LID and LeTID Impacts to PV Module Performance and System Economics
DRAFT Analysis
DuraMAT Webinar, December 14, 2020

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\(^{(2)}\) PV Reliability Group

NREL/PR-6A20-78629
1. Introduction, Harrison Dreves and Teresa Barnes (5 minutes)
2. Introduction and Modeling of BO LID and LeTID, Ingrid Repins (15 minutes)
3. Impacts to PV Project Cash Flows and LCOE (Mike, 15 minutes)
4. UV LID Overview and Solutions, David Miller and Peter Hacke (15 minutes)
5. Quantified Value Proposition of Reducing UV LID (Mike, 5 minutes)
6. Conclusions, Next Steps, and Questions (Everyone, 5 minutes)
Common Light Induced Degradation in c-Si Solar Cells

**Light induced degradation (LID)**

**Boron-oxygen (B-O) LID**
- Boron-oxygen activation
- Occurs initial exposure to light and then stabilizes.
- B-doped mono c-Si (made from Czochralski method).
- Degrades the minority carrier lifetime
- Efficiency loss ~1.5-2.5% [1-2].

**Iron-boron (Fe-B) LID**
- Iron-boron pair dissociation.

**Copper-related LID**
- Formation of copper precipitates [1,3].

**Light and elevated temperature induced degradation (LeTID)**
- Light and elevated temperature [4]
- Active >65°C
- Occurs after hundreds of hours of illumination.
- Multi c-Si and PERC cells

**Ultraviolet induced degradation (UV-LID)**
- UV component of sun’s spectrum
- More prevalent with UV-transmitting encapsulants
- Increases interface defects
- Efficiency loss ~5%, with a decrease in Isc [5]

Sources:
1. J. Lindroos, et al., SOLMAT, 147, 2016
4. F. Fertig et al., Energy Procedia, 124, 2017
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5 Quantified Value Proposition of Reducing UV LID (Mike, 5 minutes)

6 Conclusions, Next Steps, and Questions (Everyone, 5 minutes)
Boron-Oxygen Light Induced Degradation (BO LID) and Light and Elevated Temperature Induced Degradation (LeTID)

Is LeTID degradation in PERC cells another degradation crisis worse than PID?

Let’s mitigate LID & LeTID!

 pv magazine 10 YEARS

March 2018

• What do these two types of degradation look like in fielded modules?
• How can we predict their behavior in different climates for use in financial models?
Background Information On BO LID and LeTID

Both effects

• Have been observed in fielded modules (examples below)
• Progress with exposure to light (or current) and temperature
• Are avoidable with processing changes (although costs or trade-offs between properties may be involved)
• Can occur with varying severity depending on processing choices.

Ishii, *PIP*, 2017

LeTID can be described similar picture, but it is caused by a different defect, and progression between states is slower for same conditions.

Worst-case observed power degradation ~10% relative

For modules with the effect, 2 to 3% is more realistic
How Do I know if LID or LeTID is 10% or 2% or 0% in a Given Product?

Measure it!

- For BO LID, compare performance before and after a low-temperature light soak (as in IEC 61215 MQT19.1)
- For LeTID, prolonged exposure to heat and applied current (IEC TS 63342 is under development, and several commercial test labs currently perform similar tests)
How Can We Calculate A Fielded Degradation Profile for BO LID or LeTID?

**Step One:** Use kinetic parameters (activation energies and attempt frequencies) from literature and published data to describe how defects transition between states (A,B,C) with time, temperature, and current.

\[
\begin{align*}
\frac{\partial N_A}{\partial t} &= k_{BA} \cdot N_B - k_{AB} \cdot N_A \\
\frac{\partial N_B}{\partial t} &= k_{AB} \cdot N_A + k_{CB} \cdot N_C - (k_{BA} + k_{BC}) \cdot N_B \\
\frac{\partial N_C}{\partial t} &= k_{BC} \cdot N_B - k_{CB} \cdot N_C \\
k_{ij} &= \nu_{ij} \cdot e\left(\frac{-E_{ij}}{k_B T}\right)
\end{align*}
\]


