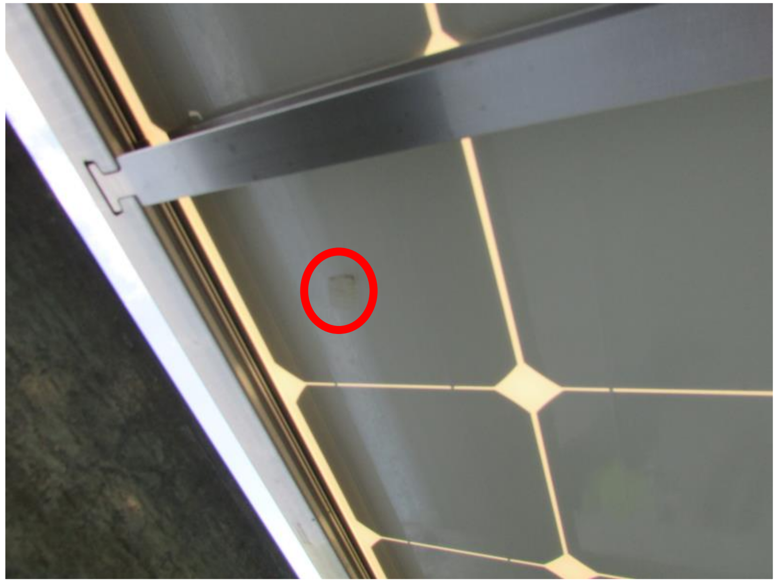
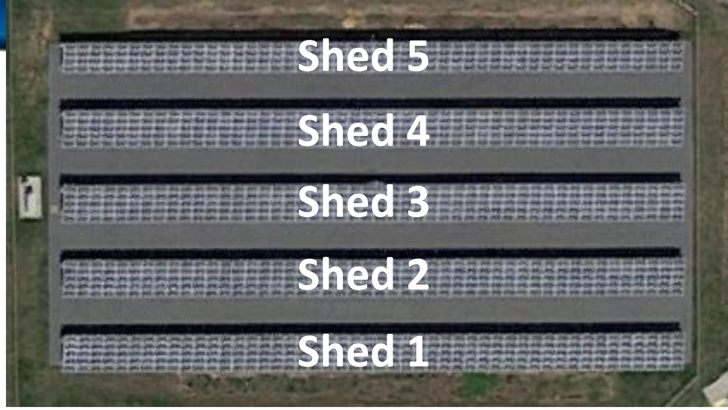
