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

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

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

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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

- Superstrate
- Encapsulant
- Cell and metallization
- Encapsulant
- Backsheet
PV module construction: backsheets

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- Core layer: electrical insulation
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Backsheets approx. $2 to $7/m², 3% to 5% of total module cost:
- More expensive: **fluoropolymer**-based: PVF, PVDF, ETFE, THV, ...
- Less expensive: **non-fluoropolymer**-based: PET, PEN, PP, PA, ...
Fluoropolymer

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

PVF – 28 years
Discoloration due to edge sealant
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.

- PET – 18 years
  Delamination, yellowing
- PA – 4 years
  Hairline cracks, yellowing
- PA – 5 years
  Large cracks, chalking, yellowing
- PVF – 28 years
  Discoloration due to edge sealant
Fluoropolymer vs. non-fluoropolymer

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


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

1) Burn-throughs
   • Observed in ~3% of modules, less common on bottom row
   • 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
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

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
Backside irradiance

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

![Graph showing backside irradiance for different rows at noon on 28 April 2017.](image)
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
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%

*Dupeyrat P, et al. Investigations on albedo dependency 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

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

Irradiance modelling: view factor and ray tracing

Irradiance may be higher for the lower modules during winter

An edge effect is expected

Annual backside irradiance (ray trace)

Min = 61 kWh/m²/y  Average = 162 kWh/m²/y
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?
Exposure for 3 summer months in Albuquerque, NM, field-mounted

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

<table>
<thead>
<tr>
<th>Yellow index</th>
<th>J-box</th>
<th>Whitest region:</th>
<th>Gloss (60°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.6</td>
<td>9.9</td>
<td>YI = -1.1</td>
<td>122 GU</td>
</tr>
<tr>
<td>8.5</td>
<td>8.6</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>13.8</td>
<td>14.0</td>
<td>16.9</td>
<td></td>
</tr>
</tbody>
</table>

Same module, other sites
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

<table>
<thead>
<tr>
<th>7.8</th>
<th>7.3</th>
</tr>
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<tbody>
<tr>
<td>7.2</td>
<td></td>
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<table>
<thead>
<tr>
<th>4.8</th>
<th>5.2</th>
</tr>
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<tbody>
<tr>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>11.2</th>
<th>15.4</th>
<th>7.1</th>
</tr>
</thead>
</table>

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

Visual inspection
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...
Edge effect: columns

**Diagram**

- **Bottom row**
  - Chart showing variations in yellow index across different module columns.
  - Data points for each shed (Shed 1 to Shed 5).

**Shed Locations**

- Shed 1
- Shed 2
- Shed 3
- Shed 4
- Shed 5
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

Min = 61 kWh/m²/y  Average = 162 kWh/m²/y