<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Transition</th>
<th>( \nu ) (s(^{-1}))</th>
<th>Inj. Level (suns)</th>
<th>( E_A ) (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO LID</td>
<td>A to B</td>
<td>( 4 \cdot 10^3 )</td>
<td>1</td>
<td>0.475</td>
</tr>
<tr>
<td></td>
<td>B to A</td>
<td>( 1 \cdot 10^{13} )</td>
<td>0</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>B to C</td>
<td>( 1.25 \cdot 10^0 )</td>
<td>2.7</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>C to B</td>
<td>( 5.32 \cdot 10^5 )</td>
<td>0</td>
<td>0.87</td>
</tr>
<tr>
<td>LeTID</td>
<td>A to B</td>
<td>( 6.61 \cdot 10^0 )</td>
<td>1</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>B to C</td>
<td>( 1.13 \cdot 10^7 )</td>
<td>1</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Step Two: Use meteorological data as the inputs for irradiance (current), temperature (King model), and time.
Example Result – Simulation of LeTID in Seattle or Bakersfield

A – Initial State
B – Degraded State
C – Regenerated State

Power (Fraction of Initial)

Years Deployed

Seattle
Bakersfield
Example Calculation – LeTID in Seattle or Bakersfield

- Effect happens more slowly for climate where less light and heat are available
- Seasonal effects

[Graph showing the effect of years deployed on power (fraction of initial) for Seattle and Bakersfield.]
Example Calculation – LeTID in Seattle or Bakersfield

The only free parameter is the amount of degradation

- Varies between products
- Measurable
- Polynomial fit not required
Does This Rate Prediction Work? Verify against Outdoor BO LID Data

Use METPV meteorologic database for Japan, at location from published report.
Does This Rate Prediction Work? Verify against Outdoor LeTID Data

Use JRC meteorologic database for locations in published report (Thalheim and Cyprus)

11% maximum LeTID based on other papers from the same group.
Results are Estimates Only

- Year-to-year climate variations
- Loading conditions
- Variations in amount of degradation between modules of same product
- Kinetic parameters are extrapolated from higher T laboratory experiments
- Ignoring performance changes in as module degrades, or between different modules.
Long-Term Degradation Rate Predictions - Seattle

Even in coolest climate, BO LID is very fast

**BO LID transitions are much faster than LeTID transitions**
Long-Term Degradation Rate Predictions – Multiple Climates

BO LID is very fast for all climates. Probably won’t see it in system data. Might see it in an initial indoor flash.

What are the financial implications of location and degradation type?....
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# NREL’s Solar + Storage Technoeconomic Analysis Portfolio

## Component Manufacturing Costs ($)

<table>
<thead>
<tr>
<th>Modules</th>
<th>Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline Silicon</td>
<td>Batteries</td>
</tr>
<tr>
<td>Thin-Film</td>
<td>Solar Fuels</td>
</tr>
</tbody>
</table>

## System Capital Costs ($)

<table>
<thead>
<tr>
<th>PV Systems</th>
<th>PV Plus Storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIT or PPA Revenues</td>
<td>Residual Value (+/-)</td>
</tr>
</tbody>
</table>

### Cash Inflows
- Any applicable incentives (e.g., ITC)
- FIT or PPA Revenues

### Cash Outflows
- Any preventative and routine O&M, including asset management and module cleaning
- Any corrective O&M including module, battery and inverter repairs and replacements and unplanned weather-related events
- Upfront Capital Cost for System Installation

### Years
- Residual Value (+/-)

Illustration by Al Hicks, NREL
Photo from iStock, 1033236964
Photo by Dennis Schroeder, NREL 56318
Photo from iStock, 932140864
Photo from iStock, 938053682
Photo from iStock, 1128871378
Project Pro Forma Discounted Cash Flow Analysis

• Levelized Cost of Electricity (LCOE), or “Minimum PPA Price to Achieve Target IRR”
• Internal Rate of Return (IRR) when the PPA or FIT rate structure is given
• Levelized Cost of Solar + Storage (LCOSS)

FIT or PPA Revenues:
\[
\text{Energy Yield (kWh}_{\text{AC}}/\text{kW}_{\text{DC}}) \times \text{FIT or PPA Price ($/kWh}_{\text{AC}})
\]

Any applicable incentives (e.g., ITC)

Any preventative and routine O&M, including asset management and module cleaning

Any corrective O&M including module, battery and inverter repairs and replacements and unplanned weather-related events

Residual Value (+/-)

Upfront Capital Cost for System Installation
• Module
• Inverter
• Electrical and Structural BOS
• Soft Costs (Permitting, Project Acquisition, etc.)
Efficiency versus Energy Yield

Efficiency = Power Rating (Watts at Standard Testing Conditions (STC))

(1) The initial indoor power rating determined by flash testing during module assembly (and by independent testing labs) determines the DC rating with zero losses.