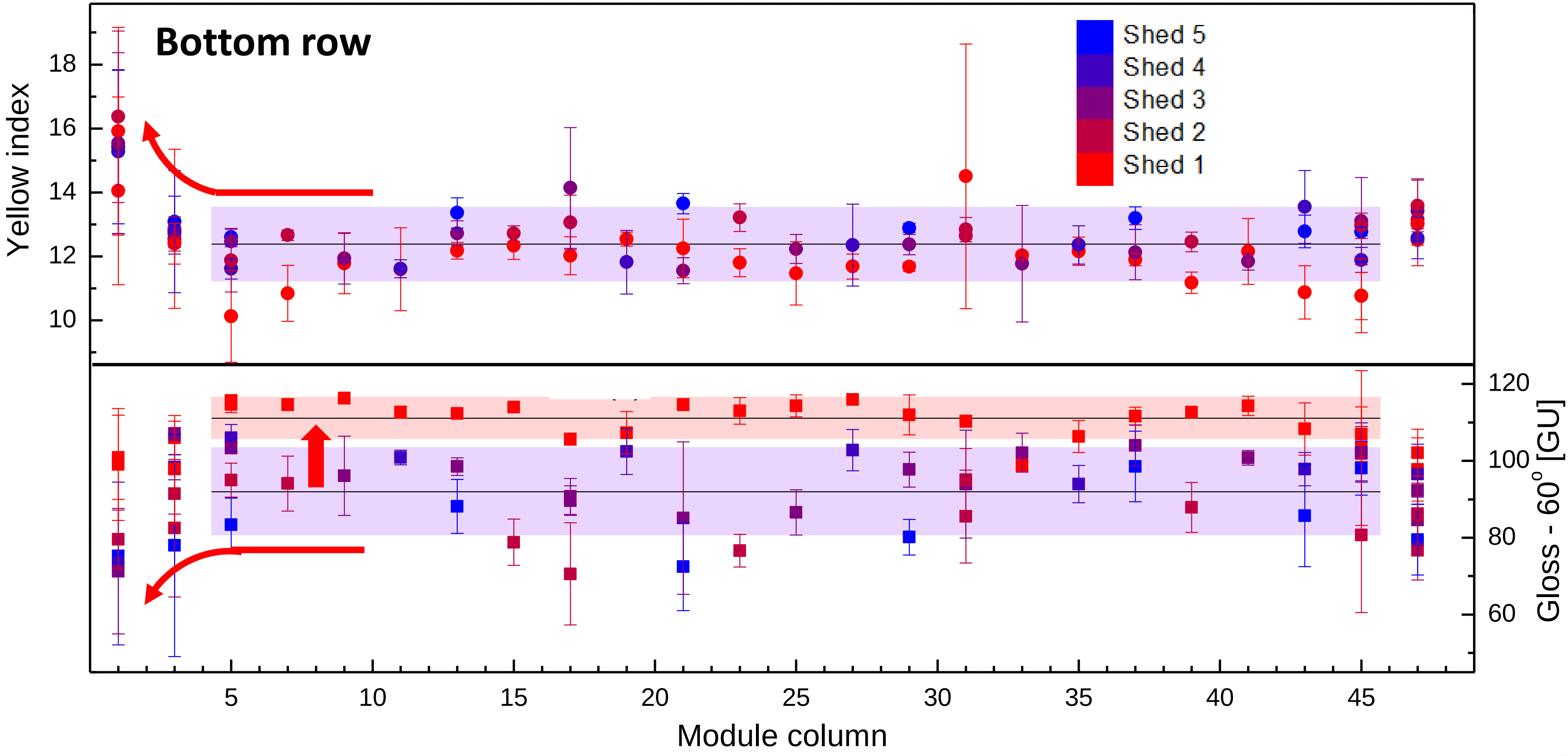
   - Dirt, scratches, tape, epoxy, etc…





