DuraMAT
Durable Module Materials Consortium

LID and LeTID Impacts to PV Module Performance and System Economics

DRAFT Analysis

DuraMAT Webinar, December 14, 2020

Michael Woodhouse[(1)], Ingrid Repins[(2)], and David Miller[(2)]

(1) NREL Strategic Energy Analysis Center (SEAC)

(2) PV Reliability Group

NREL/PR-6A20-78629

Presentation Outline

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
2. T. Niewelt, et al., IEEE J. Photovoltaics, 7, 2017
3. J. Lindroos et al., Jour App Phys., 116, 2014
4. F. Fertig et al., Energy Procedia,124, 2017
5. R. Witteck et al., Phys. Status Solidi - Rapid Res. Lett., 11, 2017

Presentation Outline

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?

PVTECH

November 2018

Let's mitigate LID & LeTID!

pv magazine 10 YEARS

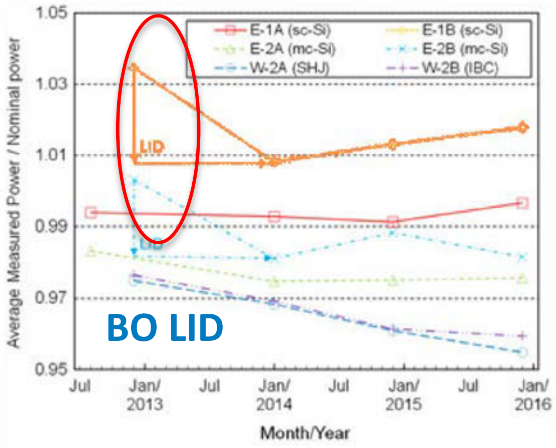
March 2018

- 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?

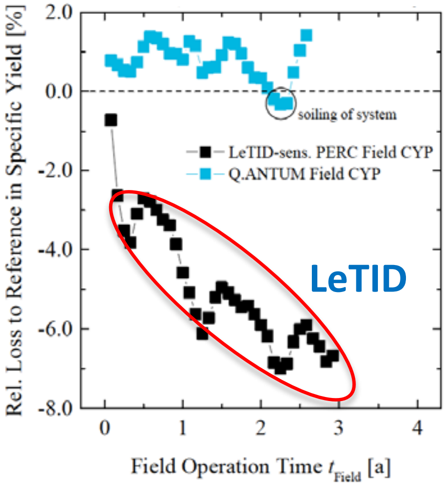
Background Information On BO LID and LeTID

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.

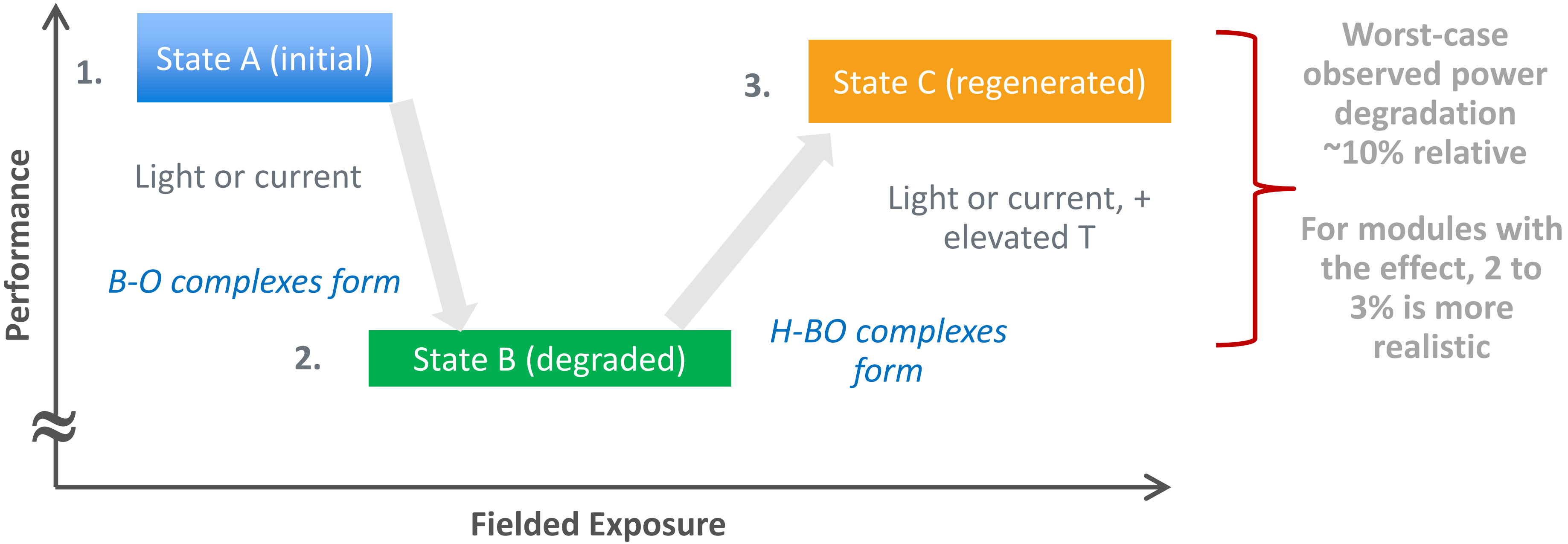


Ishii, *PIP*, 2017



Kersten, *Energy Proc*, 2017

Simplified Description of How BO LID Affects Performance

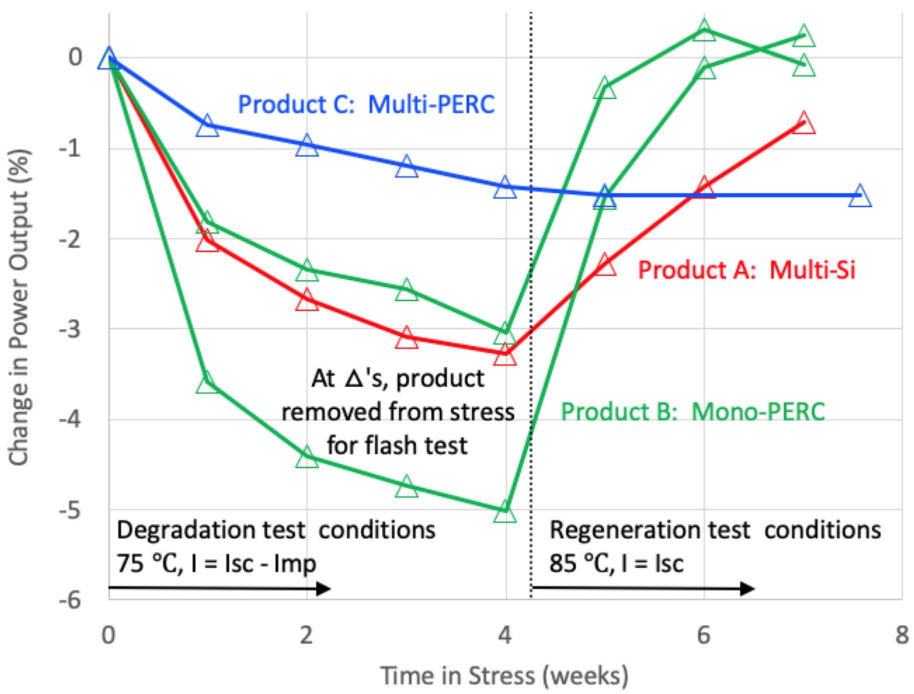


LeTID can be described similar picture, but it is caused by a different defect, and progression between states is slower for same conditions.

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)



Example of LeTID test data from NREL

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 to describe how defects transition between states (A,B,C) with time, temperature, and current.

$$\frac{\partial N_A}{\partial t} = k_{BA} \cdot N_B - k_{AB} \cdot N_A$$

$$\frac{\partial N_B}{\partial t} = k_{AB} \cdot N_A + k_{CB} \cdot N_C - (k_{BA} + k_{BC}) \cdot N_B$$

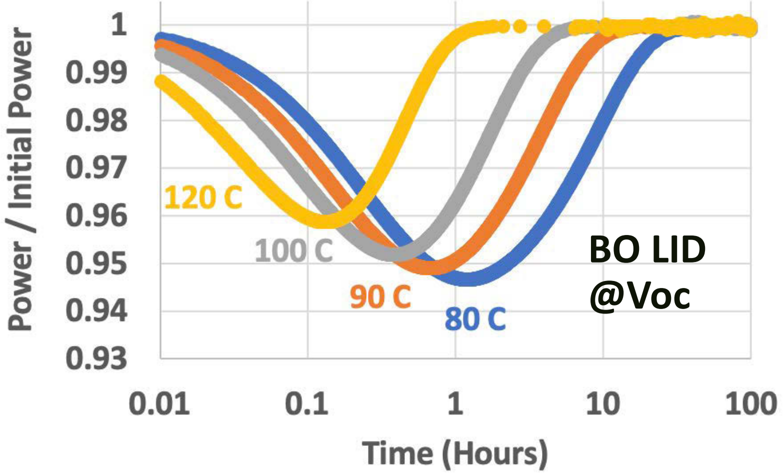
$$\frac{\partial N_C}{\partial t} = k_{BC} \cdot N_B - k_{CB} \cdot N_C$$

$$k_{ij} = \nu_{ij} \cdot e^{\left(\frac{-Ea_{ij}}{k_b T}\right)}$$

Hallam, *Energy Proc*, 2016

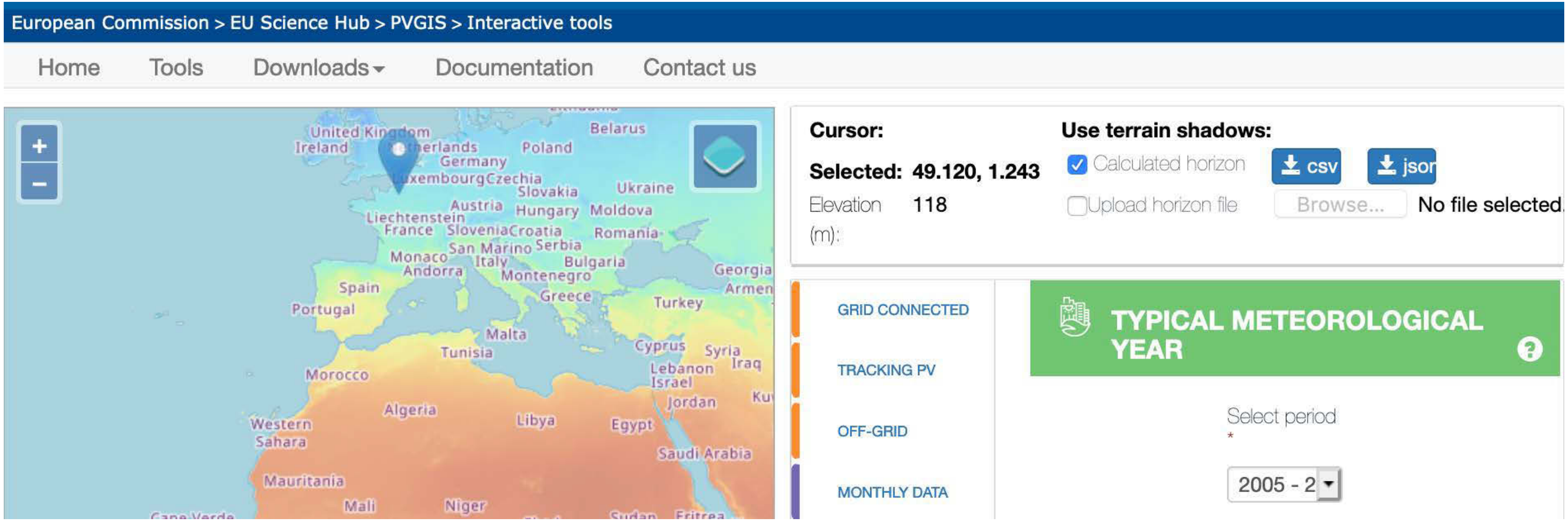
Mechanism	Transition	ν (s^{-1})	Injection Level (suns)	E_a (eV)
BO LID	A to B	$4 \cdot 10^3$	1	0.475
	B to A	$1 \cdot 10^{13}$	0	1.32
	B to C	$1.25 \cdot 10^{10}$	2.7	0.98
	C to B	$5.32 \cdot 10^5$	0	0.87
LeTID	A to B	$6.61 \cdot 10^{10}$	1	1.07
	B to C	$1.13 \cdot 10^7$	1	0.94

Repins, *Solar Energy*, 2020

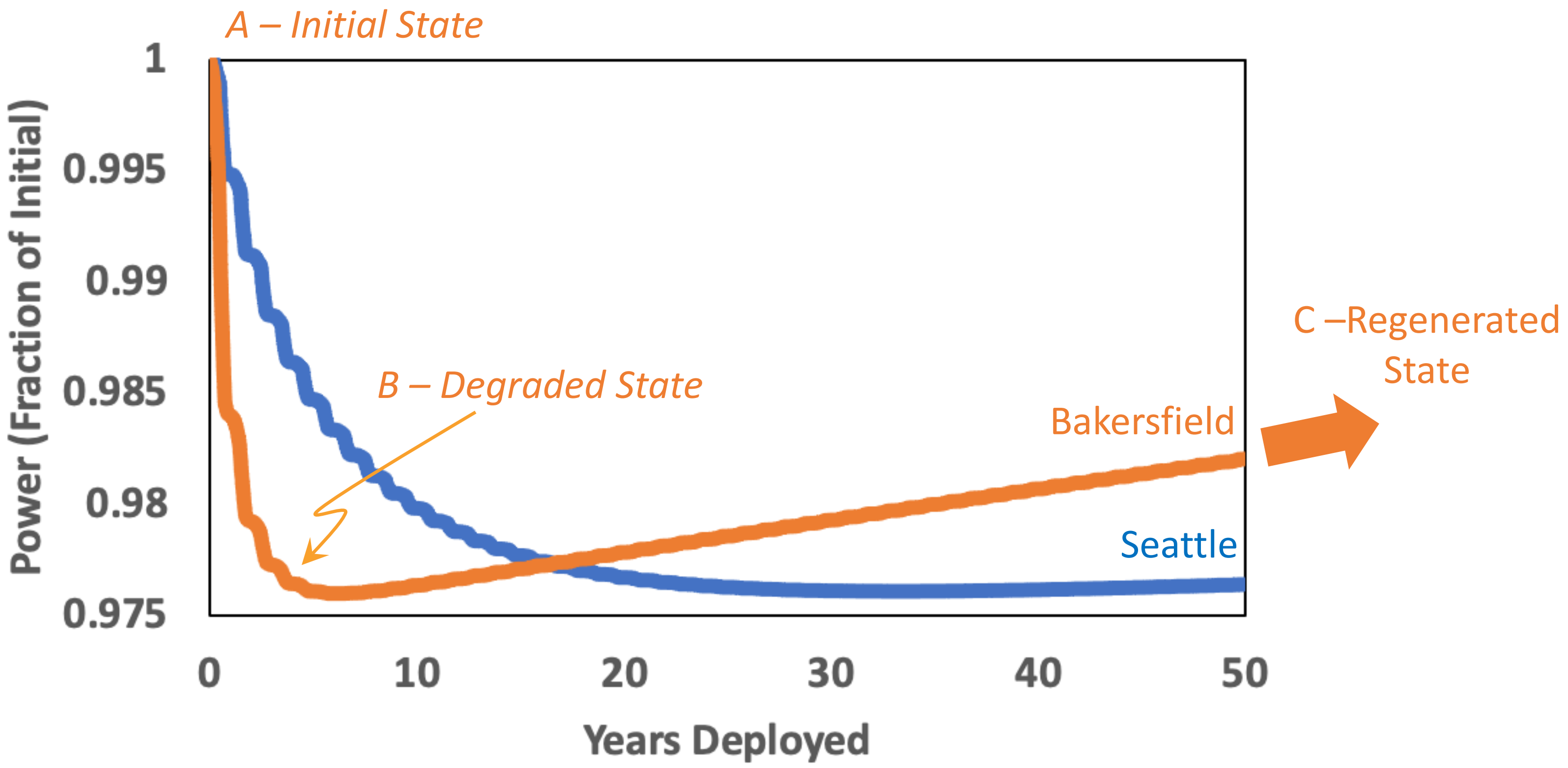


How Can We Calculate A Fielded Degradation Profile for BO LID or LeTID?