(2) Module warranty terms are assuming DC based efficiency measurements

(3) There are also system-level DC power losses including module mismatch and wiring

Energy Yield: $\text{kWh}_{(AC)}/\text{kW}_{(DC)}$

(1) A system with a DC:AC ratio of 1.0 running continuously under standard test conditions and without any DC or AC power losses would generate 8,760 $\text{kWh}_{(AC)}/\text{kW}_{(DC)}$ energy yield after 24 hours a day for 365 days

(2) $\text{kWh}_{(AC)}$ varies across climates depending upon technology- and engineering-dependent variables (next slide)

(3) Properly translating time-based changes in DC efficiency to changes in energy yield entails $\text{kWh}_{(AC)}$ modeling. It is **not** a 1:1 or linear relationship, principally because of the inverter.
How NREL’s System Advisor Model (SAM) Calculates Energy Yield

**Inputs on the DC Side**

Variables
1. Module warranty terms
2. Changes in Watts-DC at STC over time

**SAM Energy Yield Models**

Mathematical Expressions:
1. Perez model
2. Surface, self-shading and module models
3. Sandia inverter model
4. Eleven more models

Location-Dependent Variables:
1. Solar resource
2. Weather
3. Technology- and Engineering-Dependent Variables
   1. Module I-V curves at varying light intensities
   2. Module temperature coefficient
   3. Module bifaciality (optional)
   4. Fixed-tilt or tracking
   5. Inverter configuration
   6. Coupling with storage (optional)

**Inputs**

(1) Nameplate DC Losses
(2) Degradation profiles

For additional details regarding NREL’s SAM Photovoltaic Performance Model, please see: P Gilman, A Dobos, N DiOrino, J Freeman, S Janzou, and D Ryberg “SAM Photovoltaic Model Technical Reference Update” https://www.nrel.gov/docs/fy18osti/67399.pdf
State-of-the art for nameplate loss:
• 2.0% for Ga doped
• 1.0% for n-type
• 2.5% for B doped

State-of-the art for annual degradation rate:
• 0.45% for PERC double-glass
• 0.55% for PERC glass backsheet
• 0.25% for n-type

Please look to the data tables within SAM to see the exact DC degradation factors that are applied each year.

LID and LeTID profiles are site specific!

This analysis is not intended for use in product selection by project developers or installers. Warranty terms and bankability vary by vendor.
How to Reconcile SAM and Year-1 Power Loss in Warranties

Irradiance Losses

Soiling losses apply to the total solar irradiance incident on each subarray. SAM applies these losses in addition to any losses on the Shading and Snow page.

<table>
<thead>
<tr>
<th>Subarray 1</th>
<th>Subarray 2</th>
<th>Subarray 3</th>
<th>Subarray 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly soiling loss</td>
<td>Edit values...</td>
<td>Edit values...</td>
<td>Edit values...</td>
</tr>
<tr>
<td>Average annual soiling loss</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Bifacial modules only</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average annual rear irradiance loss due to soiling, mismatch, or external shading (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

DC Losses

DC losses apply to the electrical output of each subarray and account for losses not calculated by the module performance model.

| Module mismatch (%) | 2 | 2 | 2 | 2 |
| Diodes and connections (%) | 0.5 | 0.5 | 0.5 | 0.5 |
| DC wiring (%) | 2 | 2 | 2 | 2 |
| Tracking error (%) | 0 | 0 | 0 | 0 |
| Nameplate (%) | 2.5 | | | |
| DC power optimizer loss (%) | 0 | | | |
| Total DC power loss (%) | 6.829 | 4.440 | 4.440 | 4.440 |

All four subarrays are subject to the same DC power optimizer loss.

Total DC power loss = 100% * \{ 1 - the product of (1 - loss/100%) \}

Acknowledgements:

• Janine Freeman and Nate Blair (SAM team leads)
**How to Input DC-Based Degradation Profiles Into SAM (Single Value Mode)**

Please look to the data tables within SAM to see the exact DC degradation factors that are applied each year.

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### Annual Degradation for Multi-year Simulation

- **Annual DC degradation rate**: 0.6 %/year

  Applies to the photovoltaic array’s DC output in each time step.

- **In Value mode**, the degradation rate is compounded annually starting in Year 2. In **Schedule mode**, each year's rate applies to the Year 1 value. See Help for details.

### Lifetime Daily Losses

- Enable lifetime daily DC losses
- Enable lifetime daily AC losses

  Applies a daily loss to the DC output, AC output, or both over the analysis period. These inputs could be used to represent system outages or degradation.