Edge effect: columns



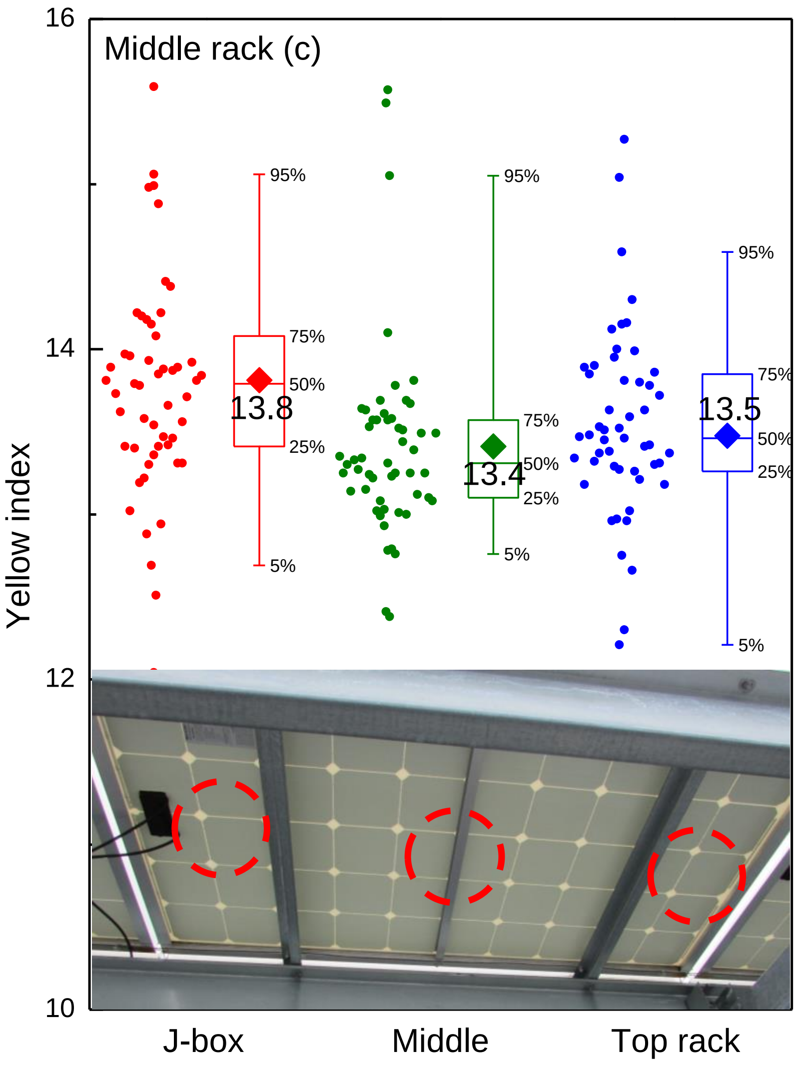


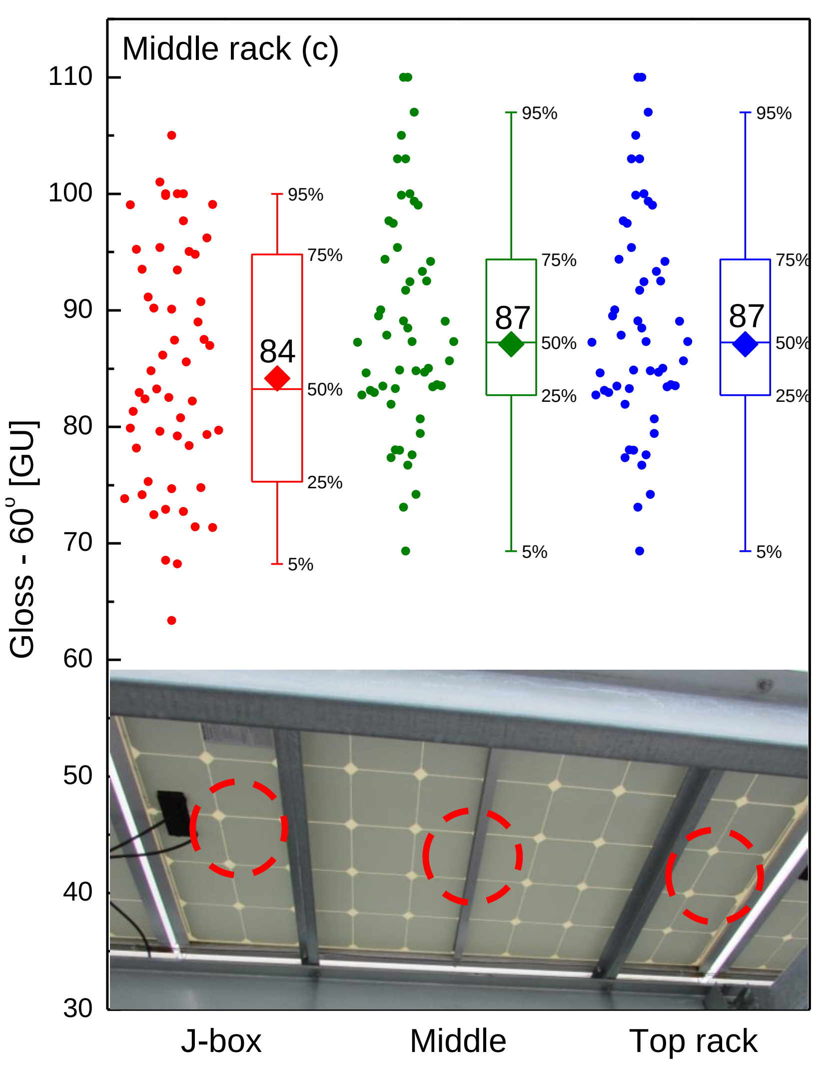
Intramodule homogeneity

Junction box region often contains by-pass diodes, which can lead to locally higher temperatures

Yellow index: j-box region higher than middle or opposite end (p<0.005)

Gloss: high standard deviation, statistically insignificant difference within modules





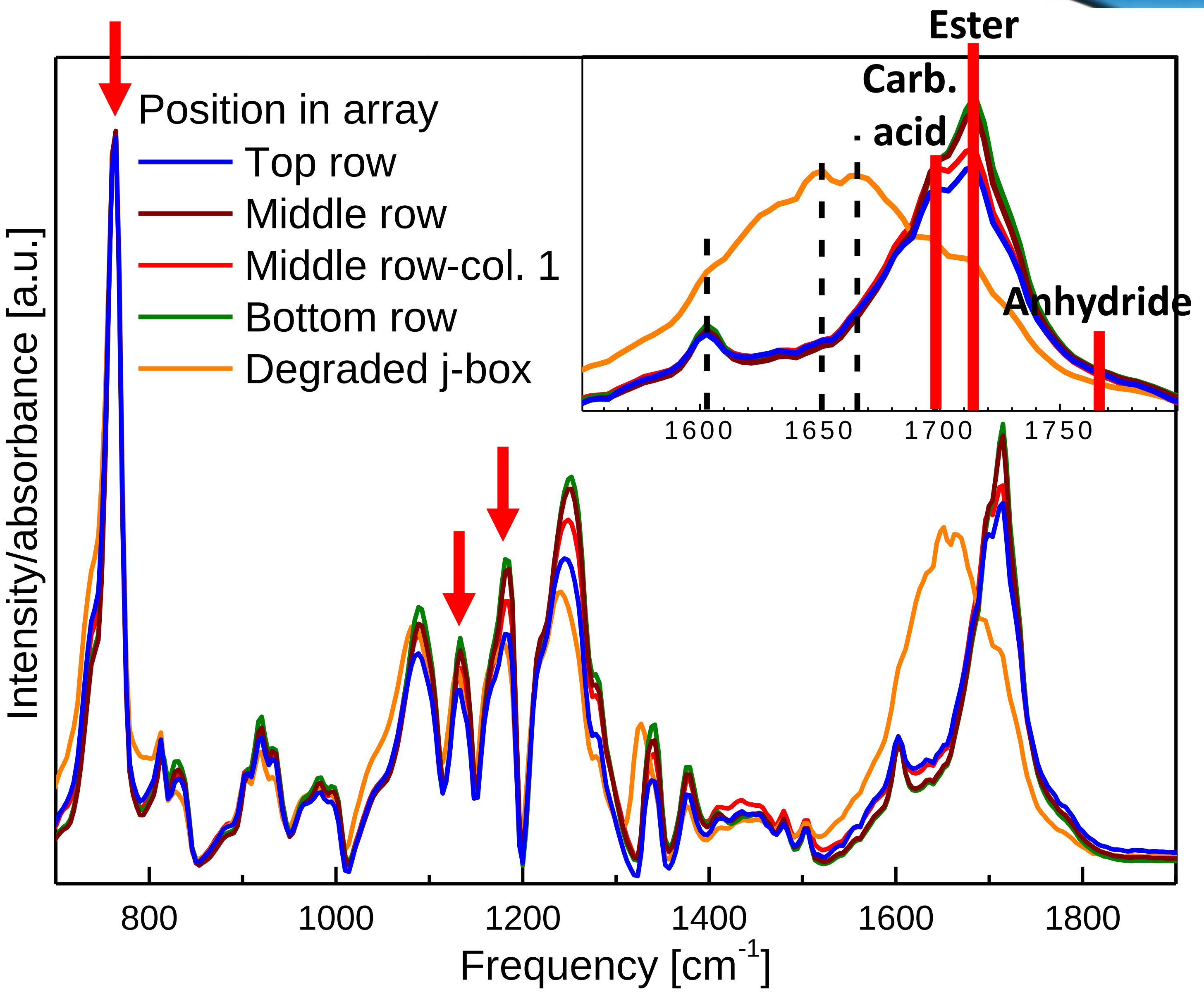
Chemical changes

PEN-based backsheet:

- **764 cm^{-1}**: Aromatic C-H out-of-plane bend (730 cm^{-1} for PET)
- **1133, 1182 cm^{-1}**: naphthalene ring vibration

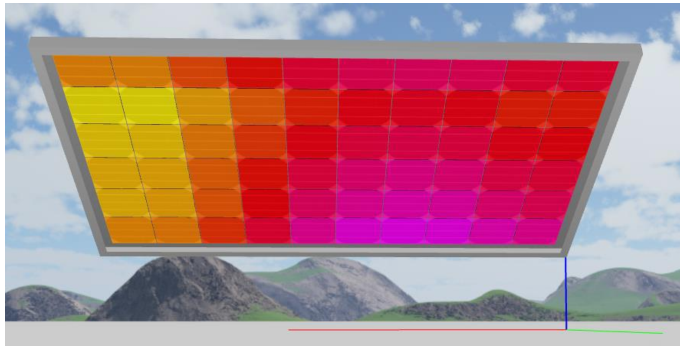
Formation of carboxylic acid and anhydrides

Changes in carbonyl (oxidation) peak consistent with those observed in YI and gloss

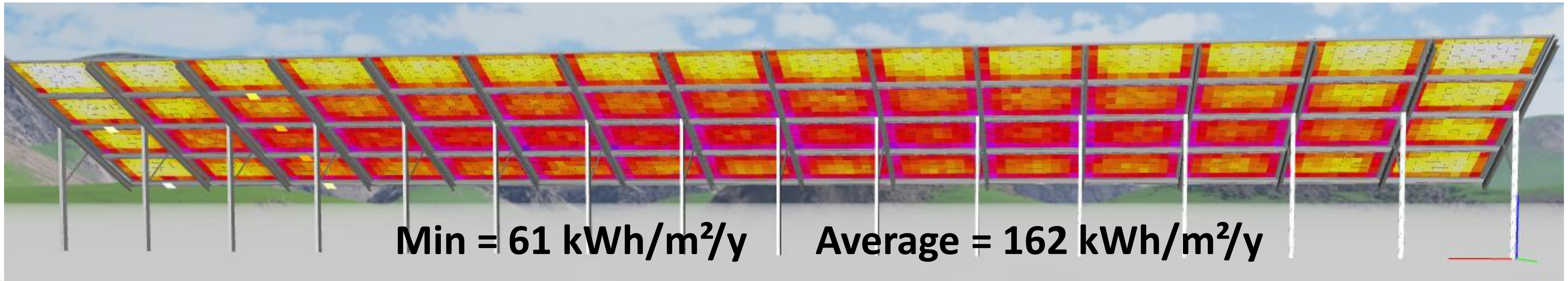


Irradiance modelling: ray tracing

Modelled annual backside irradiance (detail)



Modelled annual backside irradiance



0	50	100	150	200	250	300	kWh/m²/y

Lindsay A, et al. Enhancing bifacial PV modelling with ray-tracing, 6th PV PMC Workshop, **2016**