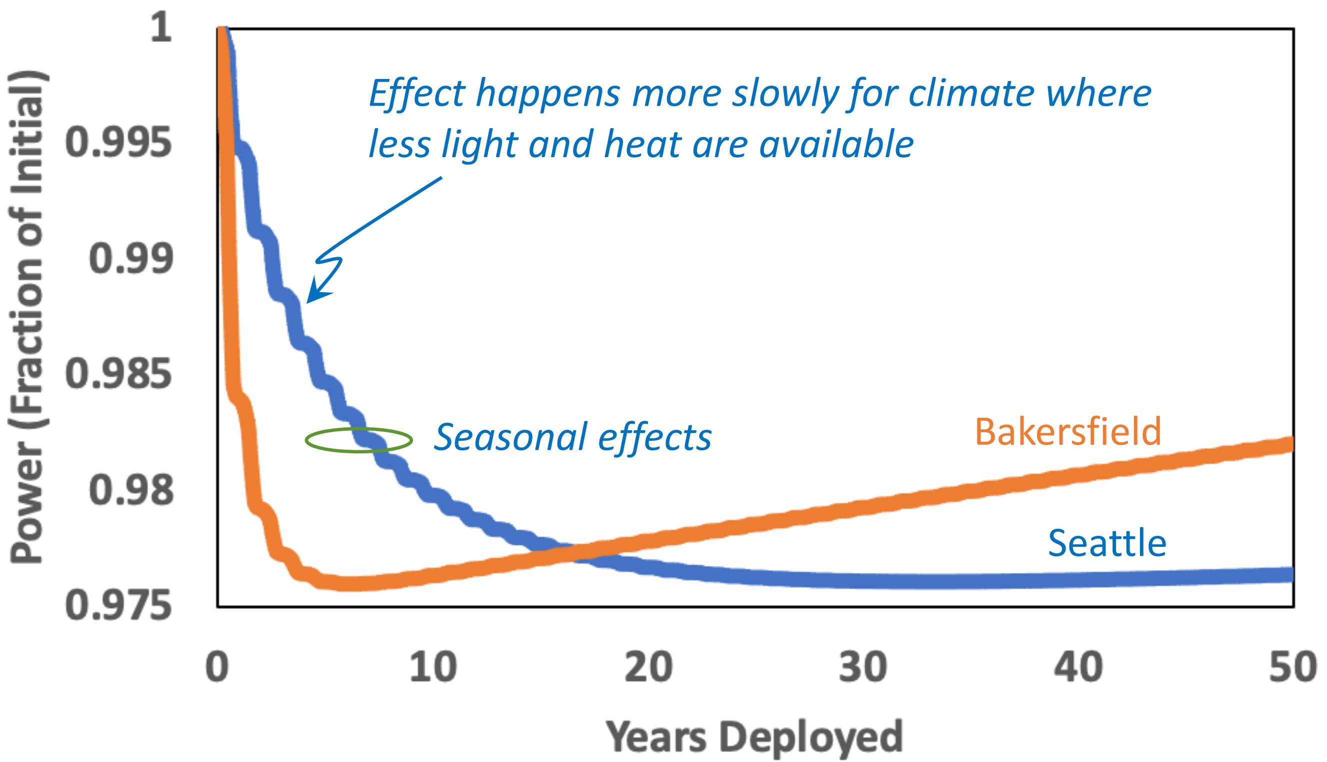
Step Two: Use meteorological data as the inputs for irradiance (current), temperature (King model), and time.



Example Result – Simulation of LeTID in Seattle or Bakersfield



Example Calculation – LeTID in Seattle or Bakersfield



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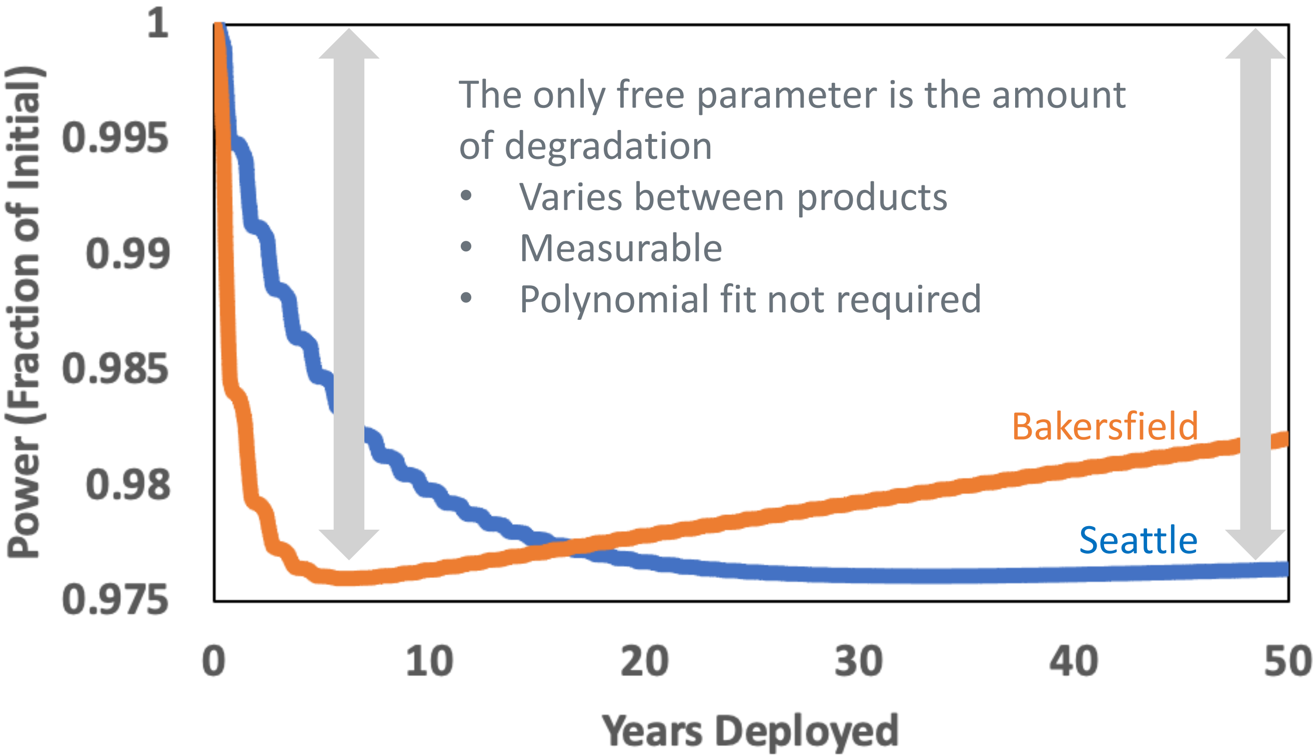
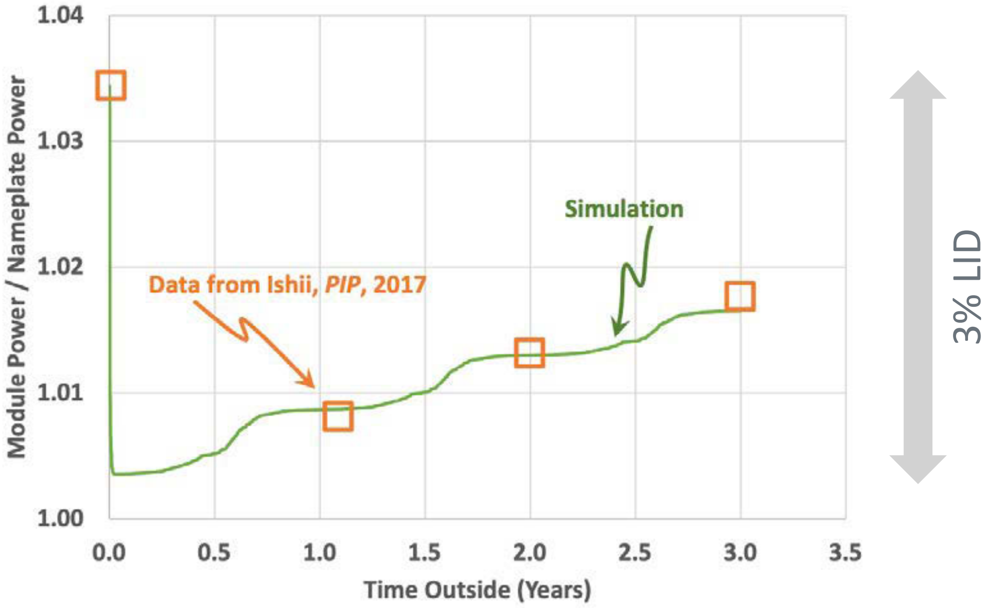


The only free parameter is the amount of degradation

- Varies between products
- Measurable
- Polynomial fit not required

Does This Rate Prediction Work? Verify against Outdoor BO LID Data

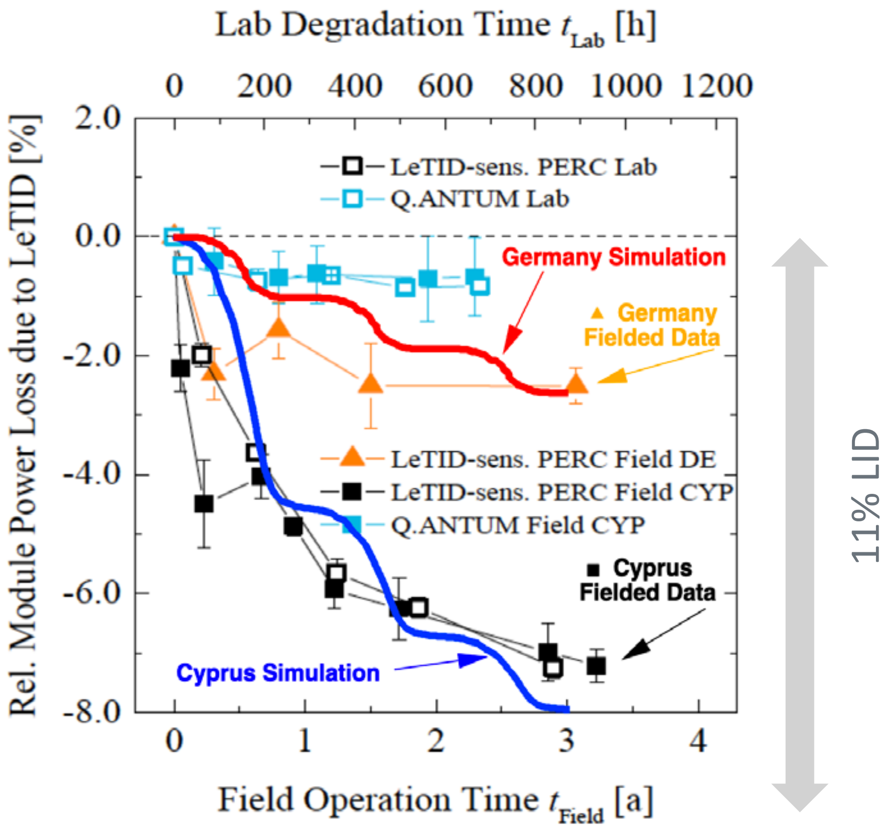
Use METPV meteorologic database for Japan, at location from published report.



Does This Rate Prediction Work? Verify against Outdoor LeTID Data

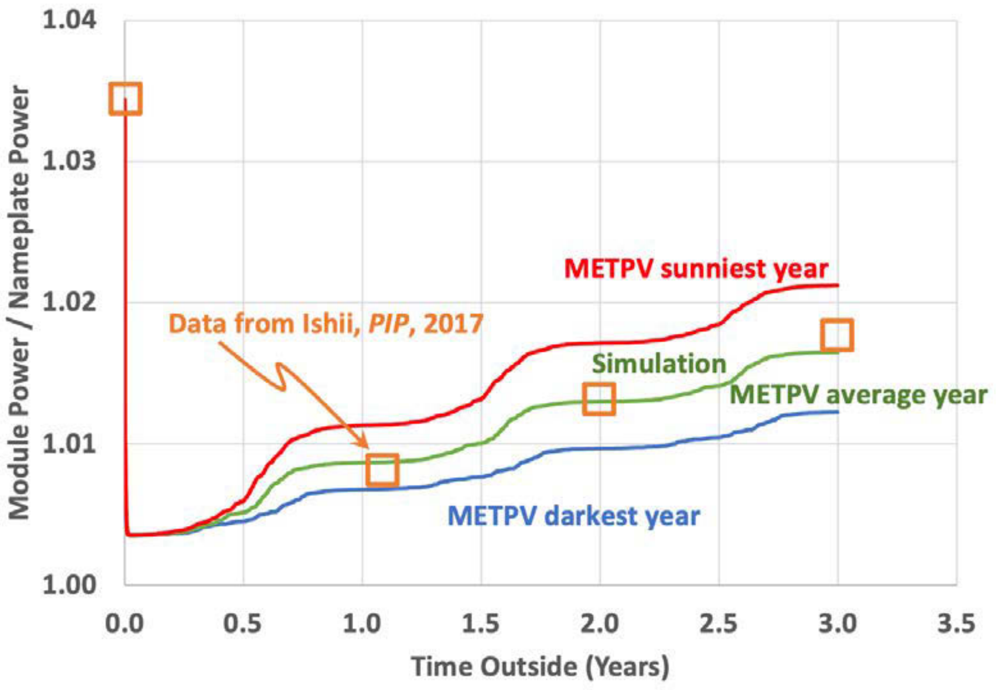
Use JRC meteorologic database for locations in published report (Thalheim and Cyprus)

11% maximum LeTID based on other papers from the same group.