### Memory Saving Option for Sub-hourly Simulations

- Save all output variables over analysis period

  If you are running sub-hourly simulations and experiencing display or memory problems on the Results page, clear the checkbox to reduce the number of variables displayed over the analysis period to a selection of key outputs. This will cause some output variables to appear on the Results page under "Hourly" instead of "Lifetime Hourly Data".
How to Input DC-Based Degradation Profiles Into SAM (Schedule Mode)

Please look to the data tables within SAM to see the exact DC degradation factors that are applied each year. There are some “tricks” to examine carefully around Year 1.
The Lost Treasure: Data Tables Showing DC Degradation Profiles and kWh\textsubscript{(AC)} Results

<table>
<thead>
<tr>
<th>Annual DC degradation factor</th>
<th>Energy produced kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>7.29417e+08</td>
</tr>
<tr>
<td>3</td>
<td>2.28056e+08</td>
</tr>
<tr>
<td>4</td>
<td>5.934417e+08</td>
</tr>
<tr>
<td>5</td>
<td>2.25398e+08</td>
</tr>
<tr>
<td>6</td>
<td>2.3924e+08</td>
</tr>
<tr>
<td>7</td>
<td>2.2213e+08</td>
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<tr>
<td>8</td>
<td>2.2118e+08</td>
</tr>
<tr>
<td>9</td>
<td>2.1979e+08</td>
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<td>1.58808e+08</td>
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<td>29</td>
<td>1.53801e+08</td>
</tr>
<tr>
<td>30</td>
<td>1.48653e+08</td>
</tr>
<tr>
<td>31</td>
<td>1.43944e+08</td>
</tr>
</tbody>
</table>
Degradation Profiles Used for the Project Cash Flow Model

Degradation Profiles for PV Modules (AC Results)
SAM Results for 1-Axis Tracking in Bakersfield, CA, with DC:AC Inverter Loading Ratio=1.3

Notes:
• Please look to the data tables within SAM to see the exact AC-based energy yields calculations.
• Changing the ILR (clipping losses) can be seen to be the greatest contributor to the differences between DC and AC degradation profiles.
• An ILR of 1.0 gives essentially the same DC and AC profiles.

This analysis has been prepared for illustrative purposes only, and is not intended to be used as a basis for product selection by project developers or installers.
Project PPA Revenues for the Different Warranty Profiles

PV Project PPA Revenues Under Variable Degradation Profiles
100 MW\(_\text{(DC)}\) Utility-Scale PV System. $30/MWh\(_\text{(AC)}\) Flat PPA Rate.

- \(\text{kWh}_{\text{AC}}/\text{kW}_{\text{DC}}\) energy yield times
- System size (DC) times
- $$/\text{kWh}_{\text{AC}}$$ (or $$$/MWh_{\text{AC}}$$) PPA rate times

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Lost revenues due to other degradation mechanisms

$5,500,000
$5,750,000
$6,000,000
$6,250,000
$6,500,000
$6,750,000
$7,000,000

$5,500,000 $5,750,000 $6,000,000 $6,250,000 $6,500,000 $6,750,000 $7,000,000

Lost revenues due to BO LID and LeTID

Revenues Using Zero Module Losses Profile (No Year-1 DC Loss and 0.0%/year)
Revenues Without LID
Revenues Without LID and Without LeTID
Revenues Using Conservative Mono PERC Warranty Terms (2.5%/DC in Year 1, then 0.60%/year(DC) for 25 years)
In SAM, PV Project Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA)

**EBITDA** = PPA Revenues — Operations and Maintenance (O&M) expenses

O&M expressed in nominal terms including real escalators (2—3%) plus inflation (2—3%) compounded over the analysis period.

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**Projected Project EBITDA for the Different Warranty Profiles**

**PV Project EBITDA Under Variable Degradation Profiles**

- 100 MW\(_{(DC)}\), $30/MWh\(_{(AC)}\) Flat PPA Rate, $6/kW\(_{(DC)}\)-yr Direct O&M Expense in Year One

**EBITDA Using Zero Module Losses Profile (No Year-1 DC Loss and 0.0%/year)**

1. PPA Revenues (Year 1, no losses):
   \[2,300 \text{kWh}_{\text{AC}}/\text{kW}_{\text{DC}} \times 100,000 \text{kW}_{\text{DC}} \times 0.03/\text{kW}_{\text{AC}} = 6,900,000\]

2. O&M Expense (Year 1):
   \[6/\text{kW}_{\text{DC}} \times 100,000 \text{kW}_{\text{DC}} = 600,000\]

3. EBITDA (Year 1, no losses):
   \[6,900,000 - 600,000 = 6,300,000\]

4. O&M Expense (Year 30, including escalators)= $2,500,000

**EBITDA Without LID**

**EBITDA Without LID and Without LeTID**

**EBITDA Using Conservative Mono PERC Warranty Terms (2.5%(DC) in Year 1, then 0.60%/year(DC) for 25 years)**

Other system-level direct O&M expenses deducted from PPA revenues.
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What are some solutions for mitigating BO LID and LeTID?

(1) P-type base wafers can be fabricated using magnetic Czochralski (Cz), which suppresses oxygen release from the Cz crucible and reduces the concentration of boron-oxygen pairs within the wafer. *Tradeoff*: Higher CapEx for ingot production

(2) Switch to an alternative p-type dopant, such as Gallium (Ga). *Tradeoff*: Ga has a very low segregation coefficient compared to B or P, leading to potentially greater yield losses in ingot, wafer, cell and module production.

(3) Move toward solar cell architectures built upon n-type base wafers (e.g., PERT/PERL/TOPCon, HJT, IBC). There are also higher efficiency benefits. *Tradeoff*: Higher module manufacturing costs and more UV LID.
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Ultraviolet-Light Induced Degradation (UV-LID) of High-Efficiency Solar Cells. RE: Technoeconomic Analysis

Peter Hacke, David Miller, Katherine Hurst, Jiadong Qian

Archana Sinha, Stephanie Moffitt, Laura Schelhas, Sona Ulicna

DuraMAT webinar on 2020/12/14
Common Light Induced Degradation in c-Si Solar Cells

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Sources:
1. J. Lindroos, et al., SOLMAT, 147, 2016
4. F. Fertig et al., Energy Procedia, 124, 2017
UV-LID: Background

**Motivation:**
- UV transmitting front encapsulants now popular (2.3% light gain).
- Emerging cell technologies (HJ, PERC, PERT,...) reportedly vulnerable to UV-Light Induced Degradation (UV-LID).

**Project goals:**
- Verify the damaging effects of UV in today’s high-efficiency commercial silicon cells.
- Quantify the magnitude of degradation.
- Investigate the underlying degradation mechanisms.
- Advise on module-level solutions for mitigating degradation.
2000 hours of UV exposure completed all samples.
3000 hours some samples.
Experimental Design

Control samples (Baseline)

Test samples (Unstressed)

UV exposure testing (Electrical bias configurations, Irradiated cell surface)

UV chamber

Test samples (Stressed)

Cored samples

Characterization: -today-

I-V (electrical performance analysis)

ellipsometry/reflectance (optical analysis)

EQE (performance analysis)

SIMS (verify H concentration)

XPS/Auger (additional chemical analysis)

-future TechTalk-
Accelerated UV Exposure Test

UV test:
- UVA-340 fluorescent lamps, $E=1.24\, W\cdot m^{-2}$ at 340 nm, cell temperature: 45 oC (prevent LETID), ambient humidity (~7%)
- Test duration: $\geq 2000\, h$, equivalent to ~4 y incident irradiation in Phoenix, USA (340 nm)
- Cells under different electrical load configurations (open-circuit, short-circuit) and irradiated surfaces (front and back);
  3 replicas/cell type in each set