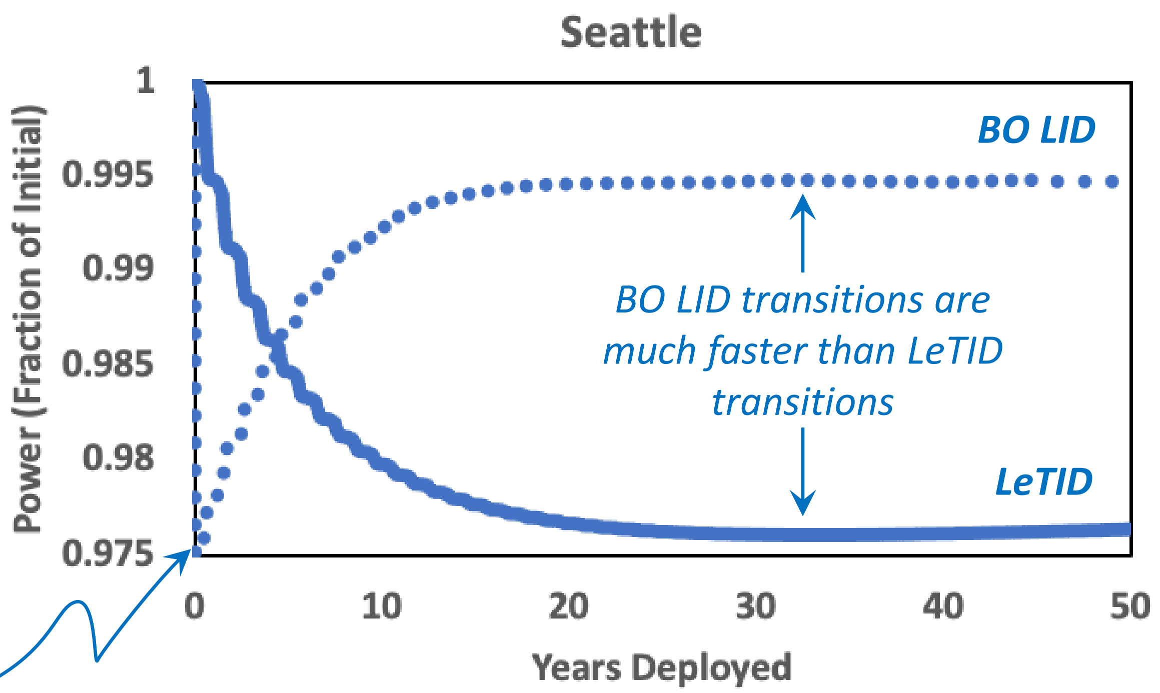


Results are Estimates Only

- 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.

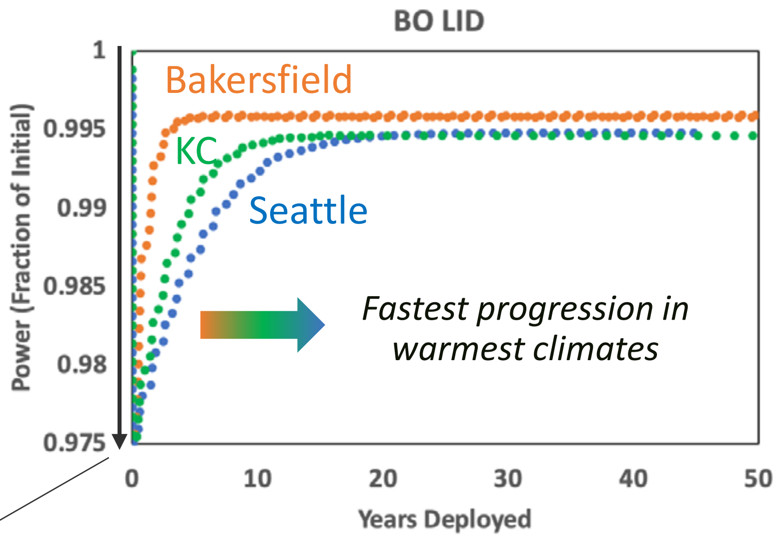


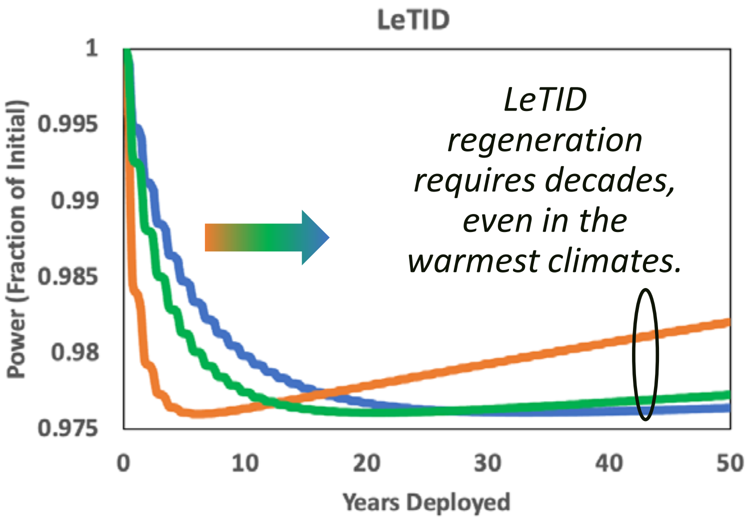
Long-Term Degradation Rate Predictions - Seattle



Even in coolest climate, BO LID is very fast

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 ($)

Modules

Crystalline Silicon

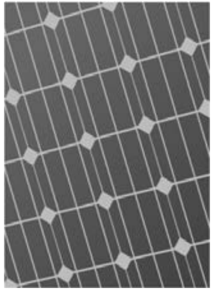


Illustration by Al Hicks, NREL

Thin-Film

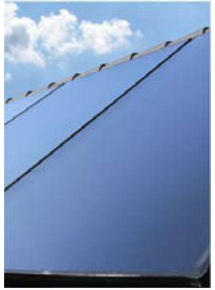


Photo from iStock, 1033236964

Storage

Batteries

Photo by Dennis Schroeder, NREL 56318

Solar Fuels

Photo from iStock, 932140864

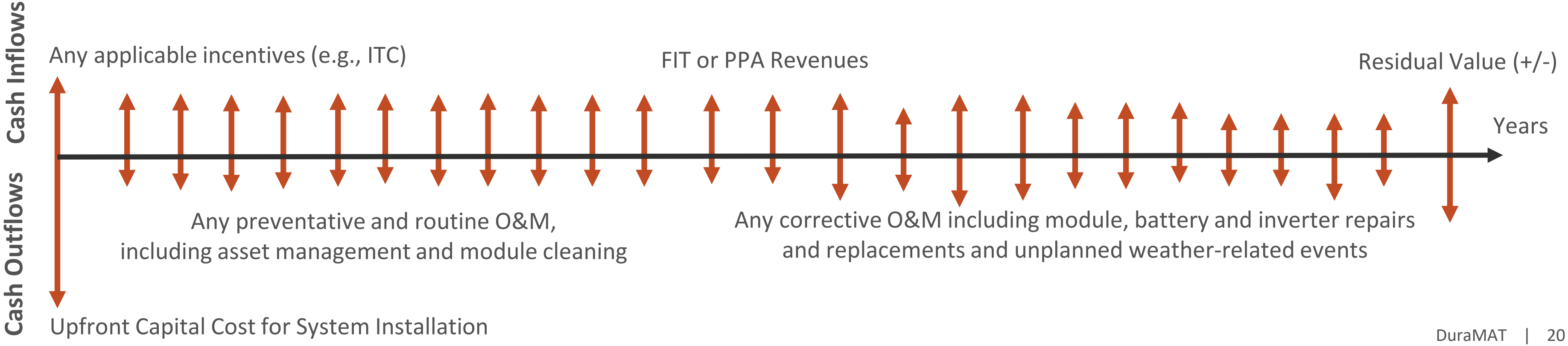
System Capital Costs ($)

PV Systems

Photo from iStock, 938053682

PV Plus Storage

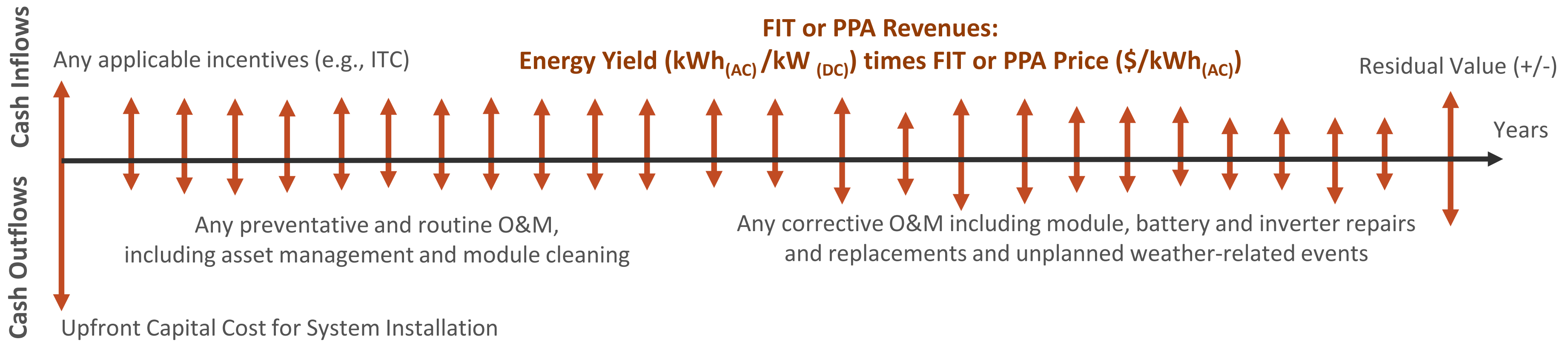
Photo from iStock, 1128871378



Technoeconomic Analysis Factors

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)



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: $kWh_{(AC)}/kW_{(DC)}$

(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 $kWh_{(AC)}/kW_{(DC)}$ energy yield after 24 hours a day for 365 days

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

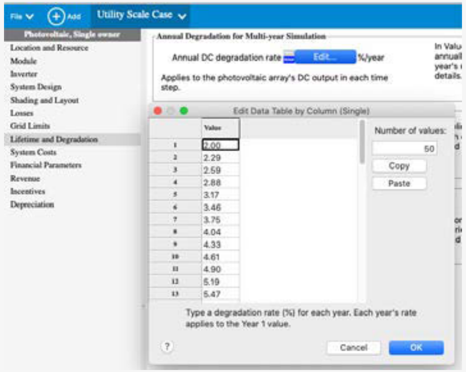
(3) Properly translating time-based changes in DC efficiency to changes in energy yield entails $kWh_{(AC)}$ modeling. It is <u>not</u> a 1:1 or linear relationship, principally because of the inverter.

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

Inputs
(1) Nameplate DC Losses
(2) Degradation profiles



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

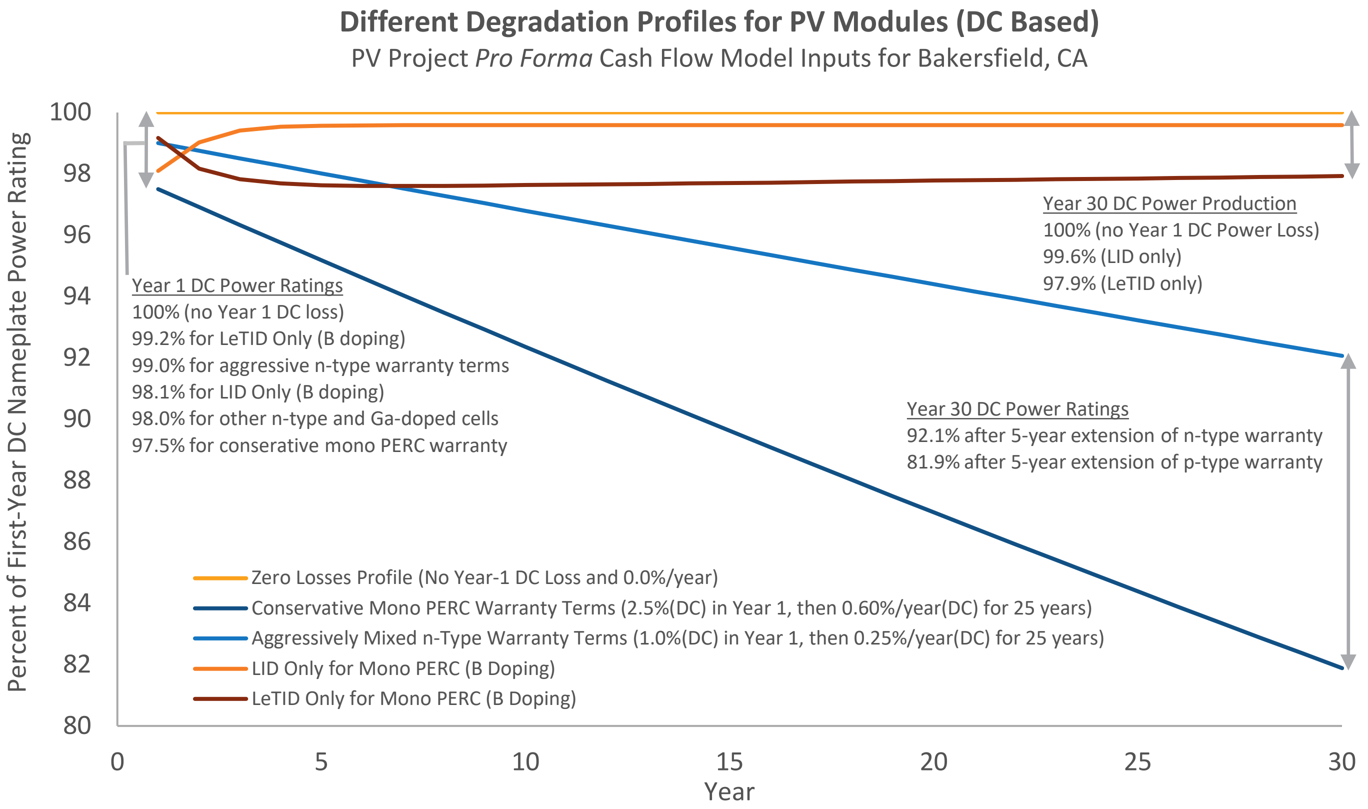
Technology- and Engineering-Dependent Variables
(1) Module I-V curves at varying light intensities
(2) Module temperature coefficient
(3) Module bifaciality (optional)
(4) Fixed-tilt or tracking
(5) Inverter configuration
(6) Coupling with storage (optional)