Samples: the sign (*) denotes bifacial cells

<table>
<thead>
<tr>
<th>Company ID</th>
<th>Cell technology</th>
<th>Cell construction</th>
<th>Bifacial?</th>
<th>Front structure</th>
<th>Rear structure</th>
<th>Test Lab</th>
<th>NREL</th>
<th>SLAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>HI</td>
<td>mono</td>
<td>y</td>
<td>ITO/(p+)-a-Si</td>
<td>n-Si/a-Si</td>
<td>NREL, SLAC</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>B</td>
<td>IBC</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/n+Si</td>
<td>-</td>
<td>NREL</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>C</td>
<td>n-PERT</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/p+Si/n Si</td>
<td>n-Si/n+SiN$_x$</td>
<td>NREL, SLAC</td>
<td>3</td>
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</tr>
<tr>
<td>D</td>
<td>n-PERT</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/p+Si/n Si</td>
<td>-</td>
<td>NREL</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>n-PERT</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/p+Si/n Si</td>
<td>n-Si/n+SiN$_x$</td>
<td>NREL, SLAC</td>
<td>3</td>
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</tr>
<tr>
<td>F</td>
<td>n-PERT</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/p+Si/n Si</td>
<td>-</td>
<td>SLAC</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>G</td>
<td>p-PERC</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/n+Si/p Si</td>
<td>p-Si/AlO$_x$/SiN$_x$/Al</td>
<td>NREL, SLAC</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>H</td>
<td>p-PERC</td>
<td>mono</td>
<td>n</td>
<td>SiN$_x$/n+Si/p Si</td>
<td>p+Si/SiN$_x$</td>
<td>NREL, SLAC</td>
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<tr>
<td>I</td>
<td>p-PERC</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/n+Si/p Si</td>
<td>-</td>
<td>NREL</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>J</td>
<td>p-PERC</td>
<td>mono</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/n+Si/p Si</td>
<td>p-Si/AlO$_x$/SiN$_x$</td>
<td>NREL</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>p-PERC</td>
<td>multi</td>
<td>y</td>
<td>SiN$_x$/SiO$_y$/n+Si/p Si</td>
<td>p-Si/AlO$_x$/SiN$_x$</td>
<td>NREL</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Al-BSF</td>
<td>multi</td>
<td>n</td>
<td>SiN$_x$/n+Si/p Si</td>
<td>-</td>
<td>NREL, SLAC</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

Bare cells (Round 1) → Bare cells with UV-cut filters (Round 2) → Mini-modules with UV-cut encapsulants (Round 3)
Test Sample Build

Laser scribed cell

Pb-Sn Soldering

ECA bonding

ECA: electrically conductive adhesive

SEM image: Laser scribe depth

Finished sample
Outdoor Preconditioning

- Clear sky, natural sunlight dose: 15-18 kWh (broadband, stabilize B-O LID)
- Cell temperature < 45°C (to prevent LETID)
- Cells under PMMA sheet (museum grade, to filter off UV radiation)

featuring Kapton (PI) tape
$P_{\text{max}}$ degradation rate $\geq -0.6\% \cdot y^{-1}$ (chamber:field UV dose @ 340 nm in Phoenix) is common, with the maximum degradation rate up to $-4\% \cdot y^{-1}$

Degradation Rate: Variation and Caveats

- Number in parenthesis indicates the total number of cells tested, including cells from different manufactures.

### 2000h of UV exposure (NREL + SLAC)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Statistic</th>
<th>AI-BSF (6)</th>
<th>HJ (6)</th>
<th>IBC (3)</th>
<th>n-PERT (18)</th>
<th>p-PERC (21)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{max} \ (% change)</td>
<td>Lowest</td>
<td>-0.45</td>
<td>-7.21</td>
<td>2.90</td>
<td>1.54</td>
<td>-0.60</td>
</tr>
<tr>
<td></td>
<td>Highest</td>
<td>-0.95</td>
<td>-15.89</td>
<td>0.07</td>
<td>-7.53</td>
<td>-3.64</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-0.72</td>
<td>-10.92</td>
<td>1.16</td>
<td>-1.83</td>
<td>-1.79</td>
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<tr>
<td></td>
<td>Std Dev (1\sigma)</td>
<td>0.02</td>
<td>0.30</td>
<td>0.15</td>
<td>0.28</td>
<td>0.08</td>
</tr>
<tr>
<td>I_{sc} \ (% change)</td>
<td>Lowest</td>
<td>-0.15</td>
<td>0.07</td>
<td>-0.04</td>
<td>0.56</td>
<td>-0.31</td>
</tr>
<tr>
<td></td>
<td>Highest</td>
<td>-0.49</td>
<td>-5.37</td>
<td>-1.36</td>
<td>-2.88</td>
<td>-3.49</td>
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<tr>
<td></td>
<td>Average</td>
<td>-0.37</td>
<td>-1.27</td>
<td>-0.80</td>
<td>-0.76</td>
<td>-0.90</td>
</tr>
<tr>
<td></td>
<td>Std Dev (1\sigma)</td>
<td>0.01</td>
<td>0.21</td>
<td>0.07</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>V_{oc} \ (% change)</td>
<td>Lowest</td>
<td>-0.18</td>
<td>-2.55</td>
<td>-0.95</td>
<td>0.89</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Highest</td>
<td>-0.54</td>
<td>-3.14</td>
<td>-1.68</td>
<td>-4.96</td>
<td>-1.96</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-0.30</td>
<td>-2.84</td>
<td>-1.32</td>
<td>-0.47</td>
<td>-0.66</td>
</tr>
<tr>
<td></td>
<td>Std Dev (1\sigma)</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>FF \ (% change)</td>
<td>Lowest</td>
<td>0.07</td>
<td>-4.85</td>
<td>4.91</td>
<td>0.25</td>
<td>1.24</td>
</tr>
<tr>
<td></td>
<td>Highest</td>
<td>-0.19</td>
<td>-9.30</td>
<td>1.91</td>
<td>-3.13</td>
<td>-1.82</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-0.06</td>
<td>-7.15</td>
<td>3.33</td>
<td>-0.61</td>
<td>-0.24</td>
</tr>
<tr>
<td></td>
<td>Std Dev (1\sigma)</td>
<td>0.01</td>
<td>0.16</td>
<td>0.15</td>
<td>0.11</td>
<td>0.06</td>
</tr>
</tbody>
</table>

- Although a limited number of samples was examined, cell technology types may be compared.
- HJ most affected (perform). Other modern cells
  - (n-PERT, IBC) more affected than Al-BSF.
- Multiple characteristics affected, with a range of impact → more data needed, including to distinguish between makes of cells.

Additional caveats for a technoeconomic analysis:
- We are assuming the degradation rate is linear (e.g., early module life).
- We make no assumption for the maximum total degradation. Suspected degradation mechanisms attributed to changes in thin layers.
- 2.3% light gain from UV transmitting encapsulant may be reduced by:
  - Cell-specific EQE, e.g., 2.3 → 0.9% for IBC.
  - TBD for partially UV transmitting encapsulant.
The Application-Specific UV Dose Rate

The UV light incident to the $\text{Si}_x\text{N}_y$ surface and $\text{AR}_c/\text{Si}$ interface in a module is less than an unpackaged cell:

- An elevated UV intensity was applied to accelerate the experiment.
- UV is reflected by the encapsulant/ARc/Si stack, and absorbed in the $\text{Si}_x\text{N}_y$ bulk.
- Additional UV is attenuated in a PV module by: ARg, front glass, encapsulant (transmitting or blocking).

- Acceleration factor of ~5 is observed between this study (UVA-340·bare cell) and (AM1.5G·UV transmitting module, SixNy surface and SixNy/Si interfaces).
- Degradation ratetypical: -0.6 %·y⁻¹ → -0.1 %·y⁻¹. Degradation ratemax: -4 %·y⁻¹ → -0.7 %·y⁻¹ (PV module).
- Additional acceleration factor of ~50 is observed between UV-transmitting and -blocking encapsulants.
- *Examples given here for 340 nm. Comparing UV dose and results of aging is wavelength dependent! (Expect an update from UV filters experiment).
Preventing UV-LID

PV packaging:
- Wavelength-tailored, partially UV blocking formulations.
- Novel formulation additives, e.g., triazine instead of benzotriazole UV absorber.
- Possible added cost.

UV blocking glass:
- Ce doped glass (from aerospace) was previously used in PV industry.
- Added cost & complexity of enhanced solarization of the glass.

PV cell:
- Improve the design and fabrication of passivation layer, where possible.
- e.g., AlxOy interlayer containing passivation found more UV-LID stable for n-PERT.
- Research needed. Some cell technologies or makes may emerge as less UV-LID sensitive.
Summary

This study:

• UV-LID verified, separate from B-O LID (stabilized beforehand) and LETID (low temperature test used).

• Common $\Delta P_{\text{max}}$ is -0.6 %·y$^{-1}$ (bare cells, chamber:field UV dose) $\rightarrow$ -0.1 %·y$^{-1}$ (AM1.5, PV module), with the maximum degradation rate up to -4 %·y$^{-1}$ $\rightarrow$ -0.7 %·y$^{-1}$ (at 340 nm).

• UV-LID more pronounced in new cell designs, including HJ, IBC, and PERT relative to Al-BSF.

• Greater examination will help clarify the typical degradation rate and least affected cells as well as the cost/benefit of solutions.

Coming soon:

• Additional characterizations (EQE, ellipsometry, reflectance, SIMS, XPS/Auger) are underway to find the correlation between power degradation and optical/chemical changes of the cell.