$kWh_{(AC)}$ / $kW_{(DC)}$ Energy Yield

For additional details regarding NREL's SAM Photovoltaic Performance Model, please see: P Gilman, A Dobos, N DiOrio, J Freeman, S Janzou, and D Ryberg "SAM Photovoltaic Model Technical Reference Update"

https://www.nrel.gov/docs/fy18osti/67399.pdf

DC-Based Degradation Profiles Used for the Project Cash Flow Model



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

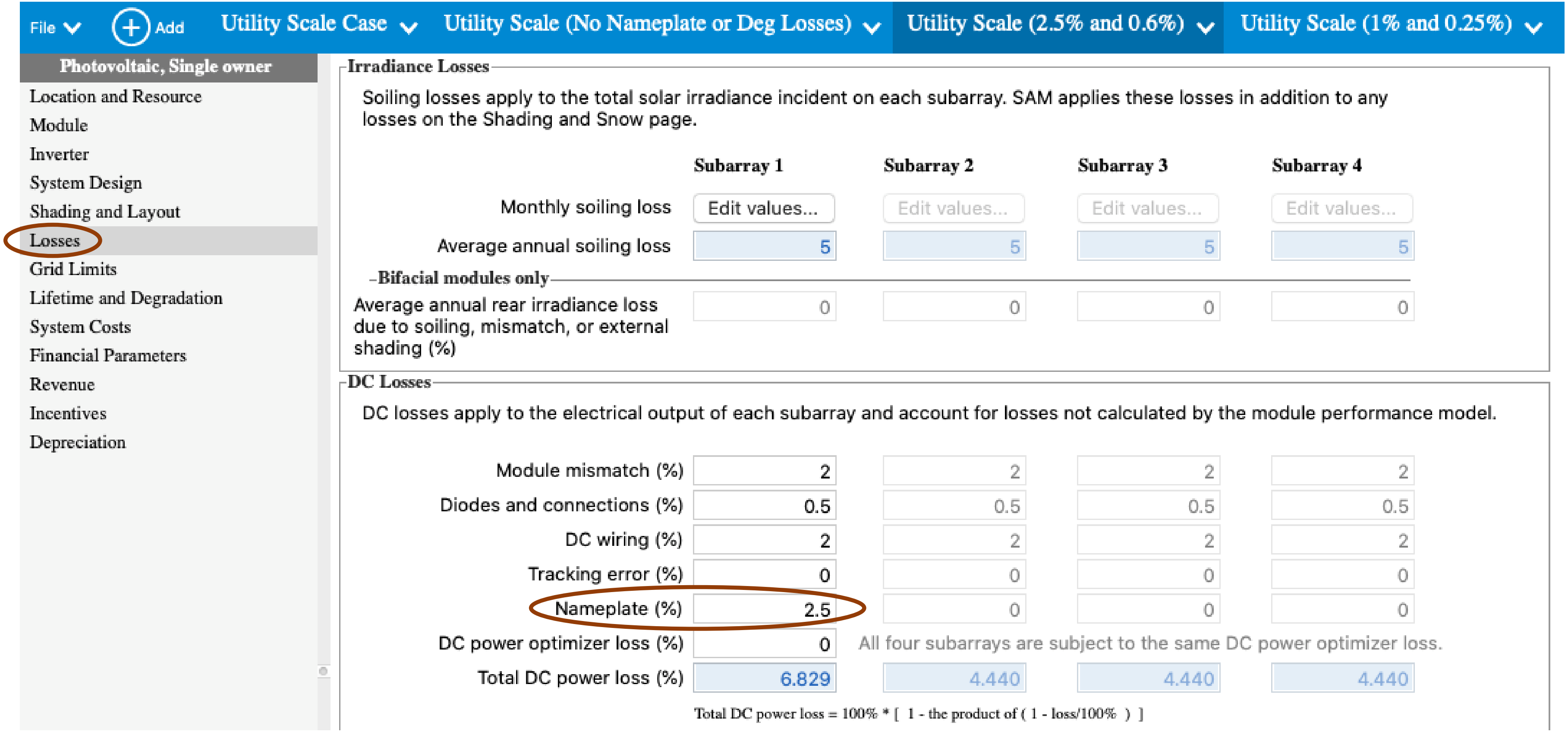
Please look to the data tables within SAM to see the exact DC degradation factors that are applied each year.

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.

Preliminary and DRAFT Analysis
Feedback and Comments Welcome

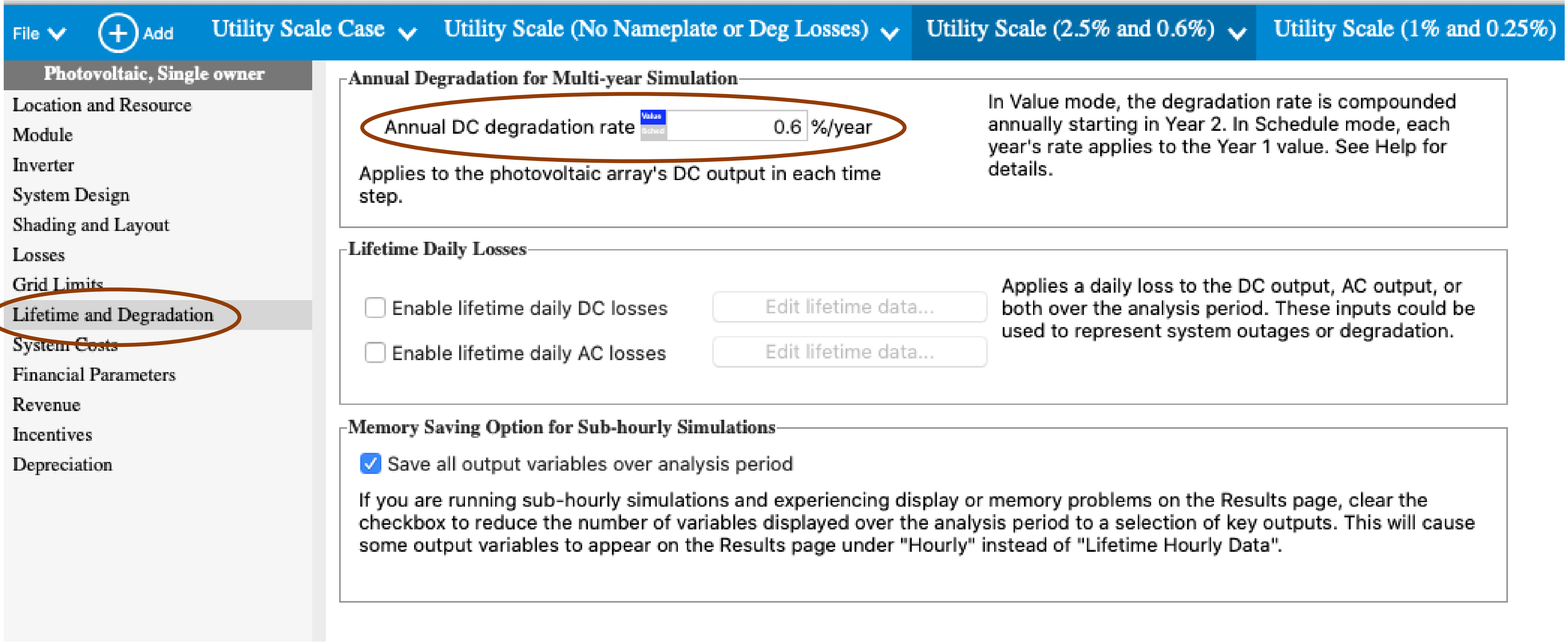
How to Reconcile SAM and Year-1 Power Loss in Warranties



Acknowledgements:

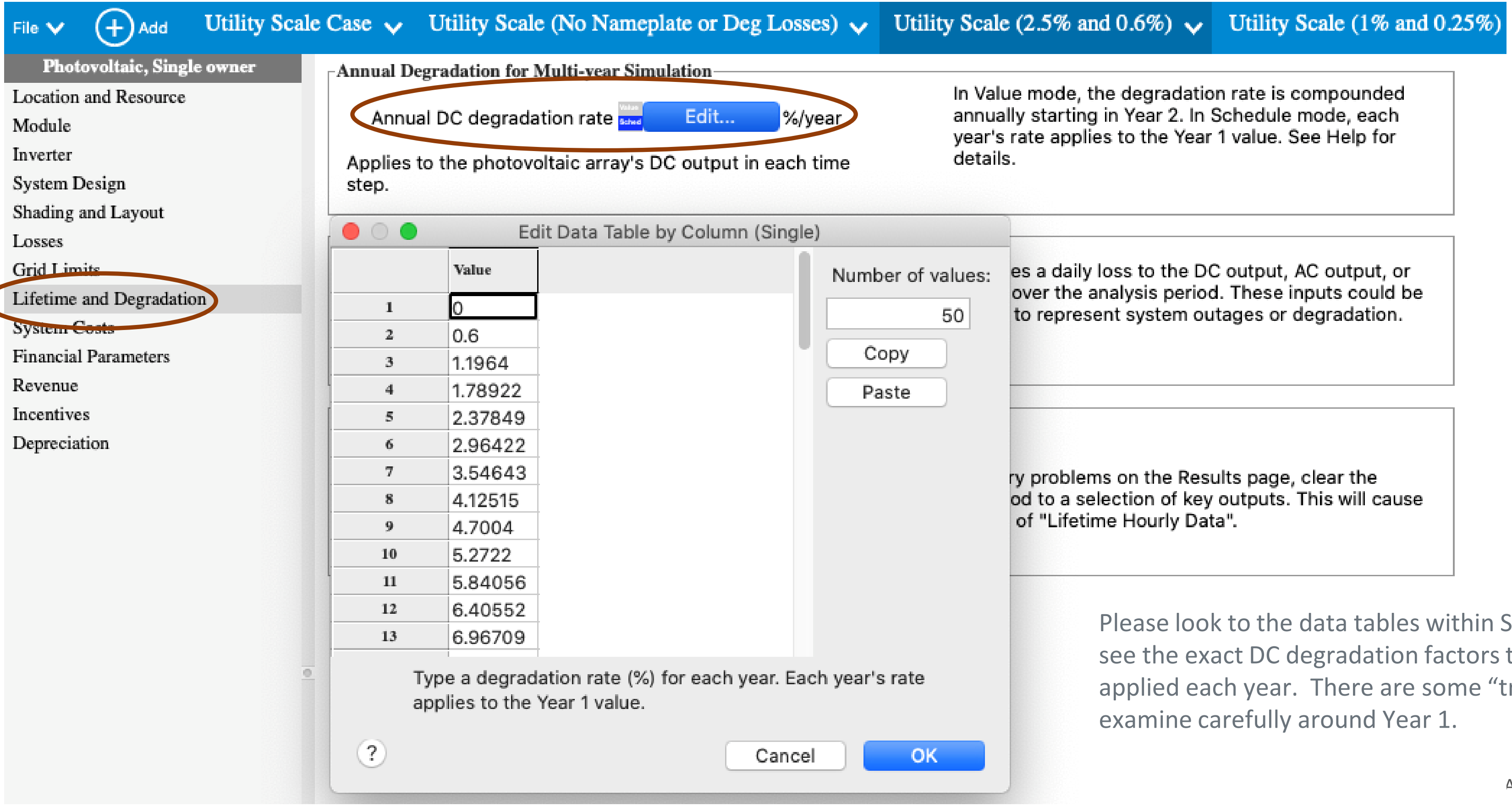
- Janine Freeman and Nate Blair (SAM team leads)

How to Input DC-Based Degradation Profiles Into SAM (Single Value Mode)



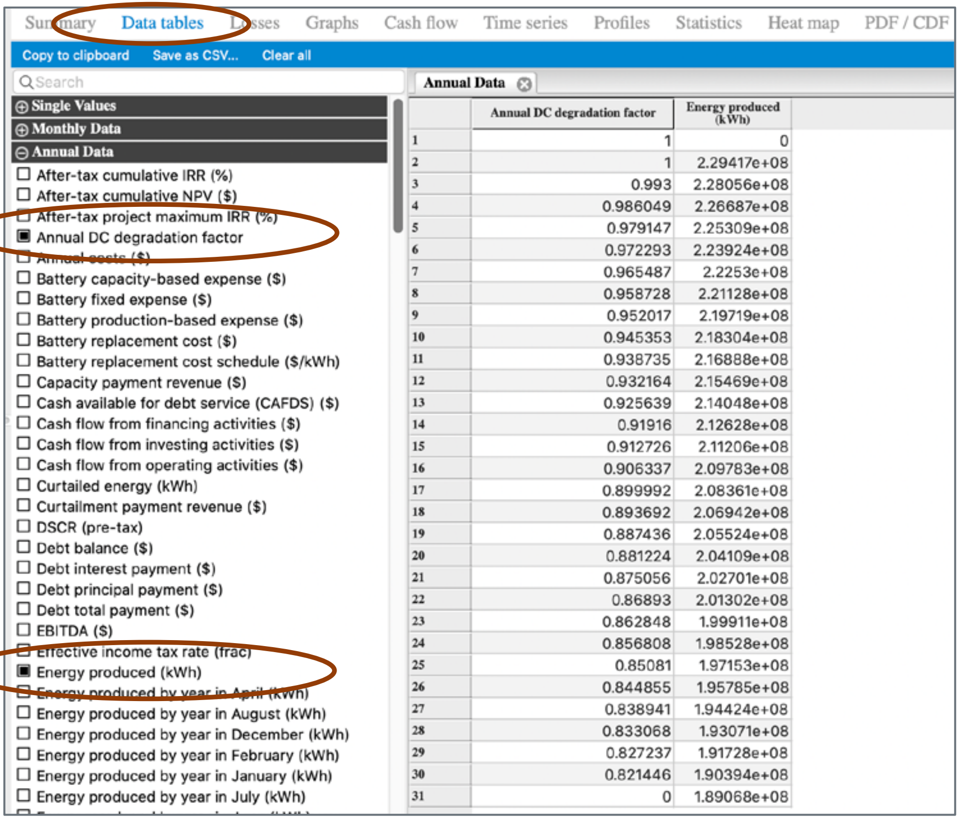
Please look to the data tables within SAM to see the exact DC degradation factors that are applied each year.

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$_{(AC)}$ Results

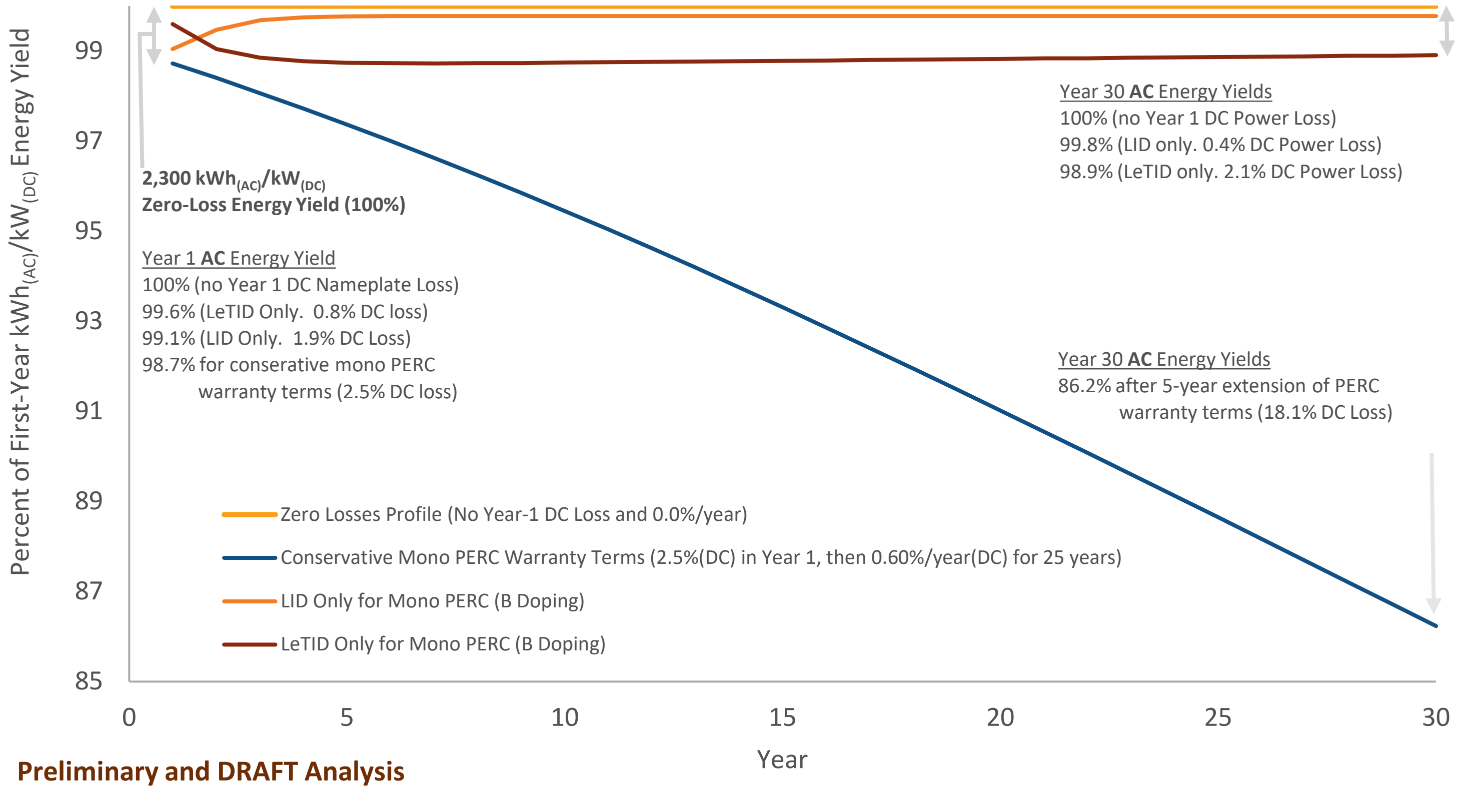


	Annual DC degradation factor	Energy produced (kWh)
1	1	0
2	1	2.29417e+08
3	0.993	2.28056e+08
4	0.986049	2.26687e+08
5	0.979147	2.25309e+08
6	0.972293	2.23924e+08
7	0.965487	2.2253e+08
8	0.958728	2.21128e+08
9	0.952017	2.19719e+08
10	0.945353	2.18304e+08
11	0.938735	2.16888e+08
12	0.932164	2.15469e+08
13	0.925639	2.14048e+08
14	0.91916	2.12628e+08
15	0.912726	2.11206e+08
16	0.906337	2.09783e+08
17	0.899992	2.08361e+08
18	0.893692	2.06942e+08
19	0.887436	2.05524e+08
20	0.881224	2.04109e+08
21	0.875056	2.02701e+08
22	0.86893	2.01302e+08
23	0.862848	1.99911e+08
24	0.856808	1.98528e+08
25	0.85081	1.97153e+08
26	0.844855	1.95785e+08
27	0.838941	1.94424e+08
28	0.833068	1.93071e+08
29	0.827237	1.91728e+08
30	0.821446	1.90394e+08
31	0	1.89068e+08

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.

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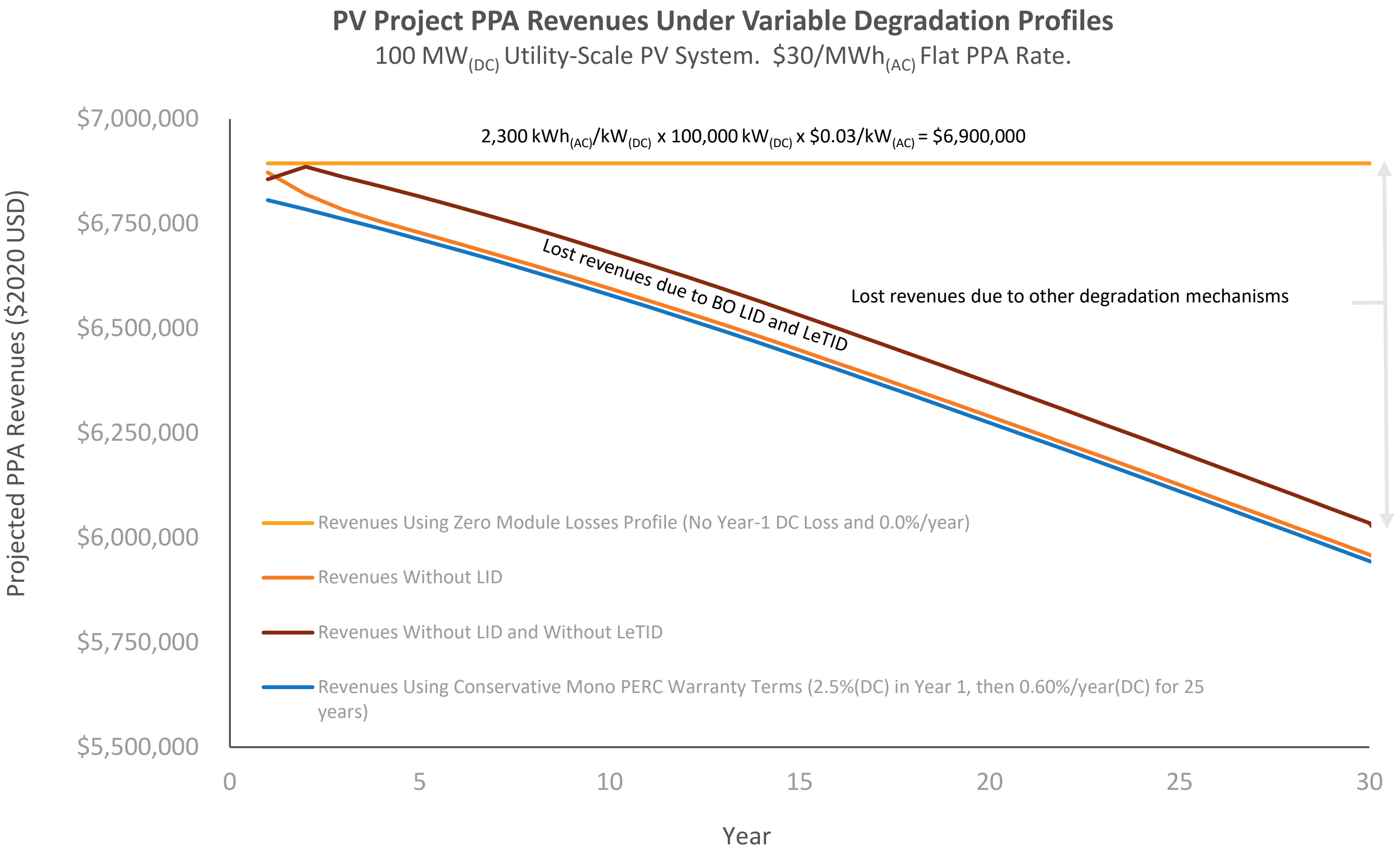
Preliminary and DRAFT Analysis
Feedback and Comments Welcome

Project PPA Revenues for the Different Warranty Profiles



Project PPA revenues ($):

- $kWh_{(AC)}/kW_{(DC)}$ energy yield *times*
- System size (DC) *times*
- $\$/kWh_{(AC)}$ (or $\$/MWh_{(AC)}$) PPA rate *times*

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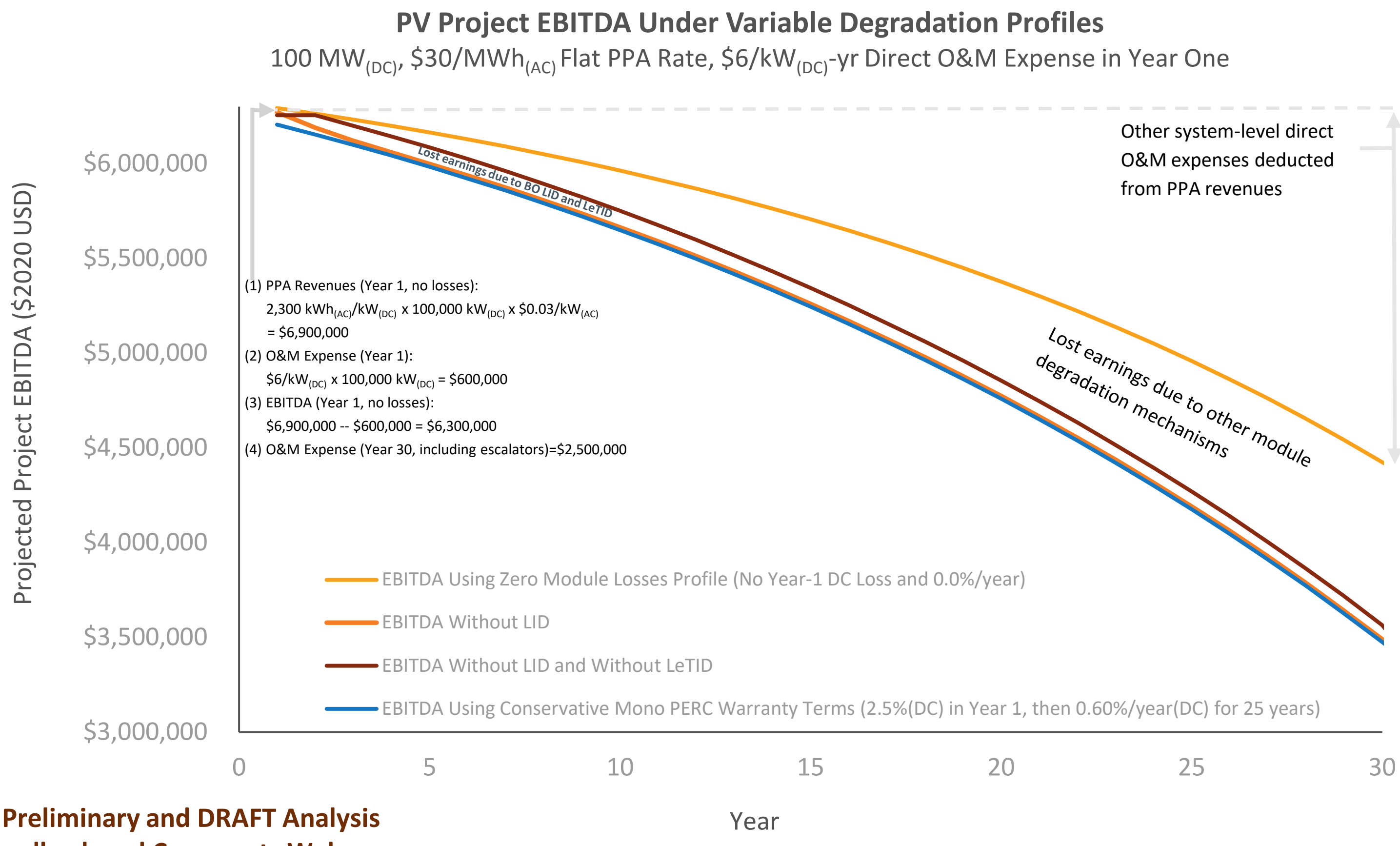
Project EBITDA for the Different Warranty Profiles



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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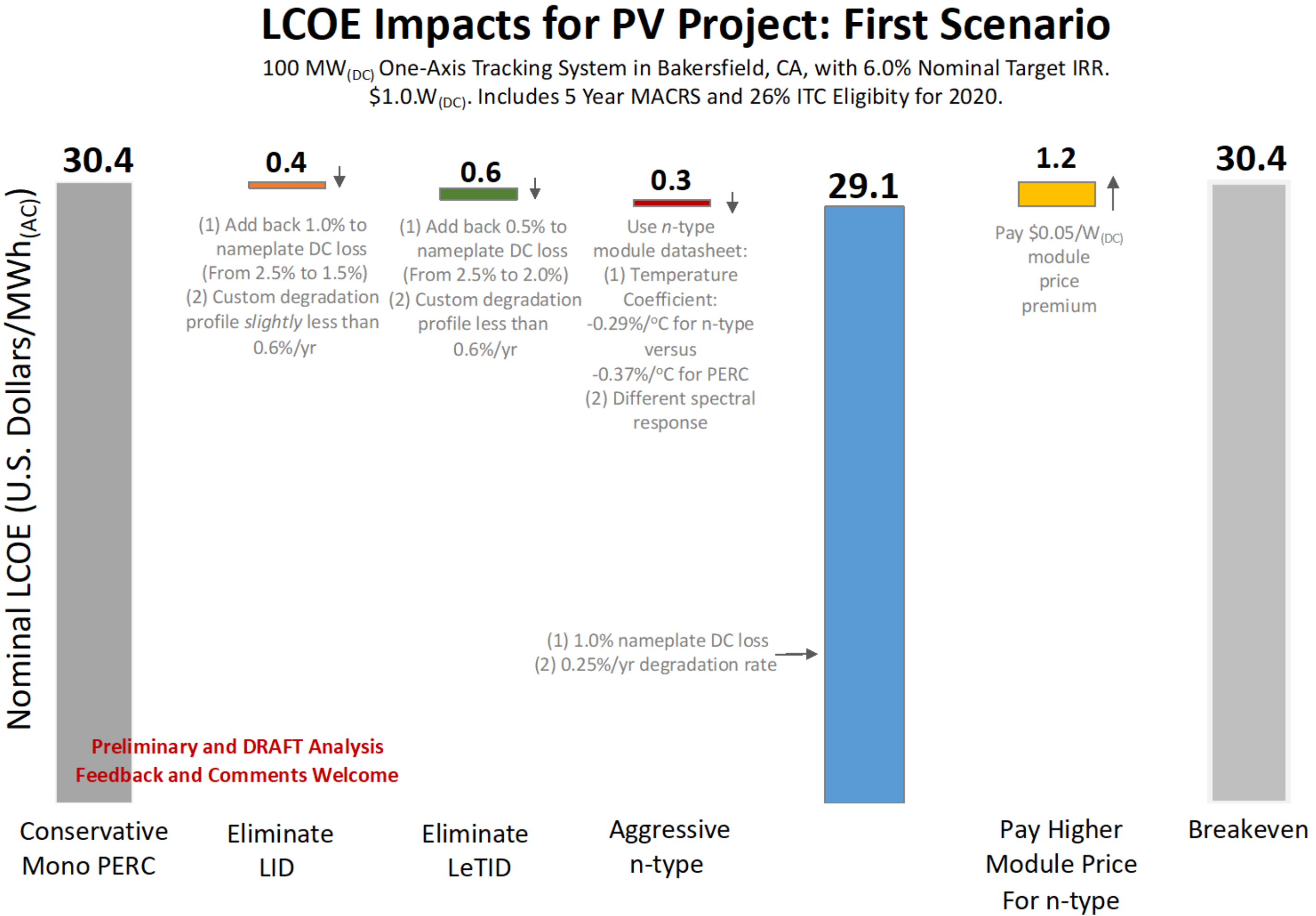
Project Financial Modeling: Conservative PERC and Aggressive n-type



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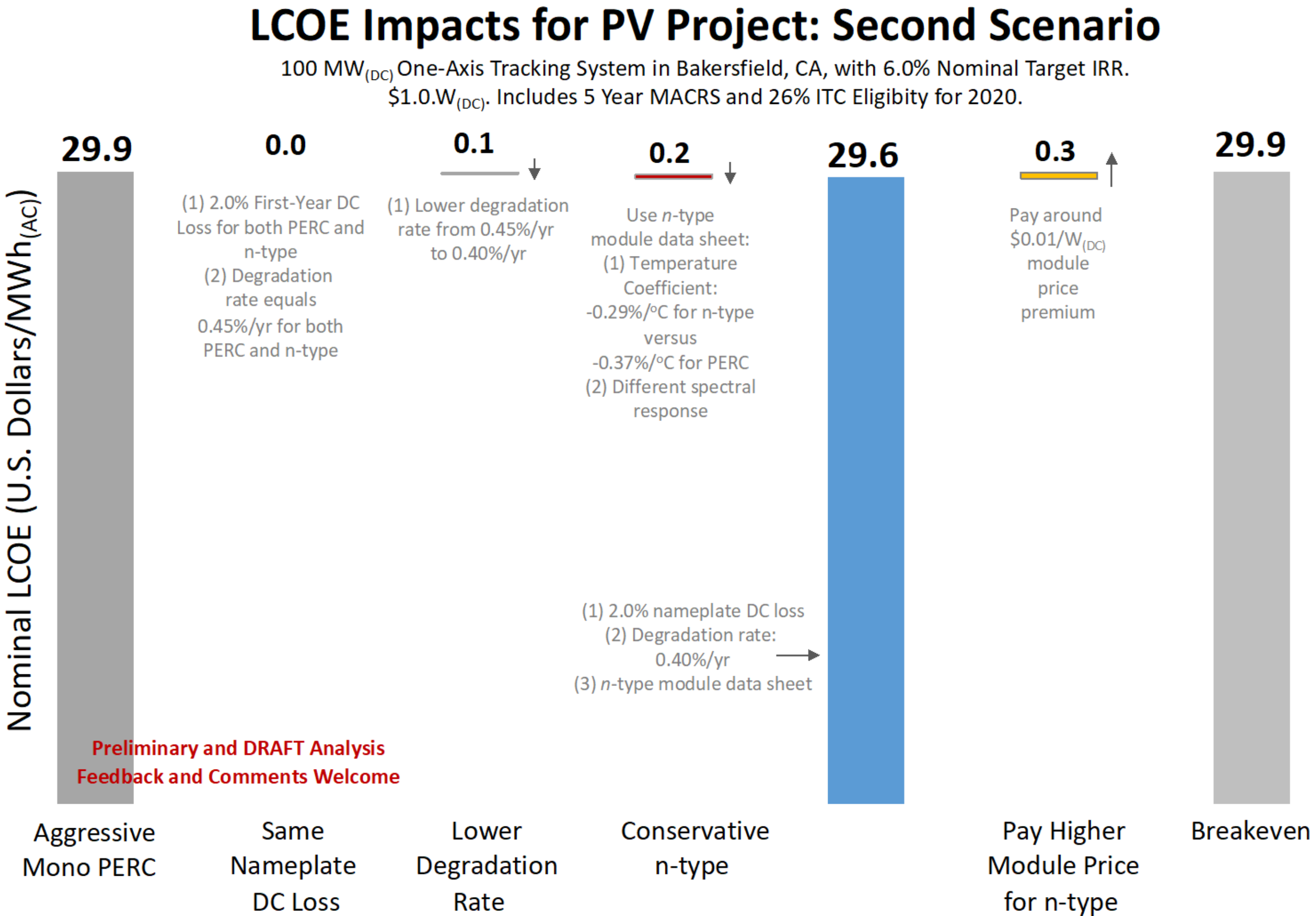
Project Financial Modeling: Aggressive PERC and Conservative n-type



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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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DuraMAT project: Module-level Solutions for Degradation by Ionization Damage

Ultraviolet-Light Induced Degradation (UV-LID) of High-Efficiency Solar Cells. RE: Technoeconomic Analysis

Peter Hacke, David Miller, Katherine Hurst, Jiadong Qian

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Archana Sinha, Stephanie Moffitt, Laura Schelhas, Sona Ulicna

SLAC NATIONAL ACCELERATOR LABORATORY

DuraMAT webinar on 2020/12/14
See also: Sinha et. al., Proc. IEEE PVSC Conf., 2020.

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2. T. Niewelt, et al., IEEE J. Photovoltaics, 7, 2017
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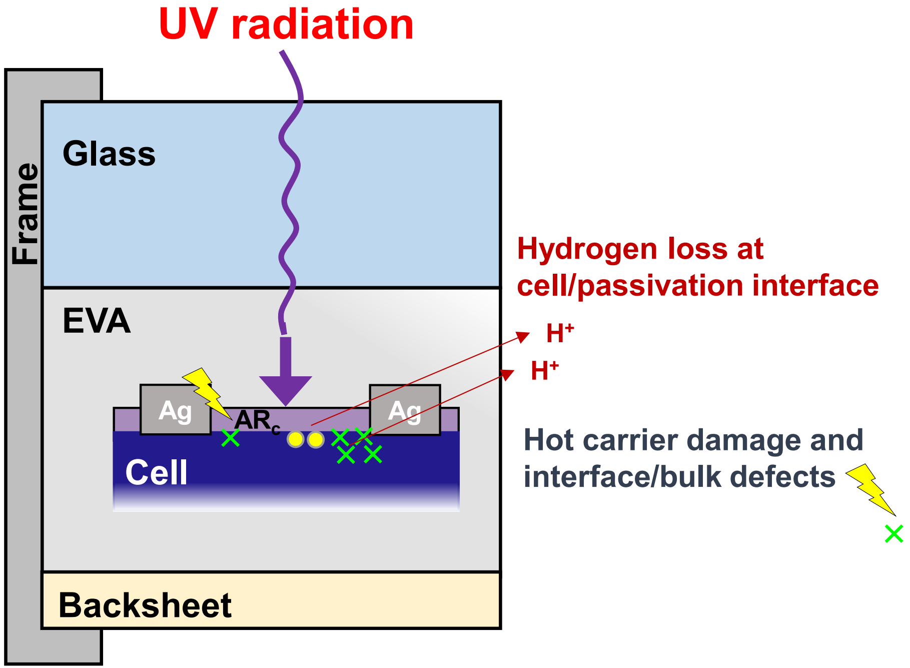
5. R. Witteck et al., Phys. Status Solidi - Rapid Res. Lett., 11, 2017

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:

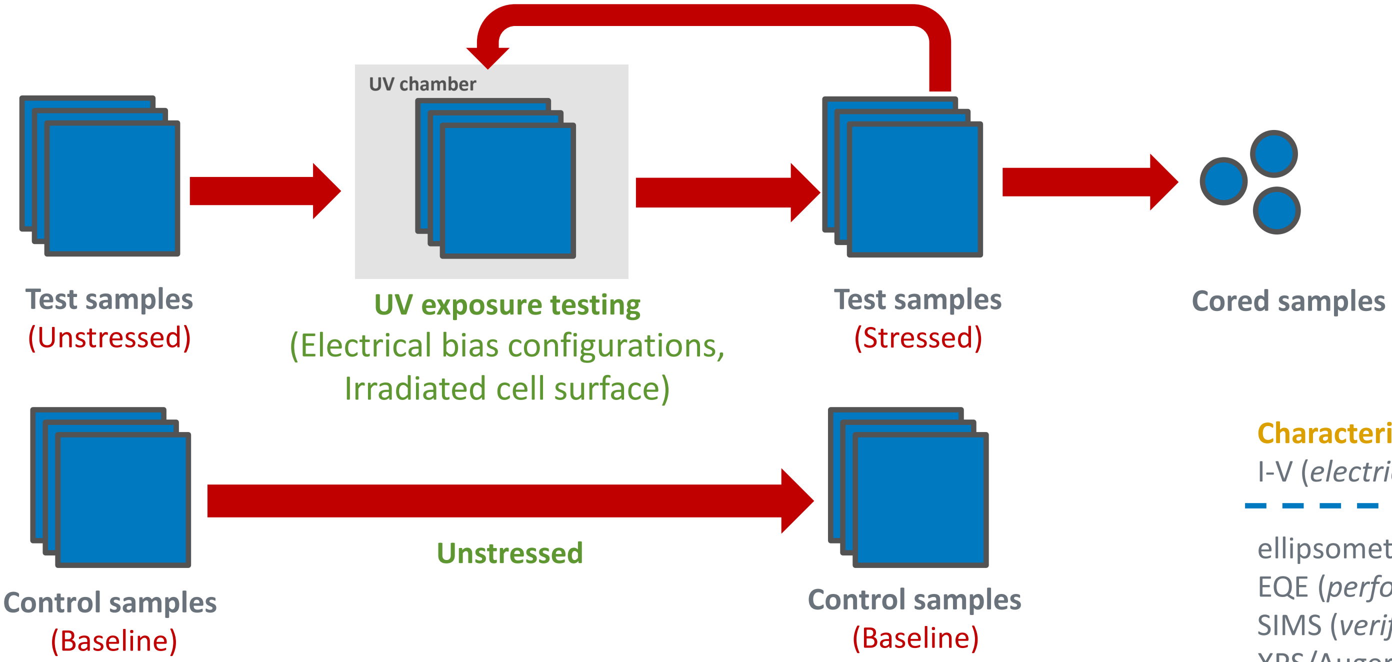
- Verify the damaging effects of UV in today's high-efficiency commercial silicon cells.
- Quantify the magnitude of degradation.
- Investigate the underlying degradation mechanisms.
- Advise on module-level solutions for mitigating degradation.

Screen test 1: Bare cells

2000 hours of UV exposure completed all samples.

3000 hours some samples.

Experimental Design



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·m-2 at 340 nm, cell temperature: 45 oC (prevent LETID), ambient humidity (~7%)
- Test duration: ≥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

FO – Front-side exposure, open-circuit bias
BO – Back-side exposure, open-circuit bias
FS – Front-side exposure, short-circuit bias

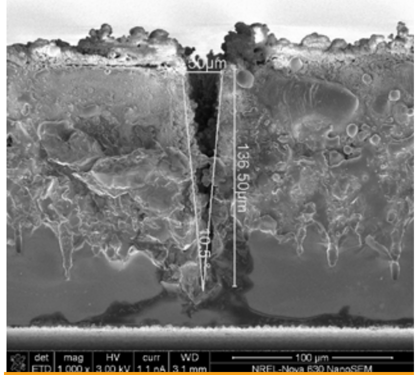
Samples: the sign (*) denotes bifacial cells

Company ID	Cell technology	Cell construction	Bifacial?	Front structure	Rear structure	Test Lab	NREL		SLAC		
		(mono-/multi-)					FO	BO	FO	BO	FS
A	HJ	mono	y	ITO/(p+)a-Si/(i)a-Si	n Si/(i)a-Si/(n+)a-Si/ITO	NREL, SLAC	3		3	3	2
B	IBC	mono	y	SiN_x/SiO_2/n+Si	-	NREL	3	3			
C	n-PERT	mono	y	SiN_x/SiO_2/p+Si/n Si	n Si/n+/SiN_x	NREL, SLAC	3		3	3	3
D	n-PERT	mono	y	SiN_x/SiO_2/p+Si/n Si	-	NREL	3				
E	n-PERT	mono	y	SiN_x/SiO_2/p+Si/n Si	n Si/n+Si/SiN_x	NREL, SLAC	3		3	3	2
F	n-PERT	mono	y	SiN_x/SiO_2/p+Si/n Si	-	SLAC			3	3	
G	p-PERC	mono	y	SiN_x/SiO_x/n+Si/p Si	p-Si/AlO_x/SiN_x/Al	NREL, SLAC	3		3	3	3
H	p-PERC	mono	n	SiN_x/n+Si/p Si	p+Si/SiN_x	NREL, SLAC	3			3	3
I	p-PERC	mono	y	SiN_x/n+Si/p Si	-	NREL	3				
J	p-PERC	mono	y	SiN_x/SiO_x/n+/p Si	p-Si/AlO_x/SiN_x	NREL	3				
K	p-PERC	multi	y	SiN_x/SiO_x/n+/p Si	p-Si/AlO_x/SiN_x	NREL	3				
L	Al-BSF	multi	n	SiN_x/n+Si/p Si	-	NREL, SLAC	3		3		

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

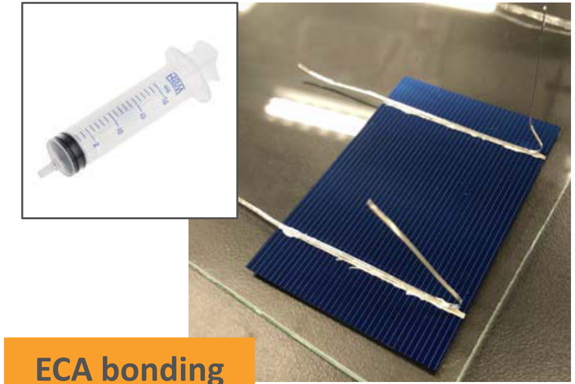
Test Sample Build

Laser scribed cell



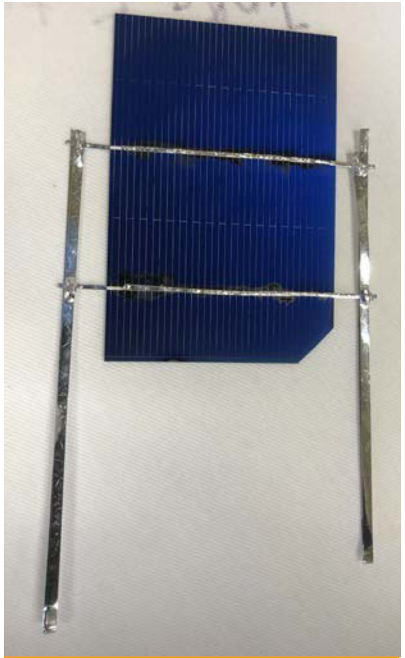
SEM image: Laser scribe depth

Pb-Sn Soldering



ECA bonding

ECA: electrically conductive adhesive



Finished sample

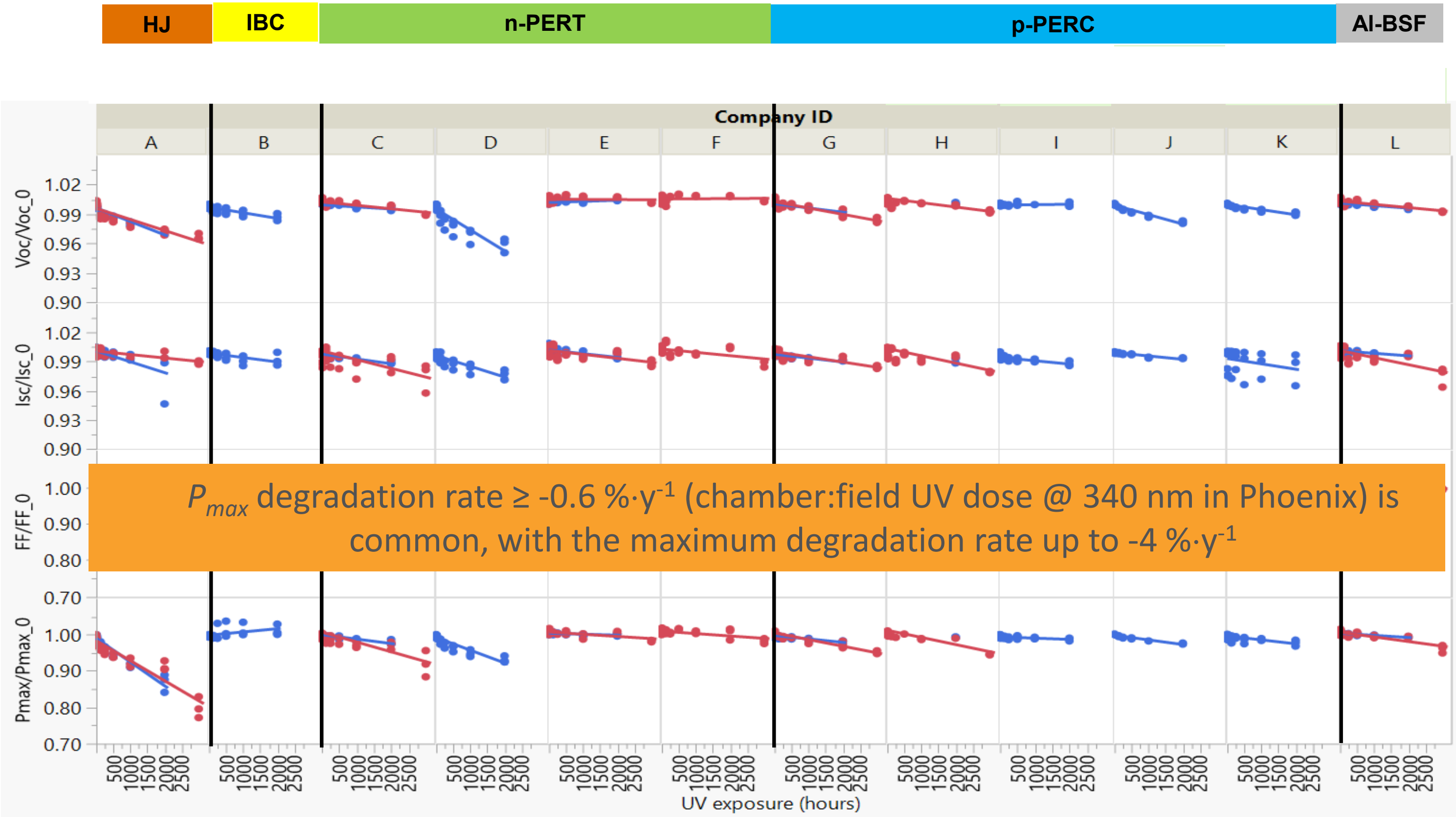
Outdoor Preconditioning

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

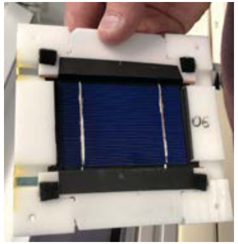
SLAC NATIONAL ACCELERATOR LABORATORY

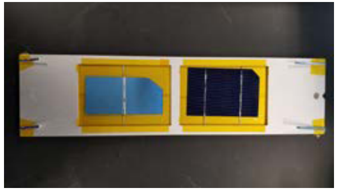
featuring Kapton (PI) tape

UV Sensitivity of Different Cell Technologies: *Front Exposure*

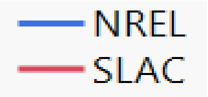


P_{max} degradation rate ≥ -0.6 %·y^{-1} (chamber:field UV dose @ 340 nm in Phoenix) is common, with the maximum degradation rate up to -4 %·y^{-1}





Sample and fixture configurations at NREL and SLAC



HJ: see also: D. Jordan, et al., Prog. Photovolt: Res. Appl. 24, 2016

Degradation Rate: Variation and Caveats

2000h of UV exposure (NREL + SLAC)						
Characteristic	**Statistic**	**Al-BSF (6)**	**HJ (6)**	**IBC (3)**	**n-PERT (18)**	**p-PERC (21)**
P_{max} {% change}	Lowest	-0.45	-7.21	2.90	1.54	-0.60
	Highest	-0.95	-15.89	0.07	-7.53	-3.64
	Average	-0.72	-10.92	1.16	-1.83	-1.79
	Std Dev (1σ)	0.02	0.30	0.15	0.28	0.08
I_{sc} {% change}	Lowest	-0.15	0.07	-0.04	0.56	-0.31
	Highest	-0.49	-5.37	-1.36	-2.88	-3.49
	Average	-0.37	-1.27	-0.80	-0.76	-0.90
	Std Dev (1σ)	0.01	0.21	0.07	0.10	0.07
V_{oc} {% change}	Lowest	-0.18	-2.55	-0.95	0.89	0.23
	Highest	-0.54	-3.14	-1.68	-4.96	-1.96
	Average	-0.30	-2.84	-1.32	-0.47	-0.66
	Std Dev (1σ)	0.01	0.02	0.04	0.18	0.07
FF {% change}	Lowest	0.07	-4.85	4.91	0.25	1.24
	Highest	-0.19	-9.30	1.91	-3.13	-1.82
	Average	-0.06	-7.15	3.33	-0.61	-0.24
	Std Dev (1σ)	0.01	0.16	0.15	0.11	0.06

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

- 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:

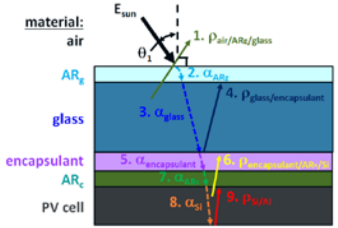
- We are assuming the degradation rate is linear
- (e.g., early module life).
- We make no assumption for the maximum total degradation. Suspected degradation mechanisms attributed to changes in thin layers.
- 2.3% light gain from UV transmitting encapsulant may be reduced by:
  - Cell-specific EQE,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

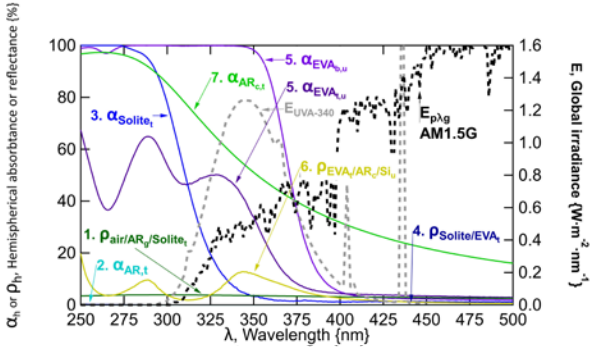
The Application-Specific UV Dose Rate

The UV light incident to the Si_xN_y surface and AR_c/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/AR_c/Si stack, and absorbed in the Si_xN_y bulk.
- Additional UV is attenuated in a PV module by: AR_g, front glass, encapsulant (transmitting or blocking).





Comparison of UV sources and PV packaging components relative to the ideal spectrum for the sun.

- 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).

"SAMPLE"	APPLICATION	INTENSITY {$W \cdot m^{-2}$}	INTENSITY FACTOR {dimensionless}
terrestrial sun (AM1.5G)	reference	0.50	1.0
UVA-340 lamp	UV-LID screen tests	1.24	2.5
UVA-340/air/Si_xN_y	UV-LID screen tests	0.77	1.5
UVA-340/air/Si_xN_y/Si	UV-LID screen tests	0.074	0.15
sun/air/AR/textured glass/POE_{UVb}/Si_xN_y	PV module	0.0078	1.6E-02
sun/air/AR/textured glass/POE_{UVt}/Si_xN_y	PV module	0.37	7.4E-01
sun/air/AR/textured glass/POE_{UVb}/Si_xN_y/Si	PV module	6.8E-04	1.4E-03
sun/air/AR/textured glass/POE_{UVt}/Si_xN_y/Si	PV module	0.032	0.064

Spectral analysis of UV (at 340 nm) in various sample "configurations".

Preventing UV-LID

PV packaging:

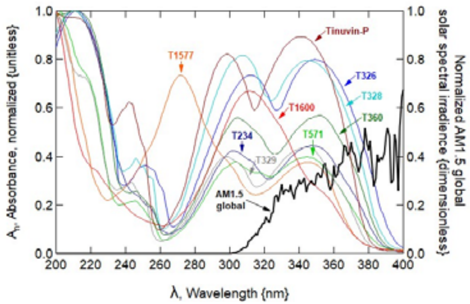
- Wavelength-tailored, partially UV blocking formulations.
- Novel formulation additives, e.g, triazine instead of benzotriazole UV absorber.
- Possible added cost.

UV blocking glass:

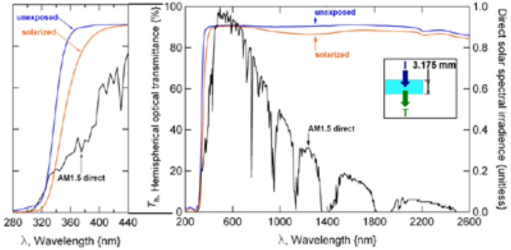
- Ce doped glass (from aerospace) was previously used in PV industry.
- Added cost & complexity of enhanced solarization of the glass.

PV cell:

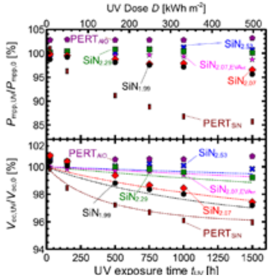
- Improve the design and fabrication of passivation layer, where possible.
- -e.g., AlxOy interlayer containing passivation found more UV-LID stable for n-PERT.
- -Research needed. Some cell technologies or makes may emerge as less UV-LID sensitive.



Comparing the spectral absorptance of UV absorbers.
Unpublished, similar to: Miller et. al., NREL/PR-5K00-70366, 2018.



Comparing the solarization of Krystal Klear (Ce containing) soda-lime glass.
Miller, NREL/PR-5J00-66584, 2016.



Comparing cell passivations. Witteck et. al. Proc. IEEE PVSC Conf., 2017.

Summary

This study:

- UV-LID verified, separate from B-O LID (stabilized beforehand) and LETID (low temperature test used).
- Common ΔP_{max} is -0.6 %·y-1 (bare cells, chamber:field UV dose) → -0.1 %·y-1 (AM1.5, PV module), with the maximum degradation rate up to -4 %·y-1 → -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 → 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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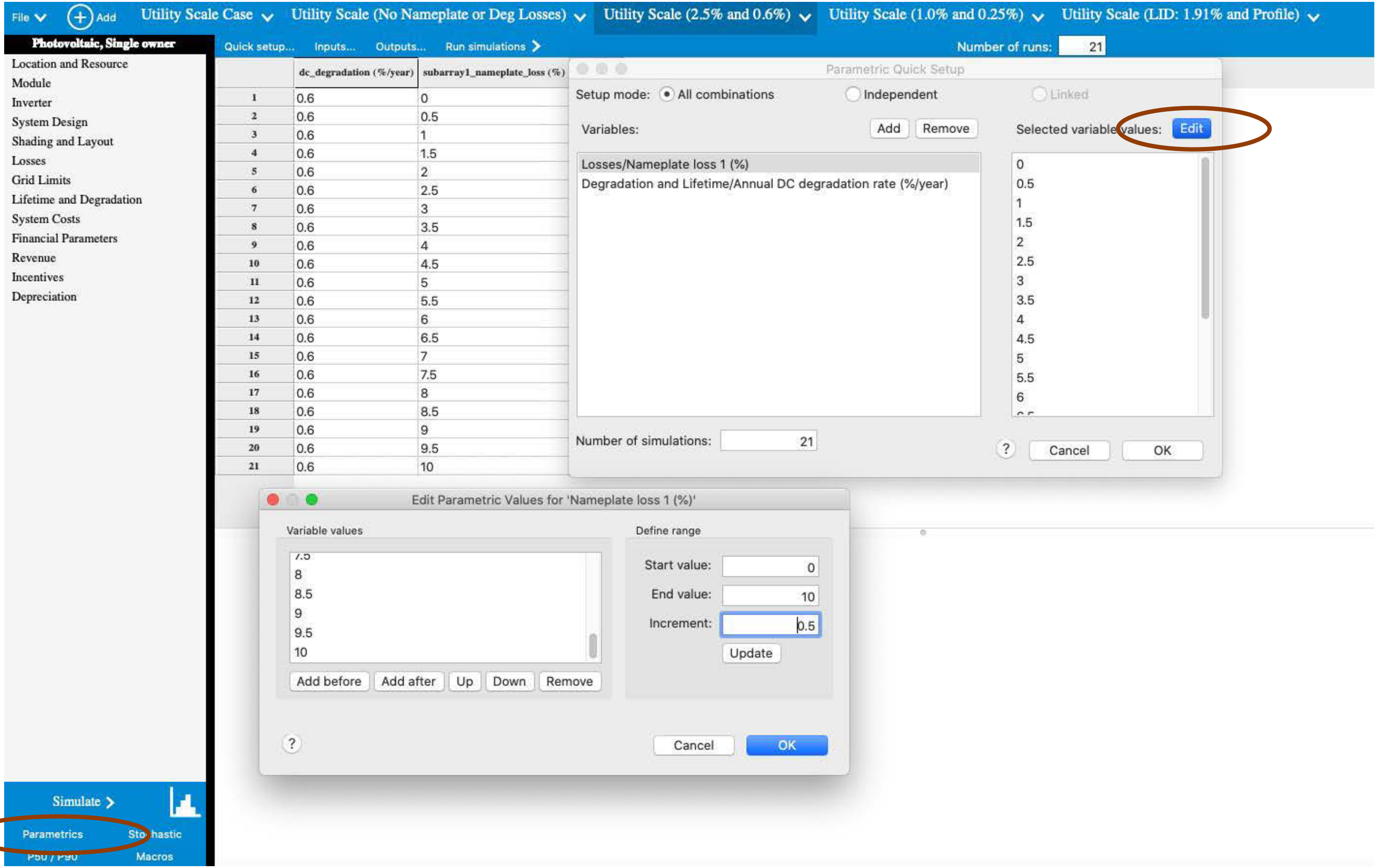
Presentation Outline

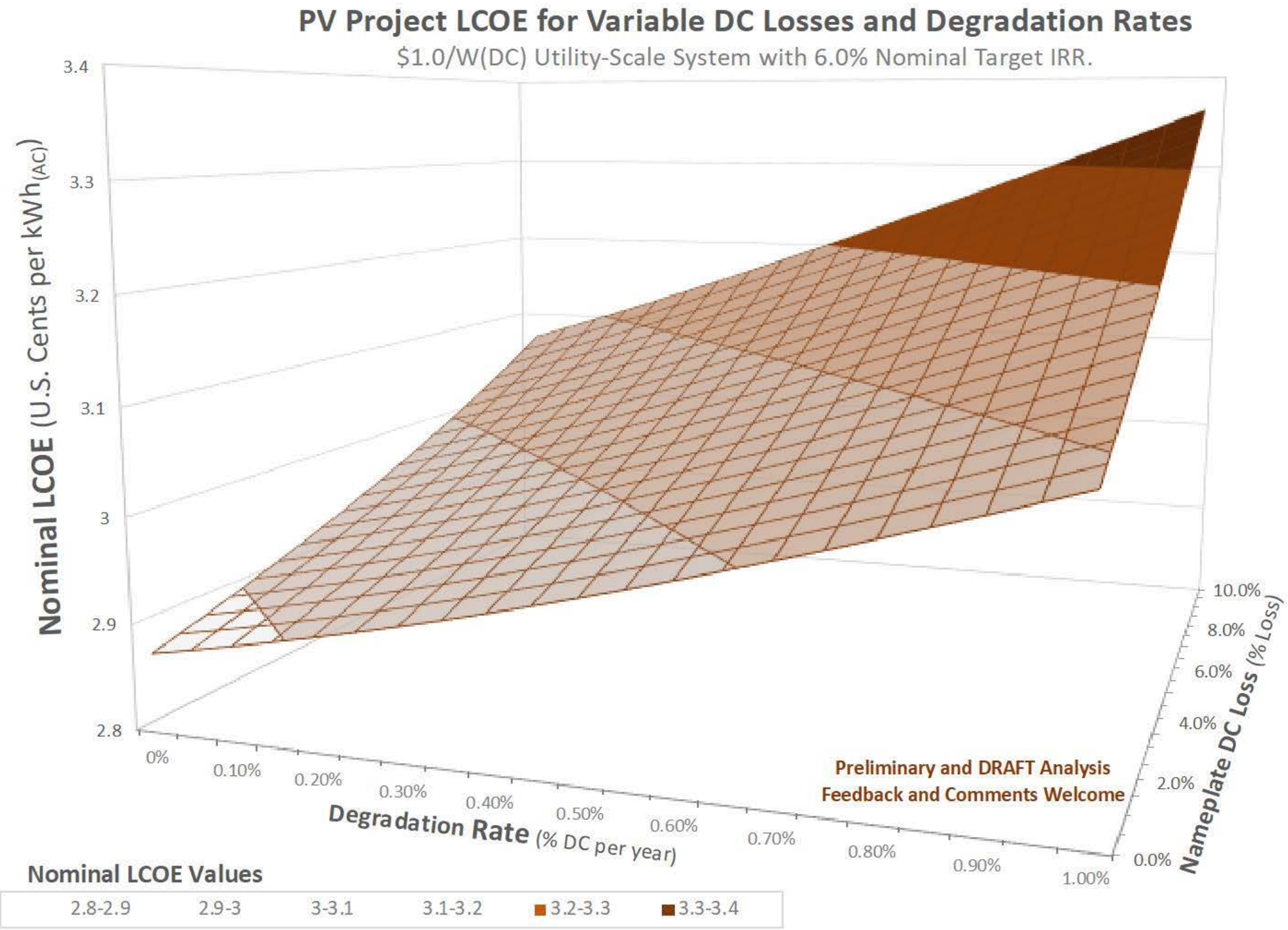
Tradeoffs Between Encapsulant Choices

	UV-Transmitting Encapsulant Typically, on the front (and back if bifacial)	**UV-Blocking Encapsulant** Typically, on the back for Glass-Backsheet
First Impact: Nameplate (DC) Module Power Rating at STC	Up to 1% (relative) advantage (e.g., 450—455 W binning)	Up to 1% (relative) loss. (e.g., 445—450 W binning)
Second Impact: Degradation Profile	Up to 0.73%/year loss in DC power rating due to degradation in the solar cell. 0.12%/year is more typical.	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.

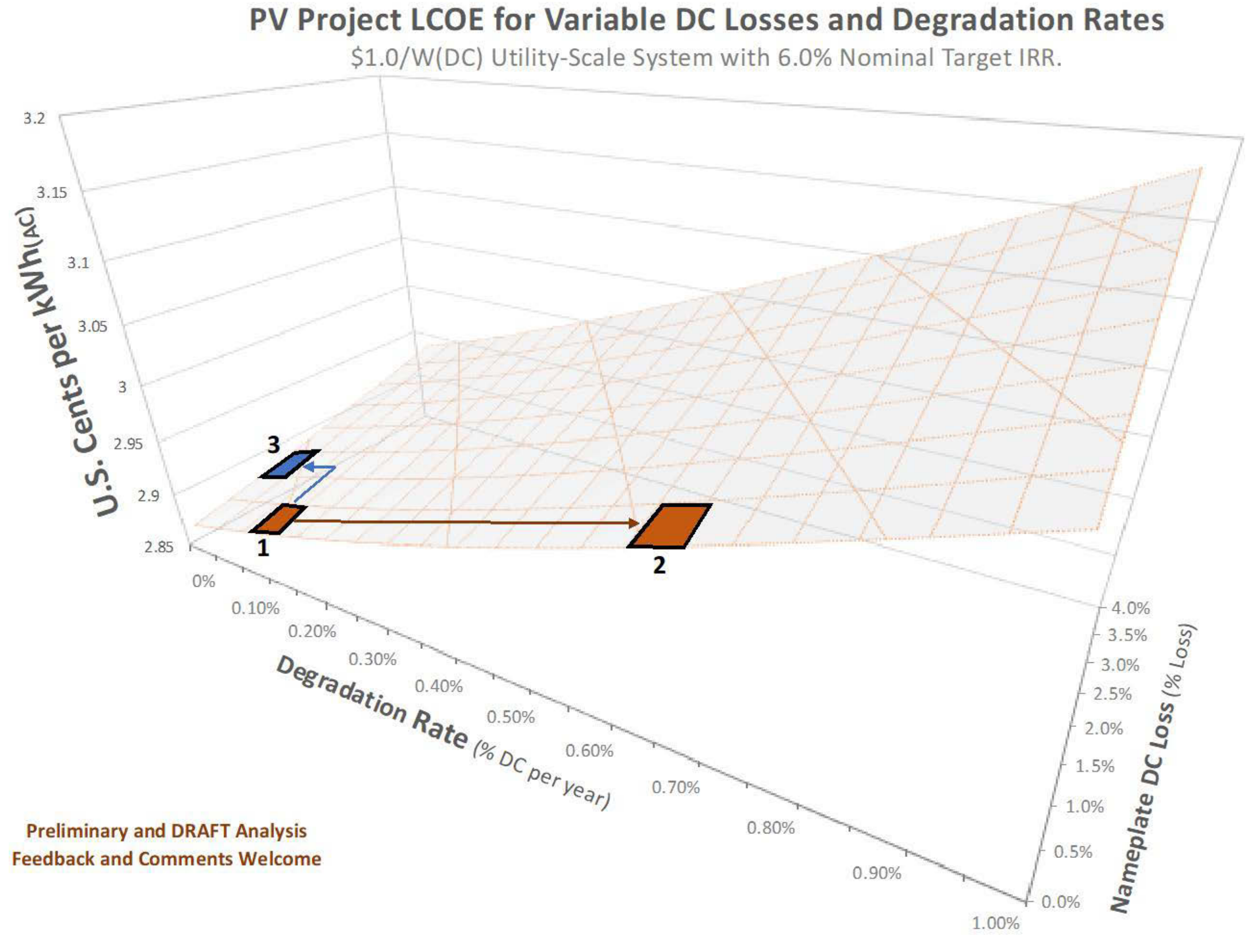
Running Parametrics Within SAM



LCOE Framework (SAM Parametrics)



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)

UV Transmitting Encapsulant

Industry standard for front
(and back, if bifacial)

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

LCOE = \$28.9/ $MWh_{(AC)}$

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

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

LCOE = \$30.2/ $MWh_{(AC)}$

UV Blocking Encapsulant

Industry standard for back

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

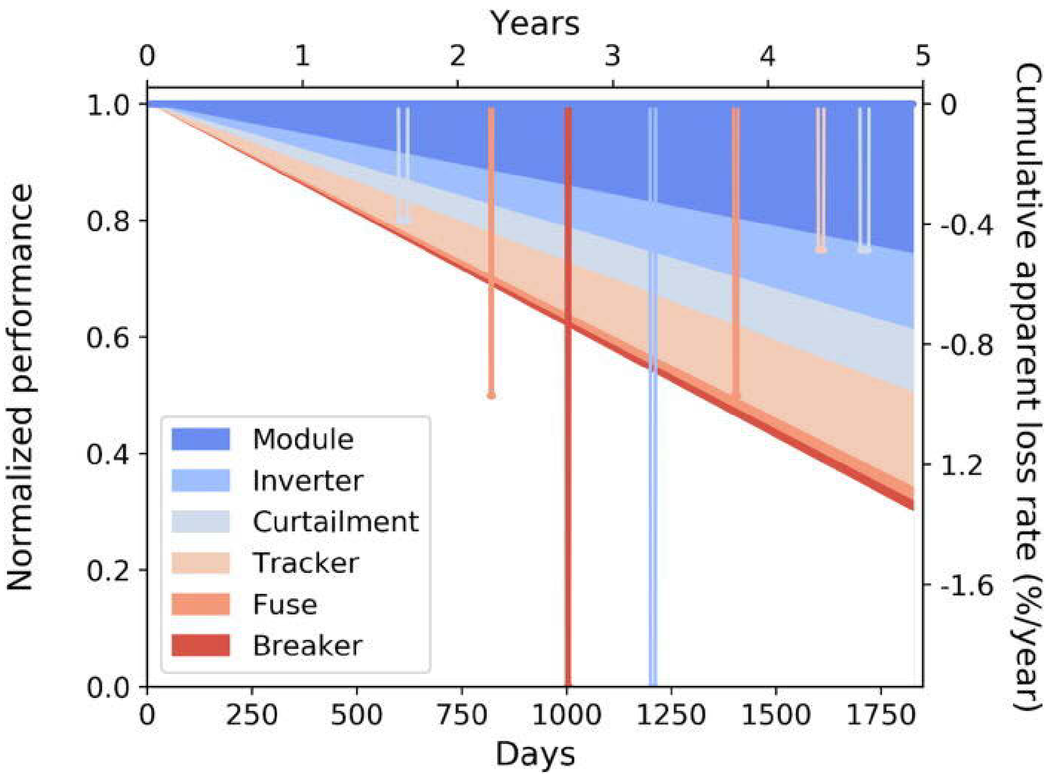
LCOE = \$28.9/ $MWh_{(AC)}$
Before considering additional capital costs

Additional Capital Costs Expected Due to Lower Rated Efficiency:

1) Module manufacturing costs
2) BOS Hardware and Labor Costs
3) Shipping

Presentation Outline

Conclusions and Proposed Next Steps



Source of **ILLUSTRATIVE** cumulative degradation rate curve:

M Bolinger, W Gorman, D Millstein, and D Jordan "System Level Performance of 21 $GW_{(DC)}$ of Utility-Scale PV Plants in the U.S.", *Journal of Renewable and Sustainable Energy*, 12, 043501 (2020).

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

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