• Follow-on experiments: sharp cut-on UV filters with cells $\rightarrow$ custom encapsulants in MiMos. Both help better assess effect on net present value and LCOE.
Acknowledgment

Thanks to our project collaborators

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<table>
<thead>
<tr>
<th></th>
<th>Introduction (Teresa Barnes, DuraMAT Director, 5 minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Introduction and Modeling of BO LID and LeTID, Ingrid Repins (15 minutes)</td>
</tr>
<tr>
<td>3</td>
<td>Impacts to PV Project Cash Flows and LCOE (Mike, 15 minutes)</td>
</tr>
<tr>
<td>4</td>
<td>Introduction to UV LID, David Miller and Peter Hacke (15 minutes)</td>
</tr>
<tr>
<td>5</td>
<td><strong>Quantified Value Proposition of Reducing UV LID (Mike, 5 minutes)</strong></td>
</tr>
<tr>
<td>6</td>
<td>Conclusions, Next Steps, and Questions (Everyone, 5 minutes)</td>
</tr>
</tbody>
</table>
## Tradeoffs Between Encapsulant Choices

<table>
<thead>
<tr>
<th>UV-Transmitting Encapsulant</th>
<th>UV-Blocking Encapsulant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typically, on the front (and back if bifacial)</td>
<td>Typically, on the back for Glass-Backsheet</td>
</tr>
</tbody>
</table>

### First Impact:
Nameplate (DC)
Module Power Rating at STC

- **UV-Transmitting Encapsulant**: Up to 1% (relative) advantage (e.g., 450—455 W binning)
- **UV-Blocking Encapsulant**: Up to 1% (relative) loss. (e.g., 445—450 W binning)

### Second Impact:
Degradation Profile

- **UV-Transmitting Encapsulant**: Up to 0.73%/year loss in DC power rating due to degradation in the solar cell. 0.12%/year is more typical.
- **UV-Blocking Encapsulant**: No expected degradation due to UV LID

### Presumptive Beneficiary

- **Module Vendor**: Lower manufacturing costs
- **Developer/Installer**: Lower BOS costs to reach nameplate DC-based system capacity.

- **Developer/Installer**: Potential benefits due to lower degradation rate.
Running Parametrics Within SAM
PV Project LCOE for Variable DC Losses and Degradation Rates

$1.0/W(DC)$ Utility-Scale System with 6.0% Nominal Target IRR.
LCOE Framework (SAM Parametrics)

UV Transmitting Encapsulant
Industry standard for front (and back, if bifacial)

1-Typical UV LID
No nameplate DC loss
0.12%/yr degradation

2-Maximum UV LID
No nameplate DC loss
0.73%/yr degradation

UV Blocking Encapsulant
Industry standard for back

3-No UV LID degradation
1.0% DC loss
0.0%/yr degradation due to UV LID
LCOE Framework (SAM Parametrics)

1 - Typical UV LID
No nameplate DC loss
0.12%/yr degradation

LCOE = $28.9/ MWh_{(AC)}

2 - Maximum UV LID
No nameplate DC loss
0.73%/yr degradation

LCOE = $30.2/ MWh_{(AC)}

A $0.05/W_{(DC)} Equivalent Issue

3 - Eliminate UV LID
1.0% DC power loss
0.0%/yr degradation due to UV LID

LCOE = $28.9/ MWh_{(AC)}

Before considering additional capital costs

UV Transmitting Encapsulant
Industry standard for front
(and back, if bifacial)

UV Blocking Encapsulant
Industry standard for back

Additional Capital Costs Expected
Due to Lower Rated Efficiency:
1) Module manufacturing costs
2) BOS Hardware and Labor Costs
3) Shipping
Presentation Outline

1. Introduction (Teresa Barnes, DuraMAT Director, 5 minutes)
2. Introduction and Modeling of BO LID and LeTID, Ingrid Repins (15 minutes)
3. Impacts to PV Project Cash Flows and LCOE (Mike, 15 minutes)
4. Introduction to UV LID, David Miller and Peter Hacke (15 minutes)
5. Quantified Value Proposition of Reducing UV LID (Mike, 5 minutes)
6. Conclusions, Next Steps, and Questions (Everyone, 5 minutes)
Conclusions and Proposed Next Steps

Potential next steps for this analysis:

(1) Write a paper!
(2) To understand each degradation mode shown on the left and to quantify the value proposition of solutions
(3) Uncertainty analysis for more sites

Conclusions:

(1) BO LID and LeTID effects are site- and project-specific
(2) Translating DC-based nameplate power ratings and degradation to kWh_{(AC)}/kW_{(DC)} energy yield over time is also site-and project-specific
(3) UV LID may pose significant downside risk for certain cell types

Source of ILLUSTRATIVE cumulative degradation rate curve: