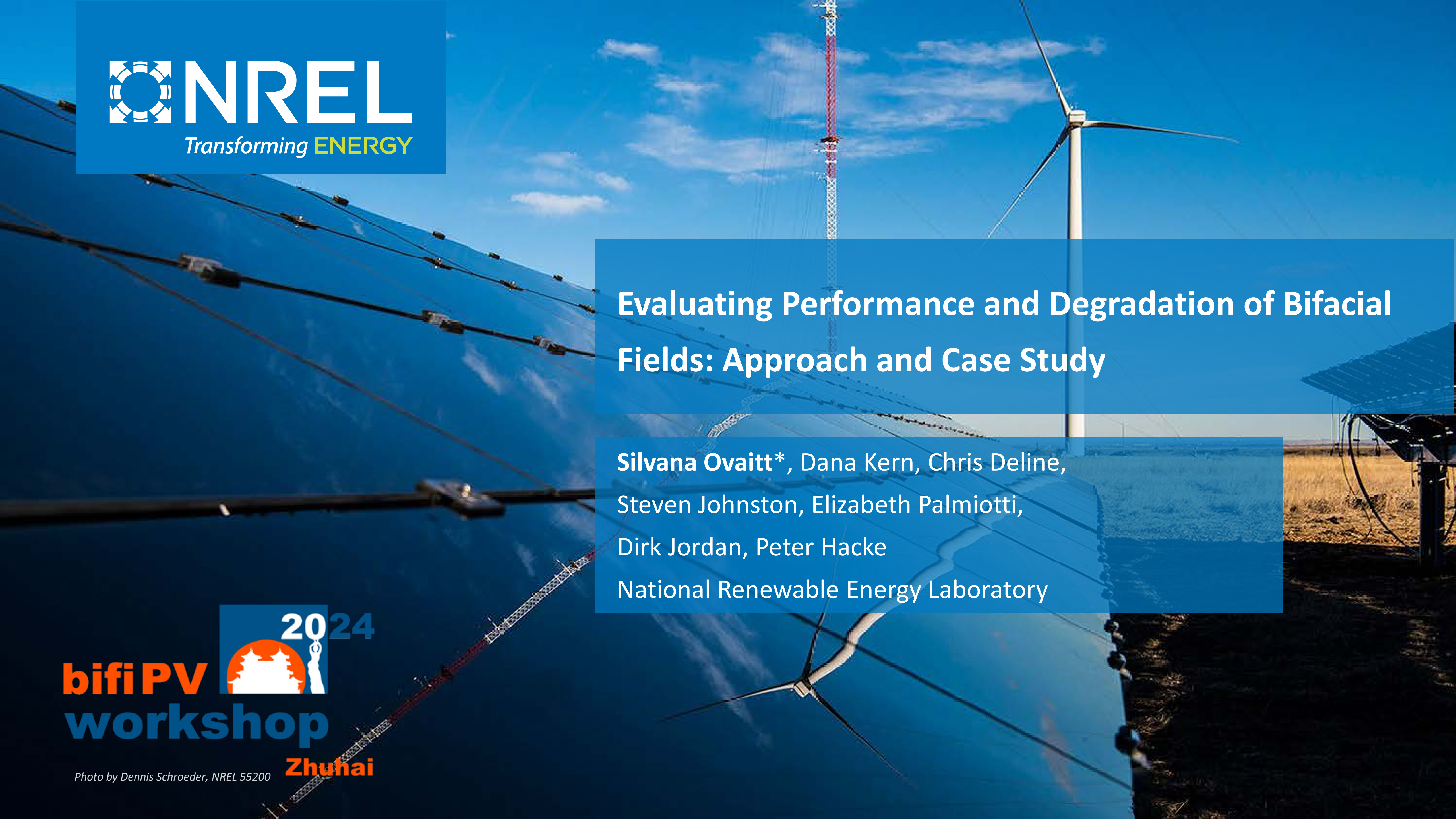


Photo by Dennis Schroeder, NREL 55200

NREL
Transforming ENERGY

Evaluating Performance and Degradation of Bifacial Fields: Approach and Case Study

Silvana Ovaitt*, Dana Kern, Chris Deline,
Steven Johnston, Elizabeth Palmiotti,
Dirk Jordan, Peter Hacke
National Renewable Energy Laboratory

2024 bifiPV workshop Zhuhai

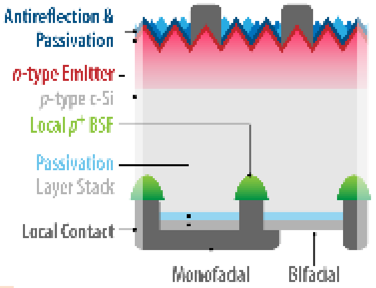
Cell Technologies Evolution

p-type

PERC (Passivated Emitter and Rear Cell)

Drivers & Benefits

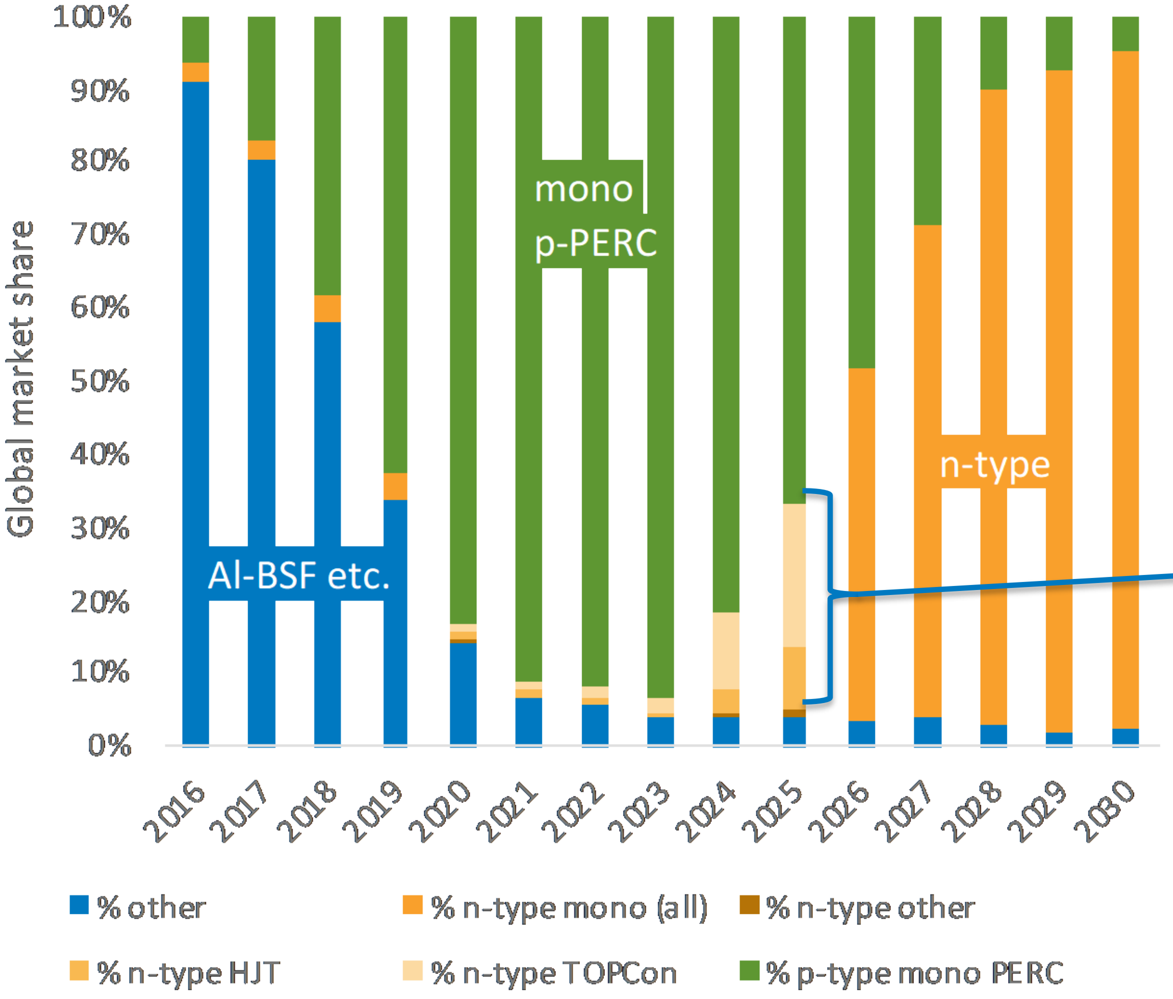
- Largest market share and longest history
- Monofacial and bifacial options
- Industry transitioned from Boron to Gallium doping to mitigate degradation



Potential Risks & Challenges

- Current production cells close to practical efficiency limits - further improvements difficult
- Bifaciality is slightly lower compared to TOPCon/SHJ

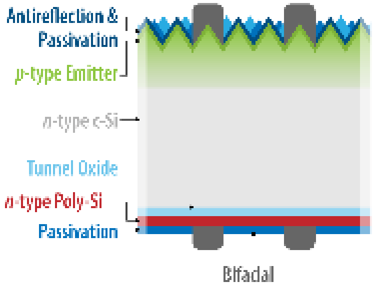
Si Cell Technologies



Jarett Zuboy et al DuraMAT Tech Scouting 2022

n-type

TOPCon (Tunnel Oxide Passivating Contact)



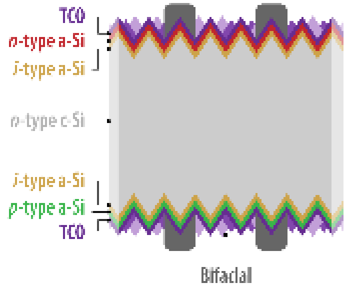
Drivers & Benefits

- Inherently bifacial
- Most easily adapted from existing PERC capacity
- Slight efficiency and bifaciality advantage over PERC

Potential Risks & Challenges

- Newer technology than SHJ - less production history, but fundamentally compatible with the conventional Si solar cell production process

SHJ (Silicon hetero-junction solar cell)



Drivers & Benefits

- Superior surface passivation quality improves carrier lifetime and increases cell voltage even further (750 mV)
- Typically, the highest bifaciality and slight efficiency advantage over PERC

Potential Risks & Challenges

- Process temperature limited to <200°C, and this impacts metallization and interconnect technologies and costs
- Substantially different manufacturing process
- Higher tool costs

M. Woodhouse, PVRW 2023

75 kW bifacial HSAT

5 bifacial tech. | Est. 2019

2019-2024

Open source data: https://datahub.duramat.org/dataset/best-field-data
https://datahub.duramat.org/dataset/best-field-degradation-research

75 kW Bifacial Experimental Single-Axis Tracking Field

- ❑ 5 bifacial technologies, including PERC & SHJ
- ❑ 3 Monofacial counterparts
- ❑ +8 Rear Irradiance Sensors (IMT, K&Z, Licor)
- ❑ Module and Row electrical data
- ❑ 3 Albedometers + 1 rotating albedometer
- ❑ Custom Irradiance Evaluating Module “Hydra”
- ❑ Spectral rear data (some)
- ❑ Weather and more spectral and albedo data <60 m from field from SRRL

Summer 2022, 2023, 2024

- ❑ AgriPV deployment: Pollinator Habitat, Crops & Pasture Grass
- ❑ Albedo materials testing (2022)

Open Source on

https://datahub.duramat.org/dataset/best-field-data
https://datahub.duramat.org/dataset/best-field-degradation-research

Technologies under discussion

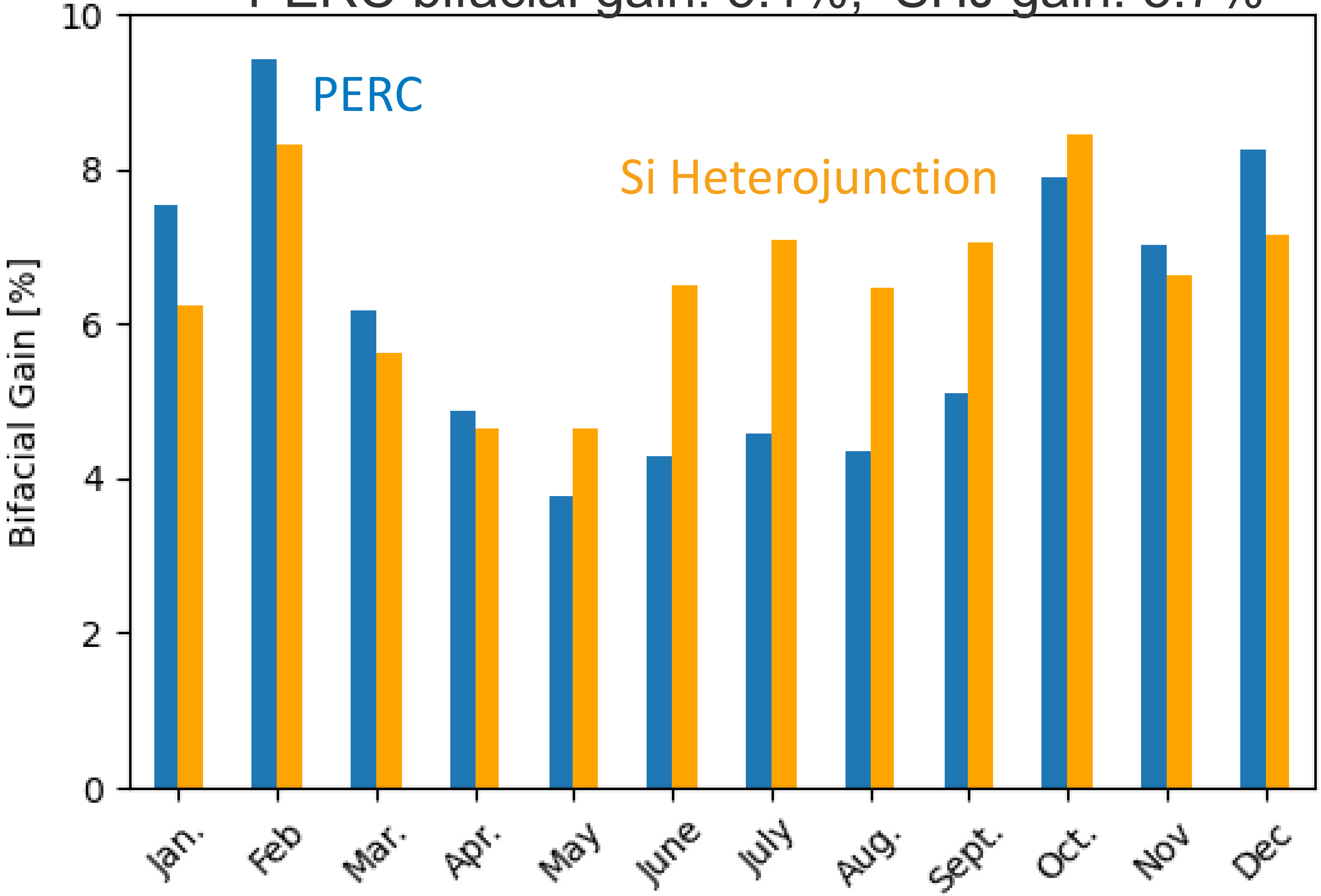
	Manufacturer A Prism	Manufacturer B Longi	Manufacturer C	Manufacturer D	Manufacturer E Sunpreme
Technology	pPERC	pPERC	pPERC	mc-pPERC	HJT
Back Surface	Glass				
Half or Full Cell	Full	Full	Half	Half	Half
JB Location	Top	Top	Center	Center	Center
Encapsulant*	EVA	*NA*	EVA	*NA*	*NA*
Control module available	Yes	Yes	Yes	No	Yes
Monofacial pair available	No	Yes	Yes	Yes	No

4.83-year Technology Comparison

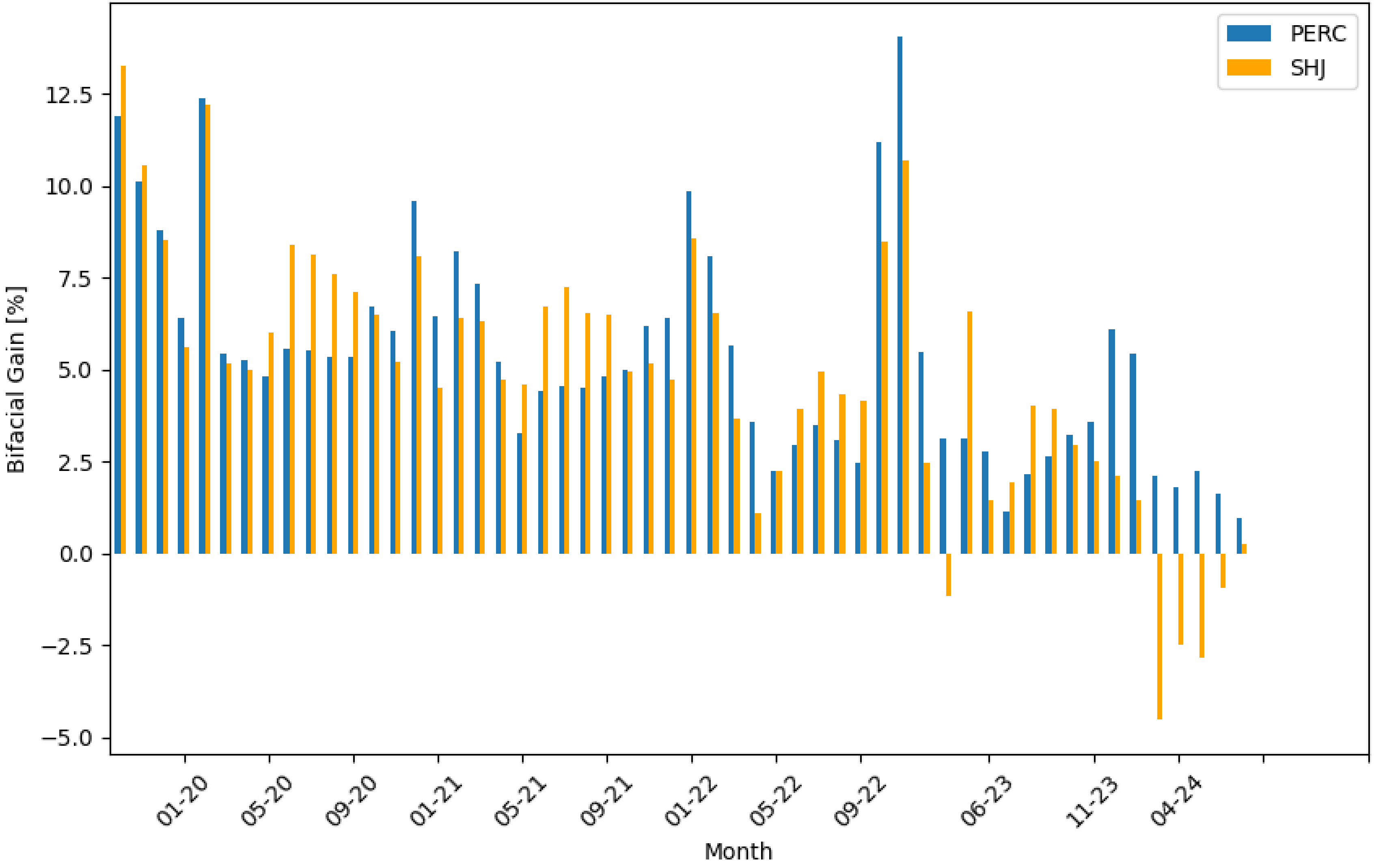
$$\frac{Energy\ bifacial}{Energy\ monofacial} - 1 \quad [\%]$$

*Grouped by Month

PERC bifacial gain: 5.1%; SHJ gain: 5.7%



Bifacial energy gain has a downward trend over the years



Bifacial Gain by year

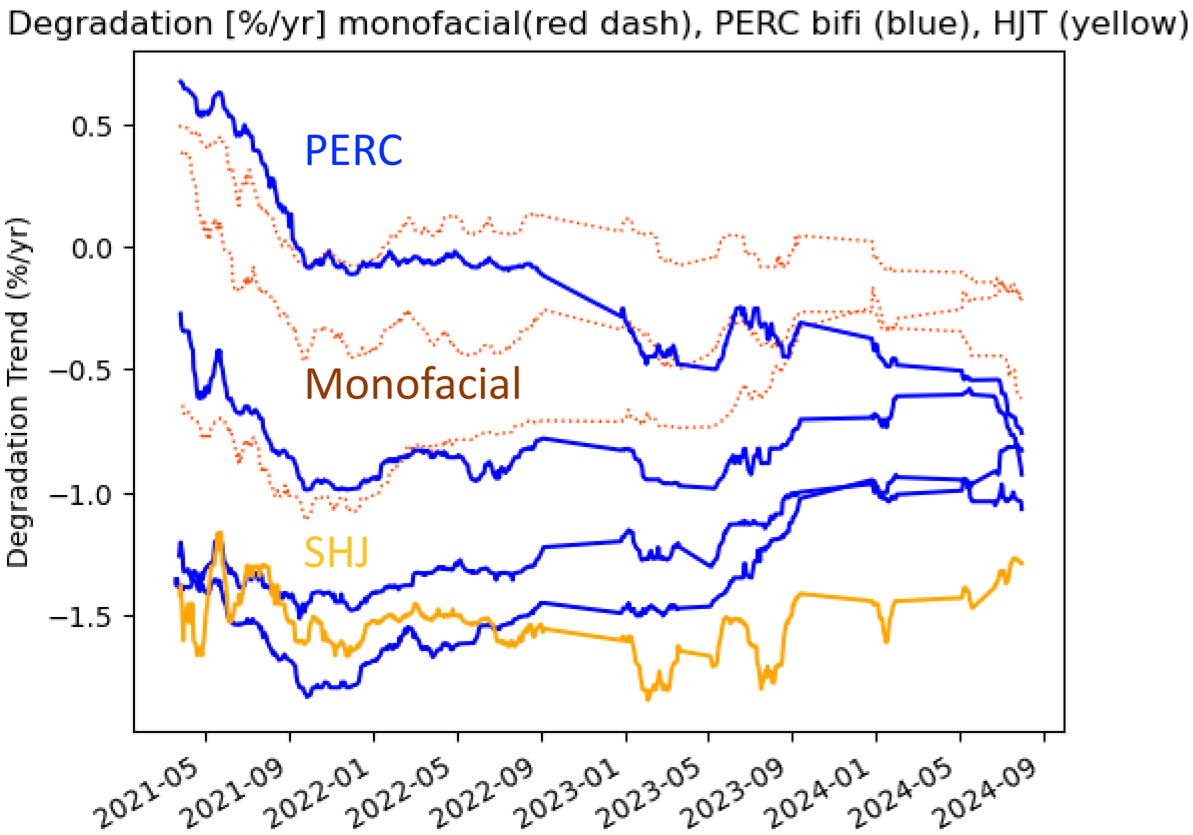
Annual Bifacial Gain	YEAR1 (partial) Oct’19–Jul’20	YEAR2 Aug'20 – Jul'21	YEAR3 Aug'21 - Jul'22	YEAR4 Aug'22 - Jul'23	YEAR5 Aug'23 - Jul'24	Average over 4.83 years
Technology A	6.2%	5.0%	3.6%	3.5%	1.5%	4.1%
Technology B	9.1%	8.8%	8.3%	8.2%	5.6%	8.1%
Technology C	4.6%	4.0%	3.2%	2.9%	1.7%	3.3%
Technology D	6.5%	5.6%	5.0%	5.0%	2.7%	5.0%
PERC Gain	6.6%	5.8%	5.0%	4.9%	2.9%	5.2%
Technology E (SHJ)	7.7%	6.9%	5.7%	5.0%	1.9%	5.7%

PLR Rates

Degradation Rates % Cumulative 10/2019 to:	8/1/2021	8/1/2022	8/1/2023	8/1/2024	AVG to Date
Technology A	-1.38	-1.32	-1.22	-1.11	
Technology B	0.29	-0.08	-0.14	-0.34	-0.94
Technology C	-1.60	-1.51	-1.42	-1.34	
Technology D	-0.78	-0.86	-0.83	-0.83	
Technology E (SHJ)	-1.30	-1.60	-1.59	-1.46	-1.46
Technology B Mono	0.14	0.06	-0.03	-0.04	
Techhnology C Mono	-0.91	-0.73	-0.71	-0.70	-0.34
Technology D Mono	-0.19	-0.38	-0.33	-0.28	

On average, **bifacial PERC and Si-HJT** are degrading faster than **monofacial counterparts**

Rolling PLR Rate



RdTools Year-on year degradation trend, 24-month rolling average

$$PR_n = daily\ perf.ratio$$

$$Rd_n = \frac{PR_{n+365*2} - PR_n}{\overline{PR}_{yr1}}$$

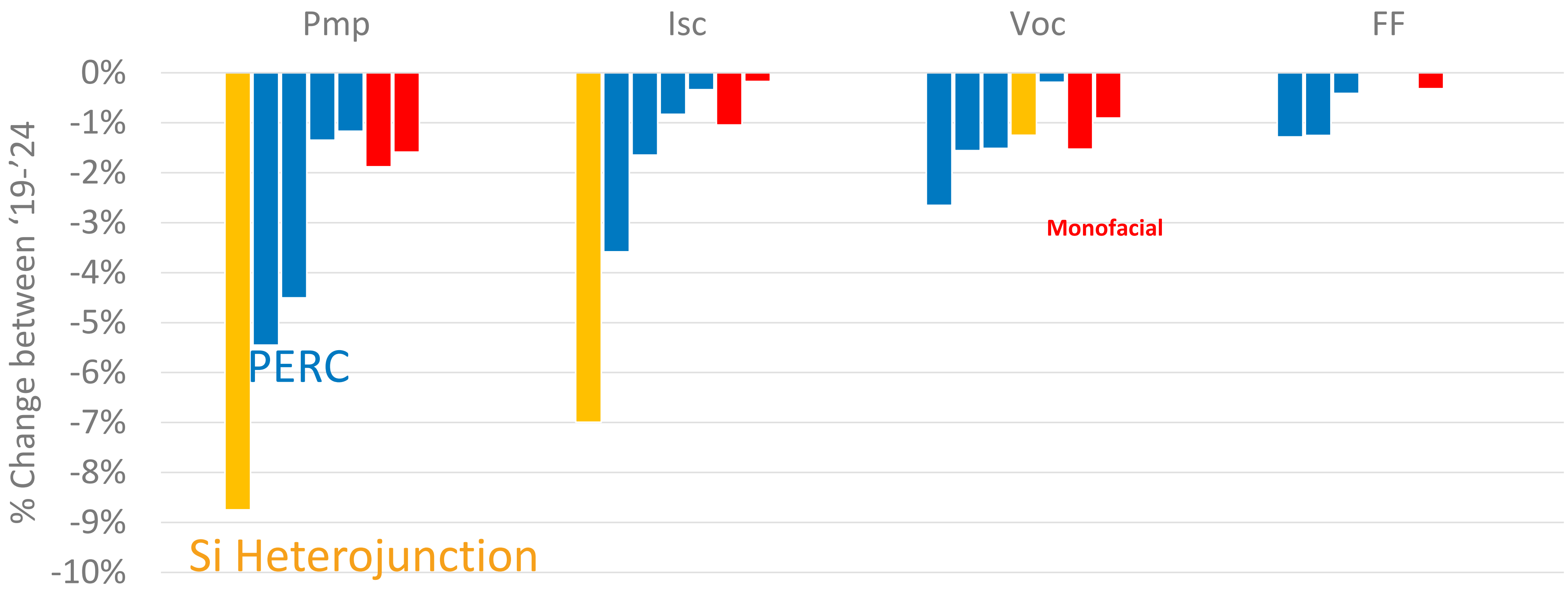
$$\frac{\sum_{365*2}^{1095} Rd_{n:(n+365*2)}}{365 * 2}$$

Cumulative Average Monofacial: -0.34 %/yr avg

Cumulative Average Bifacial: -0.97%/yr avg
Oct 2019-Jul 2024

IV Parameters Change 2019-2024

Indoor flash-test confirms performance loss; **<u>Isc change</u>** is the dominant difference



Diagnosis

RdTools
Detects long-term performance trends

IV-curve changes
Identifies passivation degradation modes, measures changes in bifacial factor

IR imaging
Identifies major defects such as broken bypass diodes, disconnected ribbons, shunts, and PID effects.

EL
Identifies cracks with more detail. Detects Potential Induced Degradation (PID) when checkered patterns are present.

PL
Assesses passivation quality and helps detect changes in the bulk and surface properties of materials

Low temp Spectral PL
Can help identify spectral features that could be useful for dopant characterization

QE Measurements
Investigates PID. Determines UV cutoff of encapsulant and glass

FTIR & hand-held gloss meter
Identifies UV dosage and degradation on backsheets

Handheld Raman Spectroscopy Detects changes in encapsulant material due to crosslinking or other chemical changes.

Handheld NIR tool
Encapsulation characteristics and changes

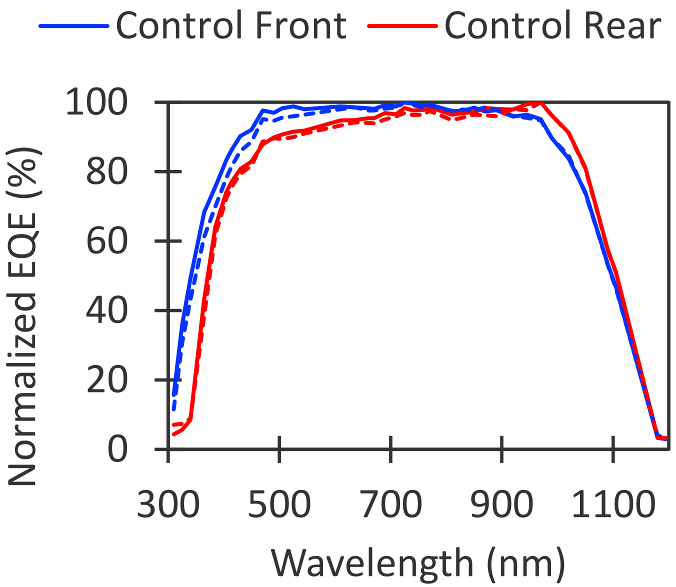
Technology A

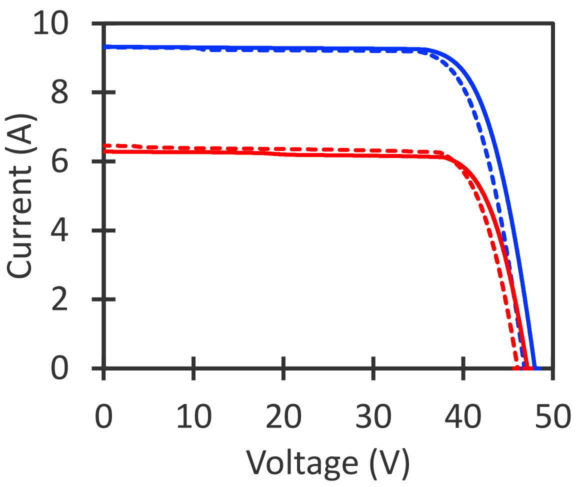
pPERC, G/G, Full cell, Top JB, EVA

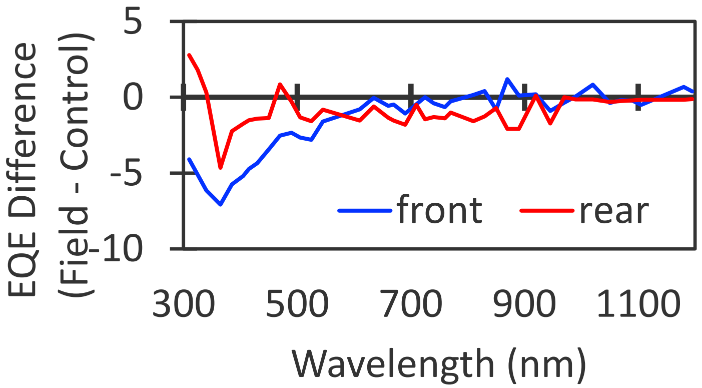
Imaging: Luminescence intensity decreases to ~55% of the control, consistent with voltage loss. Bands of high recombination become obvious in DLIT.

EQE: most loss observed on front side, short wavelengths

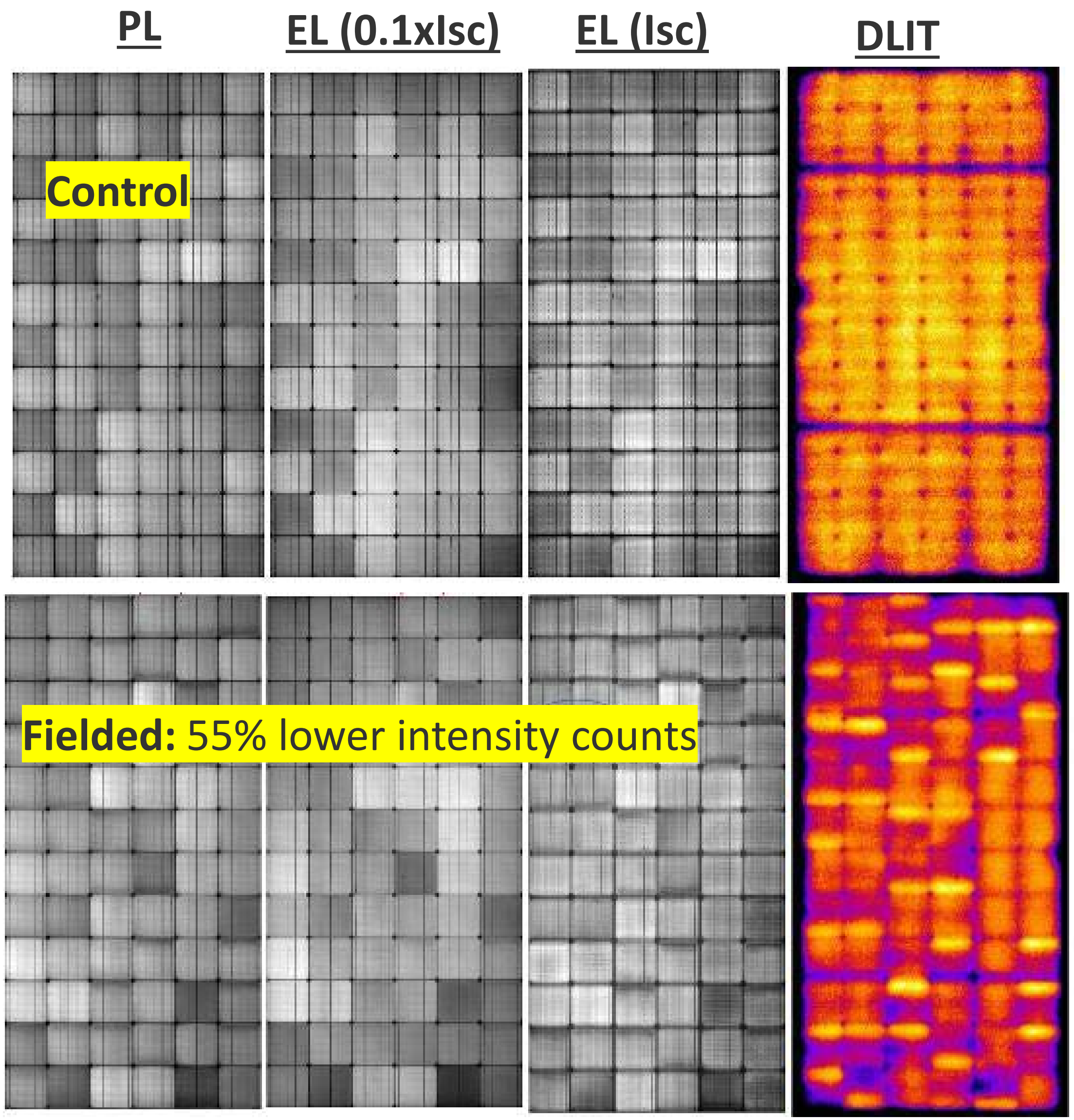
IV: Voc loss dominates. Front-side loss worse due to Isc.







IV Results	% Change Front	% Change Rear
Isc	-0.35%	2.15%
Voc	-1.39%	-1.41%
FF	-0.45%	-0.88%
Pmp	-2.17%	-0.13%



Technology A

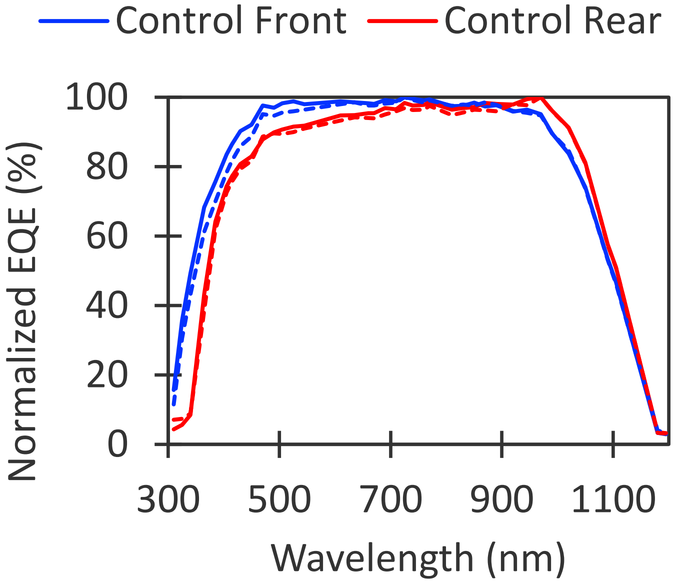
pPERC, G/G, Full cell, Top JB, EVA

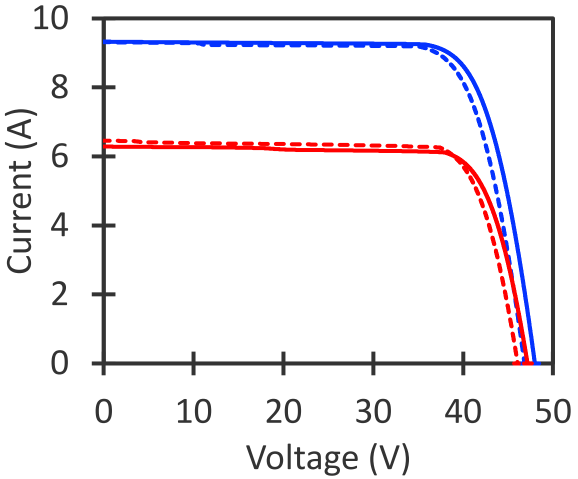
Summary: Voc loss from recombination; Optical coupling may impact Isc – loss on front and gain on rear. Minor but unusual resistive pattern affecting FF.

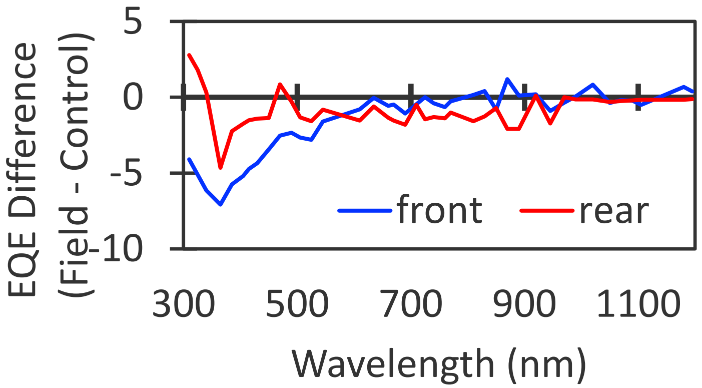
EQE: most loss observed on front side, short wavelengths

IV: Voc loss dominates. Front-side loss worse due to Isc.

Imaging: **(zoom into selected area)** Dark edge patterns in EL and PL, and hotter DLIT, suggest these are areas with increased carrier recombination.







IV Results	% Change Front	% Change Rear
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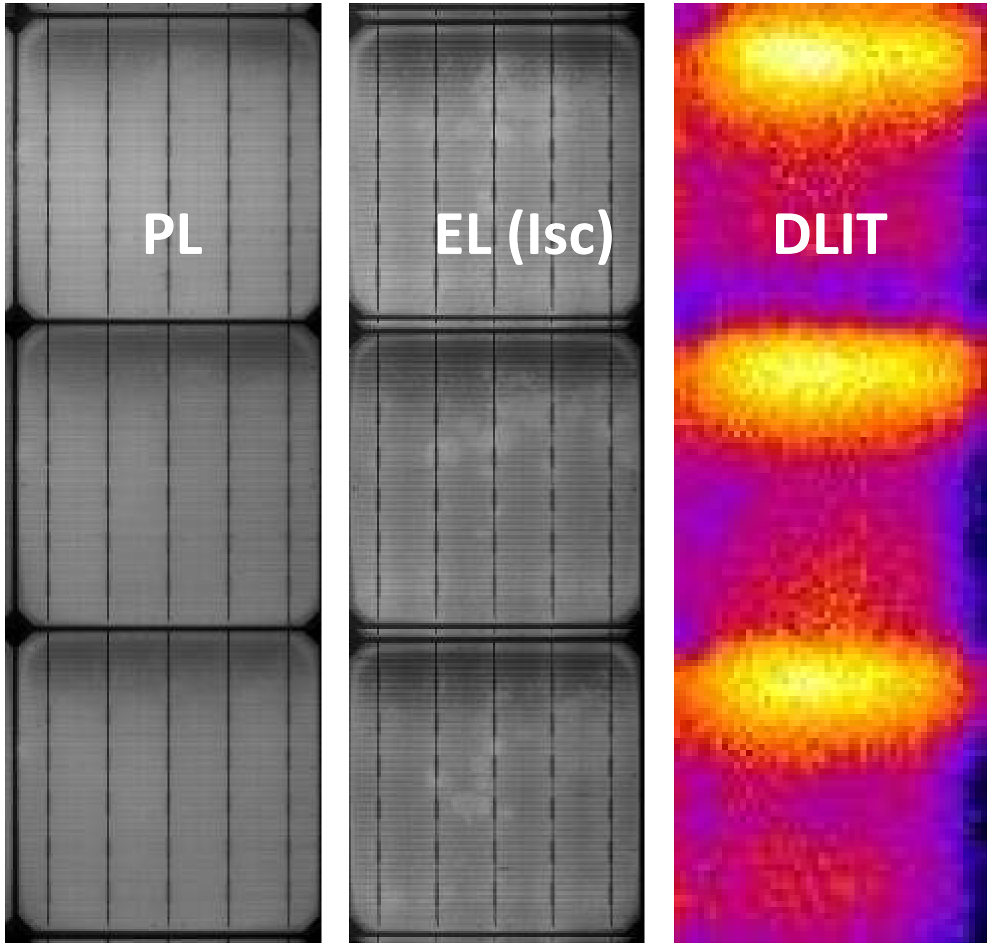


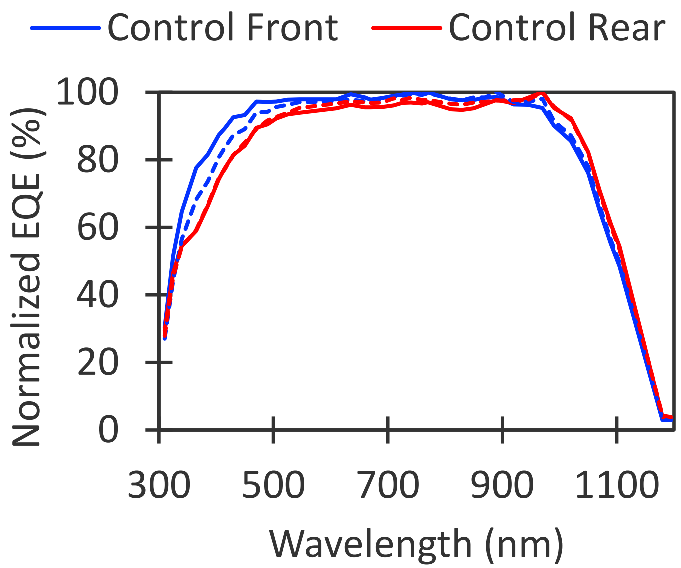
Technology C

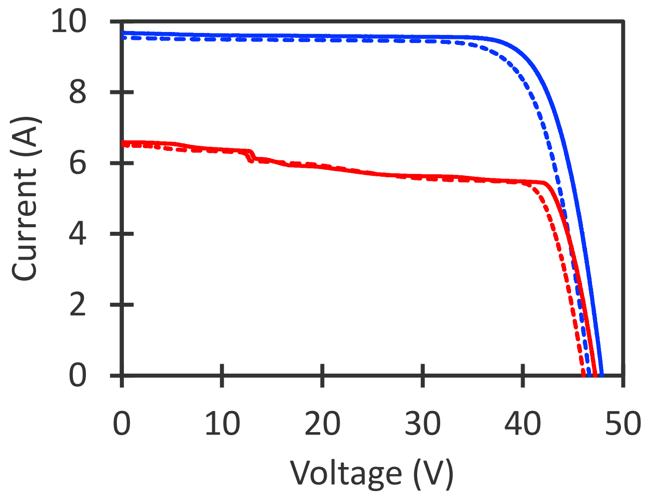
pPERC, G/G, Half-cell, Center JB, EVA

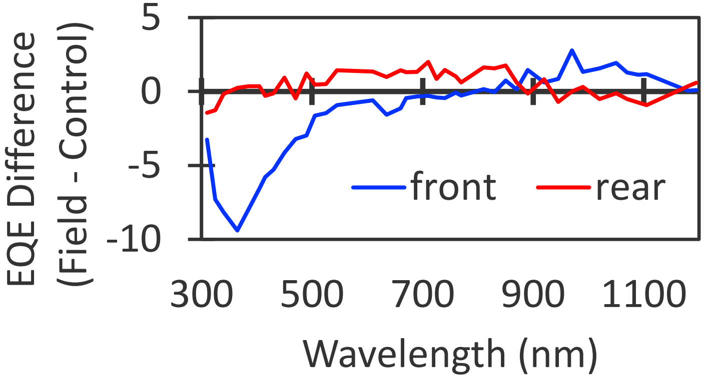
Imaging: Luminescence intensity decreases to ~55% of the control, consistent with voltage loss.

EQE: most loss observed on front side, short wavelengths

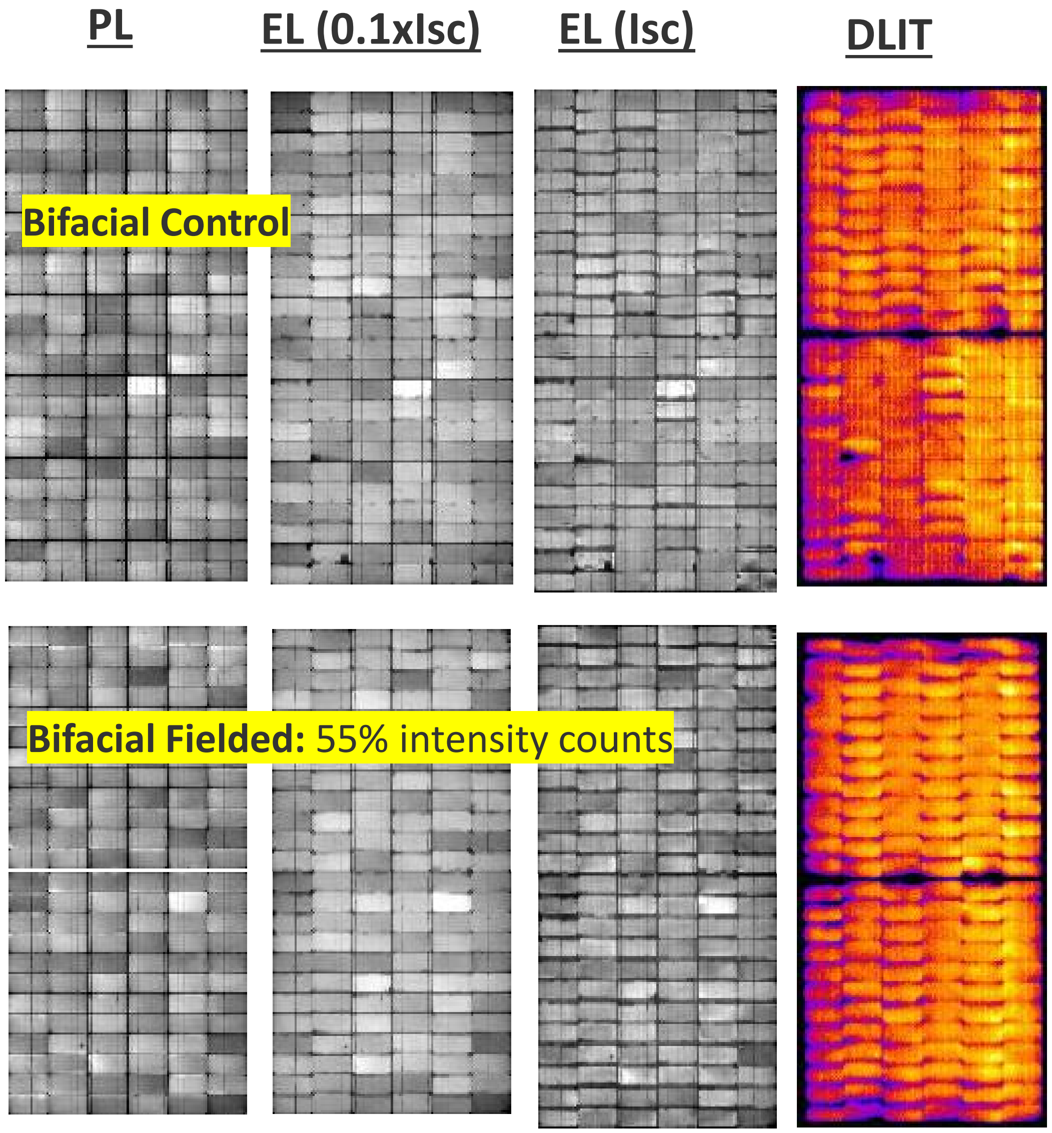
IV: Voc & Isc loss. FF worse on rear. Rear mismatch from JBs/frame.







IV Results	% Change Front	% Change Rear
Isc	-1.86 %	-2.93 %
Voc	-2.70 %	-2.81 %
FF	-1.00 %	-2.27 %
Pmp	-5.45 %	-7.82 %



Technology C

pPERC, G/G, Half-cell, Center JB, EVA

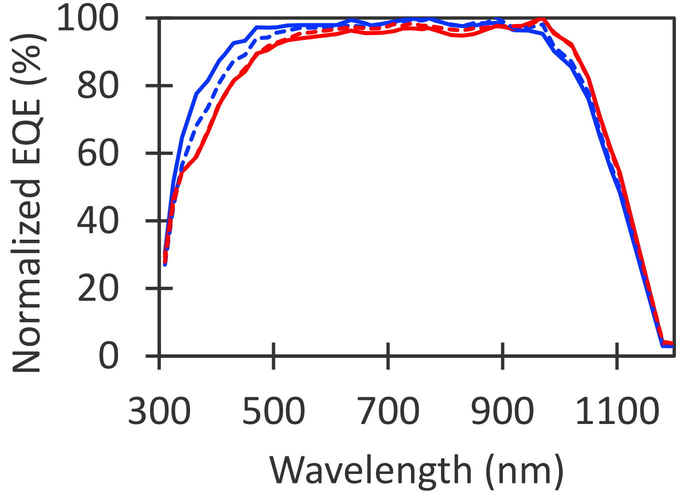
Summary: Voc and Isc loss from carrier recombination; Optical coupling may cause additional Isc loss. Resistive grid disconnection near cell edge decreases FF.

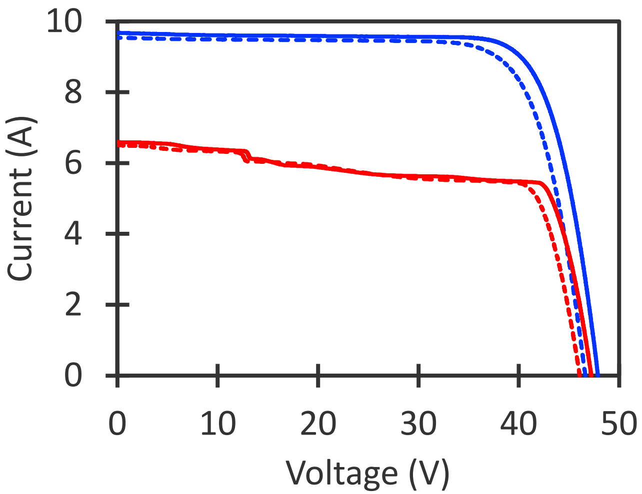
EQE: most loss observed on front side, short wavelengths

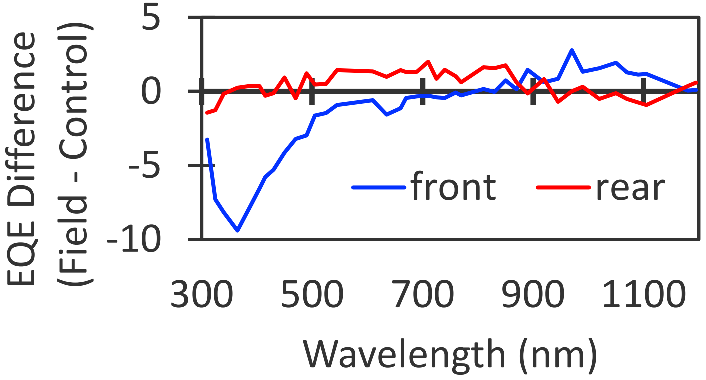
IV: Voc & Isc loss. FF worse on rear. Rear mismatch from JBs/frame.

Imaging: **(zoom into selected area)** Edge pattern dark in E,L bright in PL, colder DLIT – suggests high resistance causing FF loss.

Control Front, Control Rear, Fielded Front, Fielded Rear







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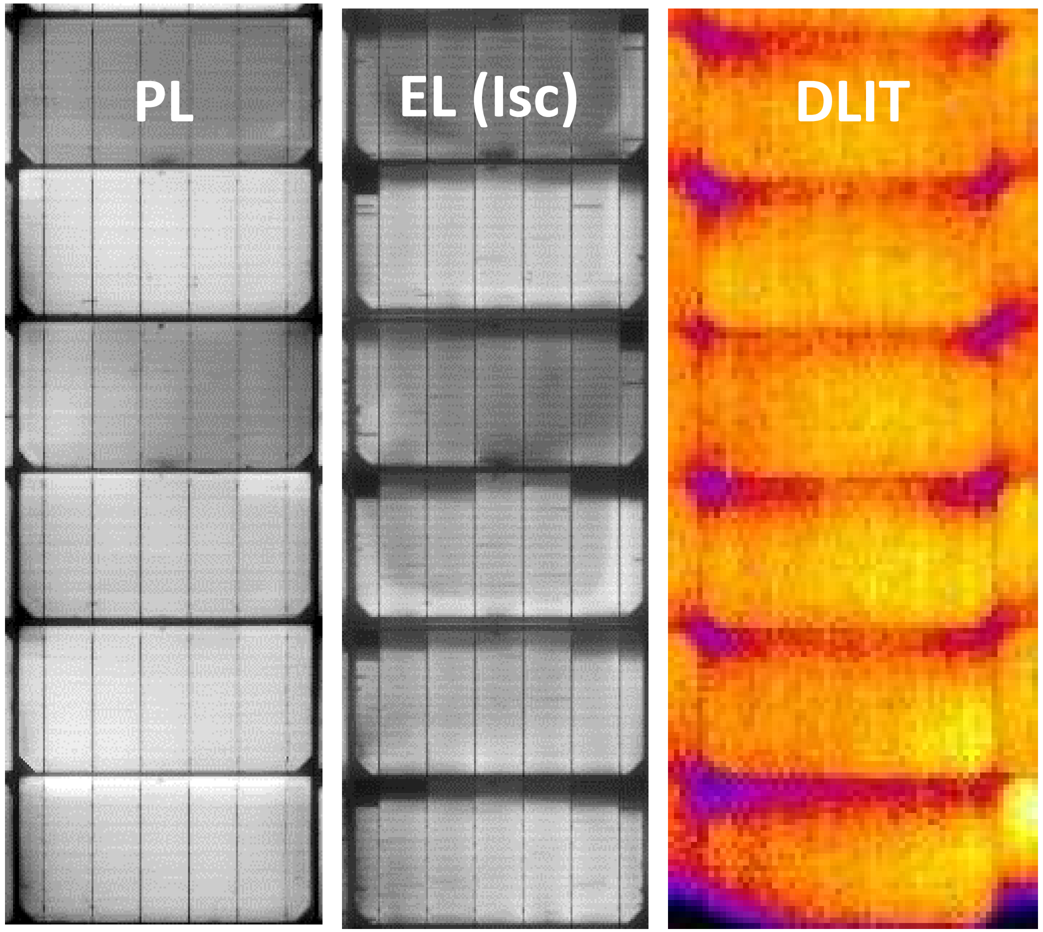


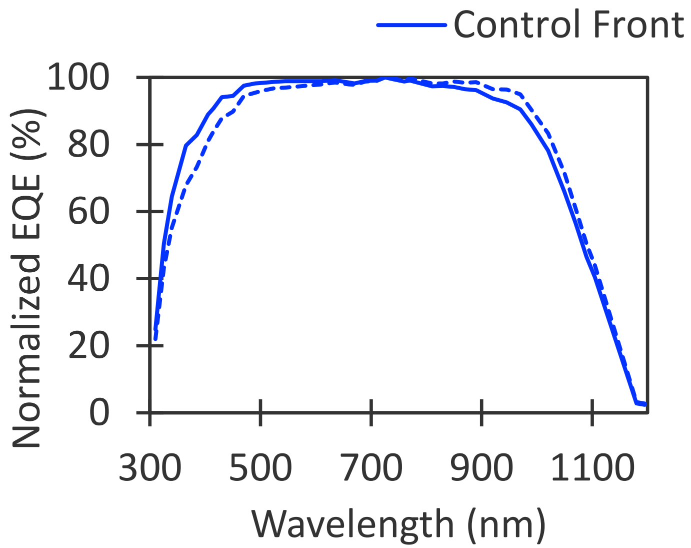
Technology C

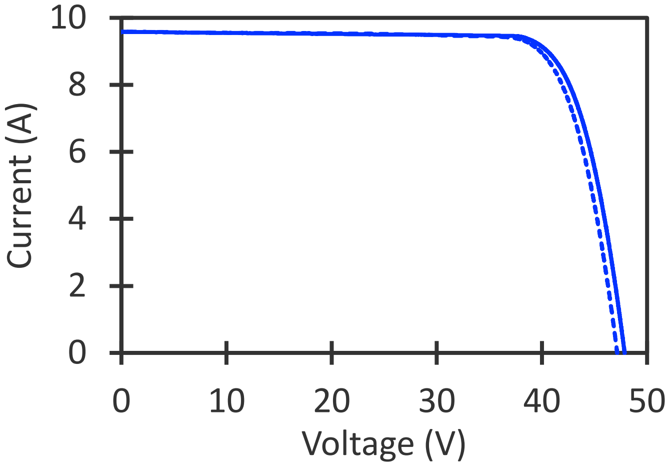
pPERC, G/G, Half-cell, Center JB, EVA

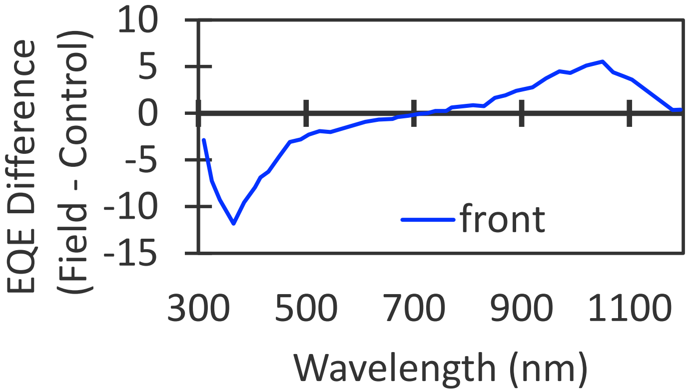
Imaging: Luminescence intensity decreases to ~75% of the control, consistent with voltage loss.

EQE: front surface loss - drop at short λ, rel. gain at long λ

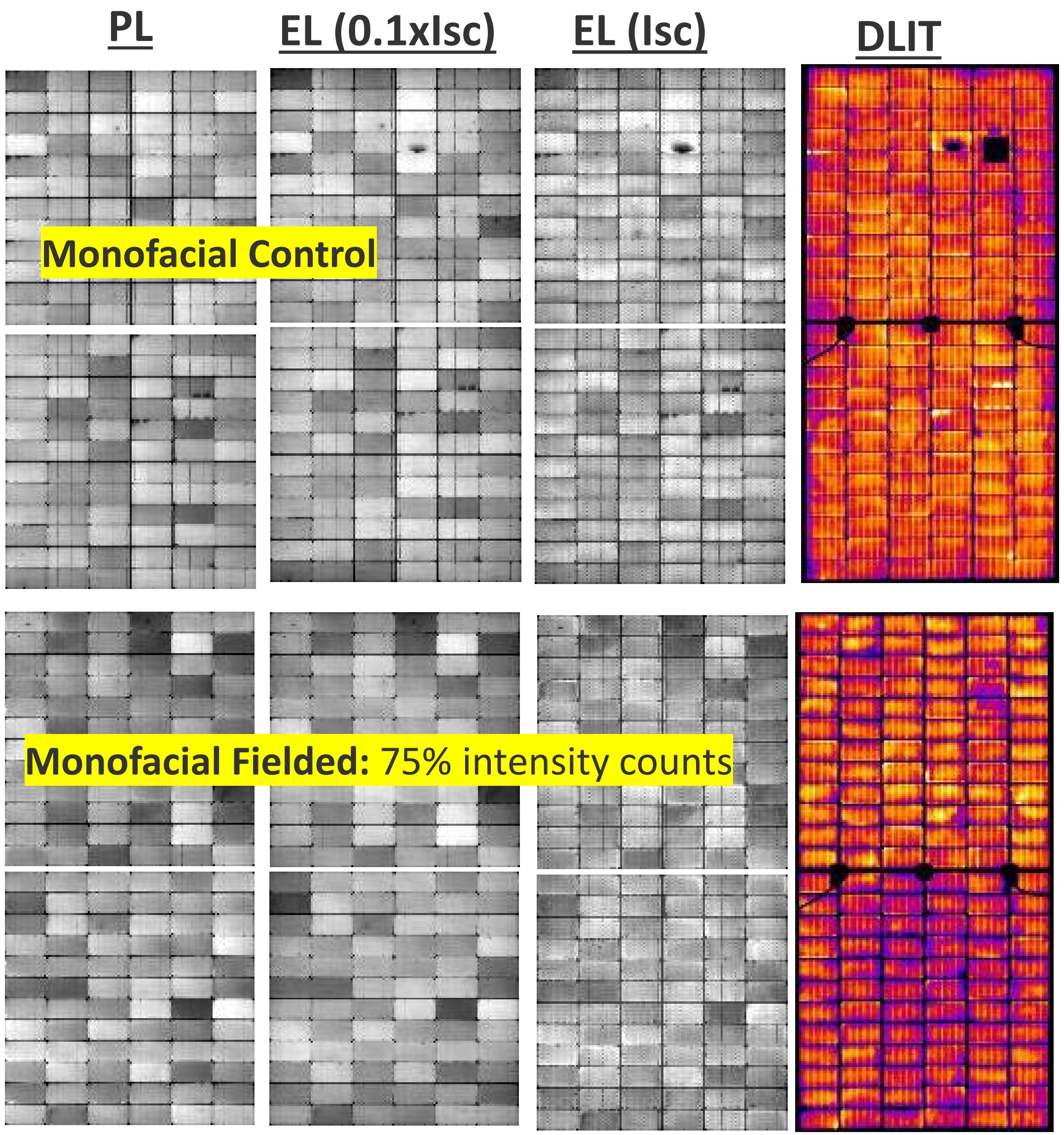
IV: Voc loss from recombination, possible passivation loss. Some Rs.







IV Results	% Change Front	% Change Rear
Isc	-0.30 %	N/A
Voc	-1.92 %	N/A
FF	-0.34 %	N/A
Pmp	-2.54 %	N/A



Technology C

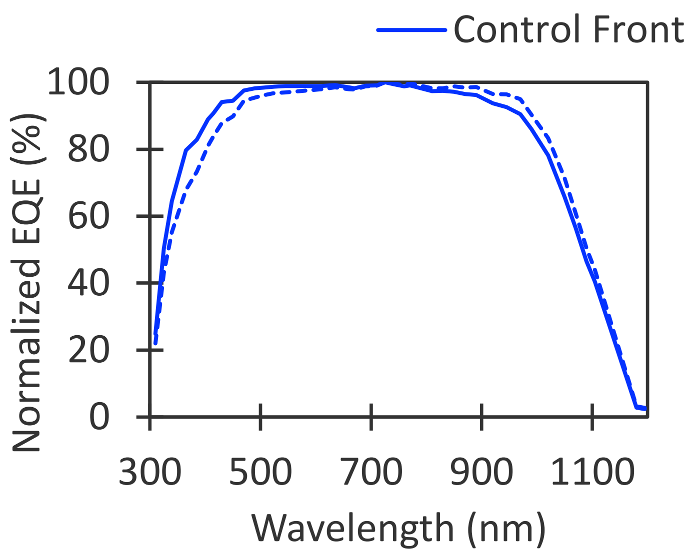
pPERC, G/G, Half-cell, Center JB, EVA

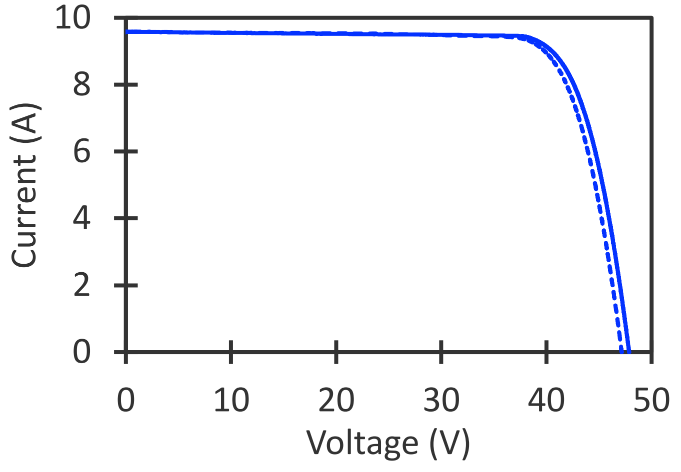
Summary: Voc loss from front surface recombination and some inconsistent cell processing observed; Minor resistive issues. Less degradation than bifacial.

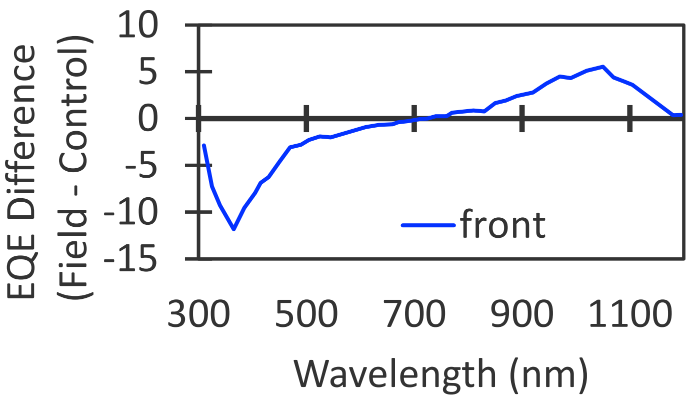
EQE: front surface loss - drop at short λ, rel. gain at long λ

IV: Voc loss from recombination, possible passivation loss. Some Rs.

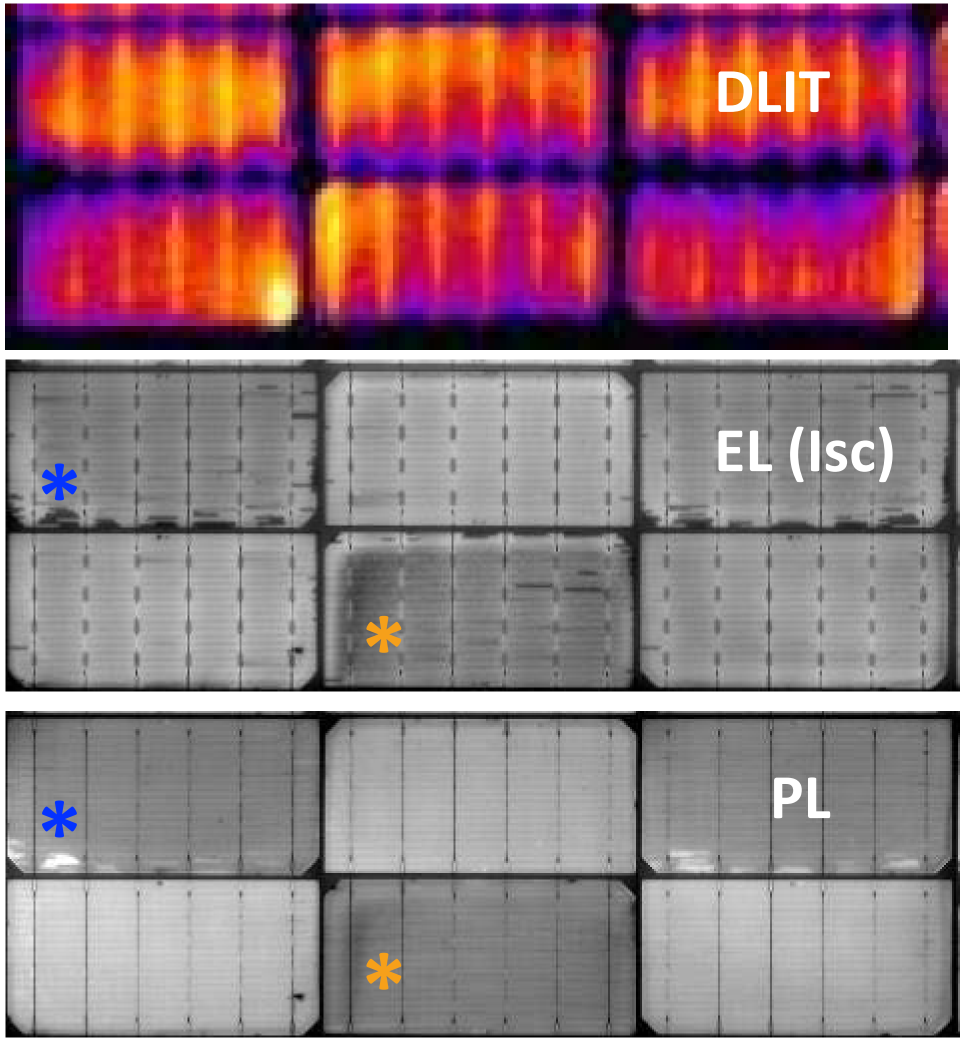
Imaging: **(zoom into selected area)** Some broken grid fingers near edges.* Local areas of high recombination from inconsistent cell processing.*







IV Results	% Change Front	% Change Rear
Isc	-0.30 %	N/A
Voc	-1.92 %	N/A
FF	-0.34 %	N/A
Pmp	-2.54 %	N/A



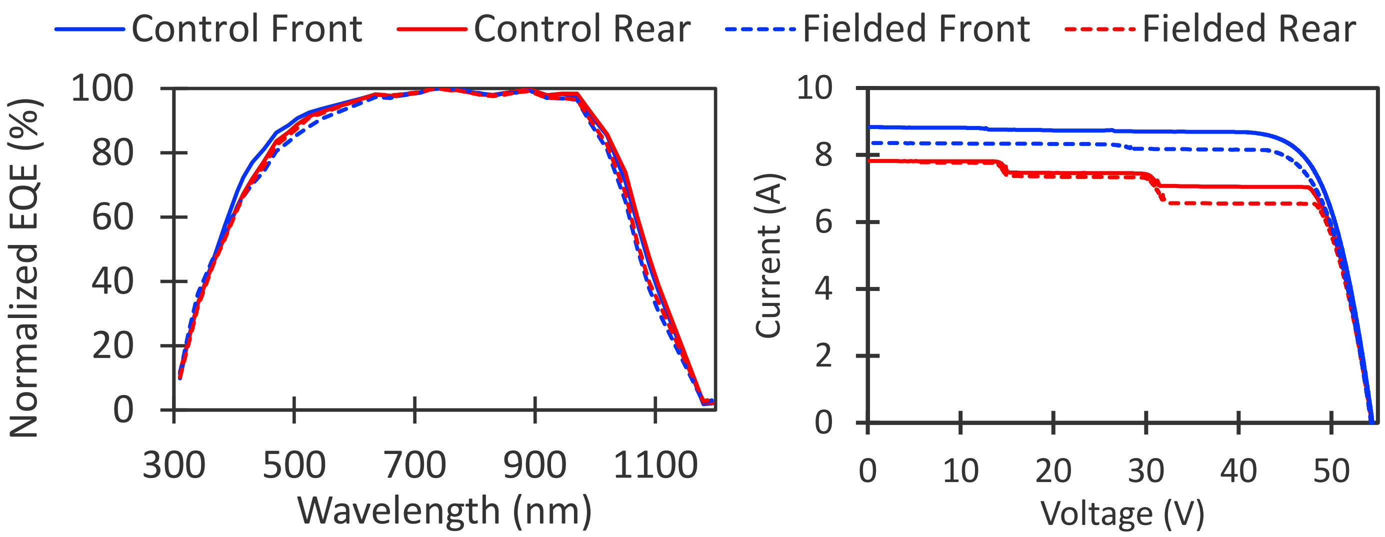
Technology E

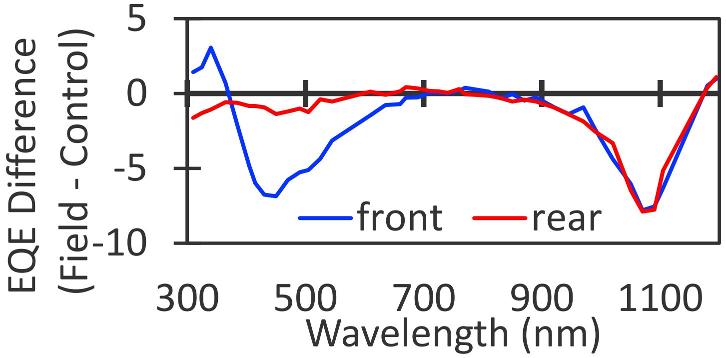
HJT, G/G, Half cell, JB center, “PE/EBA”

Imaging: Luminescence intensity decreases to ~70% of the control, consistent with voltage loss.

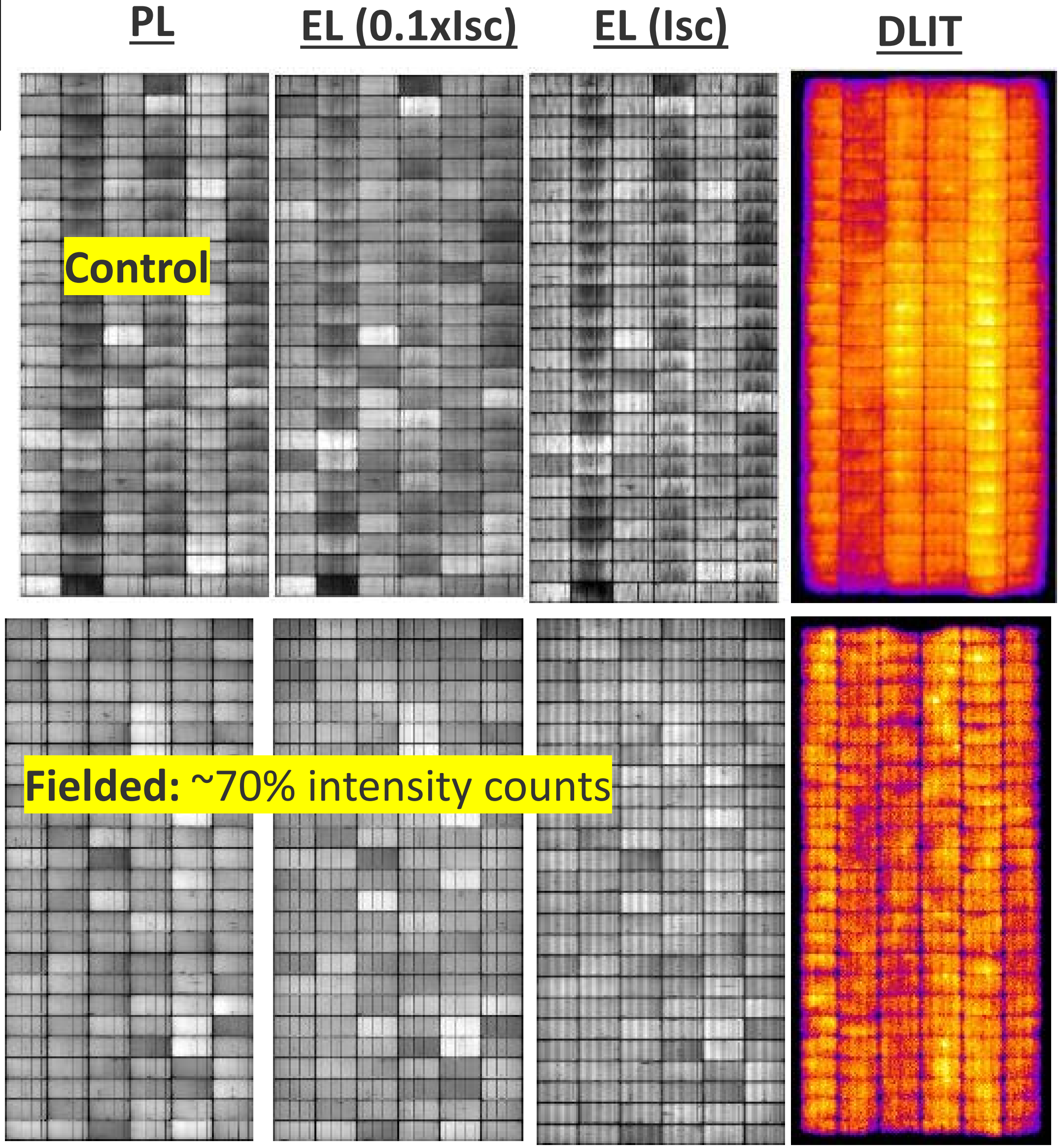
EQE: light coupling loss and recombination at both surfaces

IV: Isc loss from encapsulant deg, Voc from surface recombination.





IV Results	% Change Front	% Change Rear
Isc	-6.43 %	-3.22 %
Voc	-1.19 %	-0.89 %
FF	-0.02 %	-0.93 %
Pmp	-7.53 %	-4.96 %



Technology E

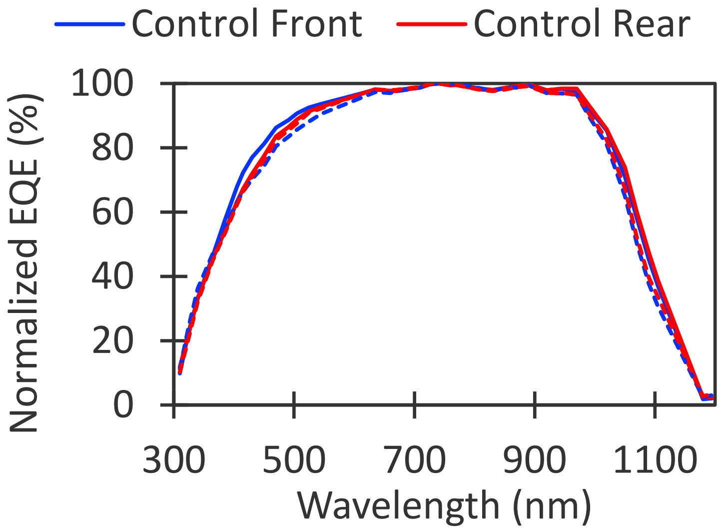
HJT, G/G, Half cell, JB center, “PE/EBA”

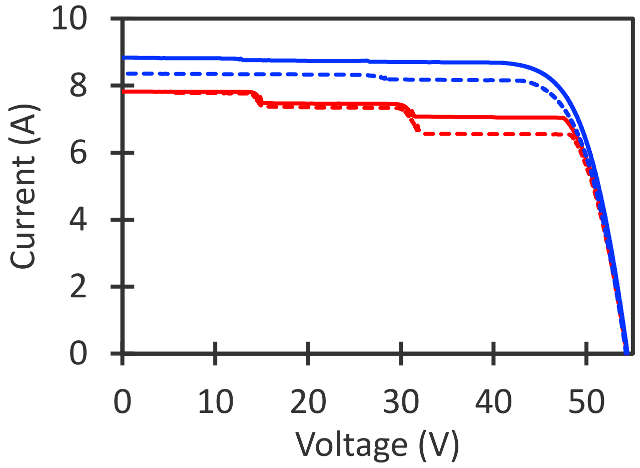
Summary: Loss dominated by Isc likely due to unstable encapsulant and optical loss. Mismatch on rear from JBs and frame. Voc loss from carrier recombination.

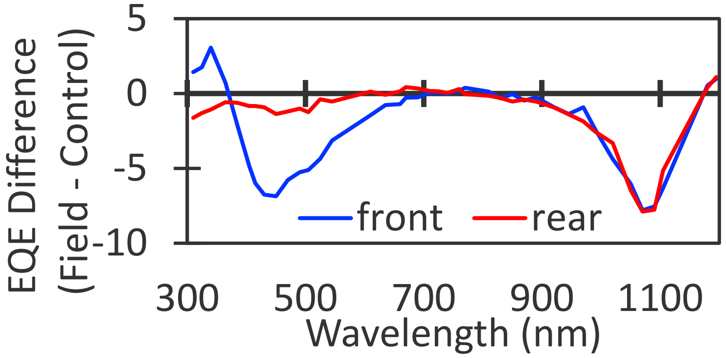
EQE: light coupling loss both surfaces; recombination at rear

IV: Isc loss from encapsulant deg, Voc from surface recombination.

Handheld Raman: shows change in fluorescence background, consistent with additives to protect SHJ and their degradation.







IV Results	% Change Front	% Change Rear
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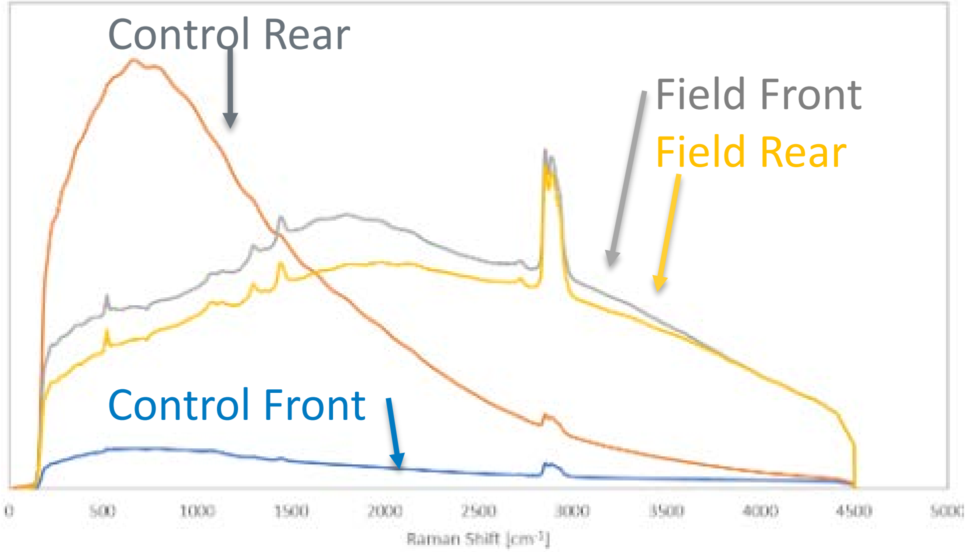
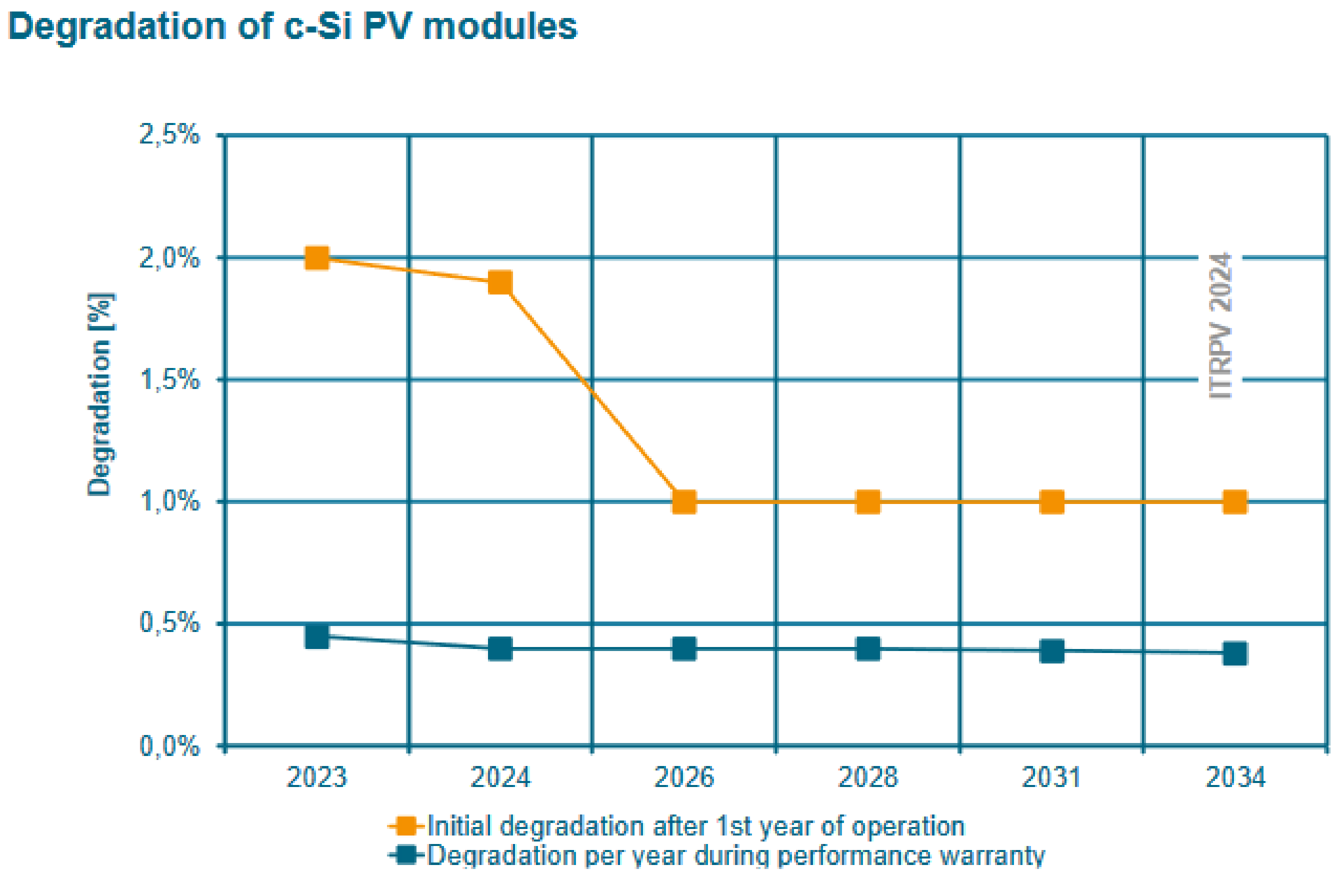


The expectation



ITRPV 2024
https://www.vdma.org/international-technology-roadmap-photovoltaic

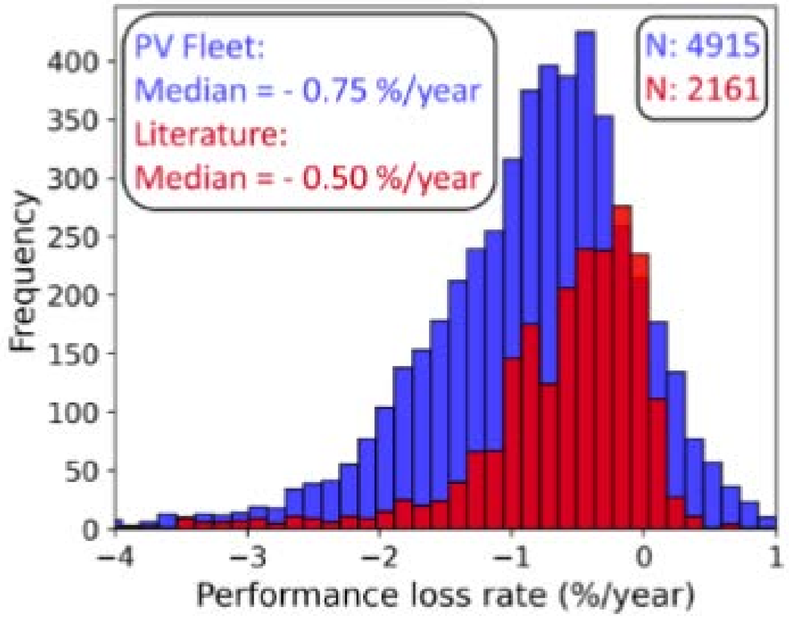


FIGURE 3 Performance loss rate distribution for the PV Fleet initiative (blue) compared with values aggregated from high-quality values (two or more measurements) from the literature (red)

Jordan https://doi.org/10.1002/pip.3566
% bifacial systems: 0-27%?

Reliability Considerations For Breakeven Evaluations

9—12¢/W	6—9¢/W	3—6¢/W	0—3¢/W	0—Negative 3¢/W	Negative 3—6¢/W	Negative 6—9¢/W

ITC	Degradation Rate 0.25%/year	0.50%/year	0.75%/year	1.0%/year	1.5%/year
-Two Std Dev					
-One Std Dev					
Mean Solar Resource	9-12 ¢/W	6-9 ¢/W	3-6 ¢/W	0-3 ¢/W	Negative -6 to -9 ¢/W
+One Std Dev					
+Two Std Dev					-3 to -6 ¢/W

PTC	Degradation Rate 0.25%/year	0.50%/year	0.75%/year	1.0%/year	1.5%/year
-Two Std Dev					Negative -3 to -6 ¢/W
-One Std Dev					
Mean Solar Resource	6-9 ¢/W		3-6 ¢/W	0-3 ¢/W	
+One Std Dev					0 to Negative -3 ¢/W
+Two Std Dev					

Results from the NREL System Advisor Model (https://sam.nrel.gov/), reeV Model, and Online LCOE Calculator (https://www.nrel.gov/pv/lcoe-calculator/)

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"Reliability is every bit more consequential than the initial cost, initial efficiency and initial energy yield"

M. Woodhouse, PV Reliability Workshop 2023
https://www.nrel.gov/docs/fy24osti/85330.pdf

Conclusions

After five years at NREL's Bifacial Experimental Single-Axis Tracked (BEST) Field, four PERC technologies showed an average bifacial gain of 5.1%, while one SHJ row showed 5.7%. Over this period, the bifacial gain has steadily declined. The Performance Loss Rates for PERC and SHJ technologies are -0.94% and -1.46% respectively, compared to -0.34% for monofacial

- The weathered modules exhibit a significant decrease in luminescence intensity, suggesting a comprehensive loss in module efficiency and voltage, with specific concerns about fill factor reduction due to broken grid fingers and lower current densities.
- Predominant losses on the front side, with worse outcomes for bifacial technologies.
- **External Quantum Efficiency (EQE)** shows more significant drop at short wavelengths.
- **Imaging techniques** highlight broken grid fingers and local high recombination zones.

Bifacial Experimental Single-Axis Tracked (BEST) Field at NREL

- Performance Data Available on Duramat Datahub https://datahub.duramat.org/project/about/nrel-bifacial-experimental-single-axis-tracking-field
- New data from this research added on Duramat: https://datahub.duramat.org/dataset/best-field-degradation-research

1-hr deep dive webinar into this material:

https://tinyurl.com/Duramat2024Ovaitt

NREL/PR-5K00-92280

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https://datahub.duramat.org/project/about/best-field-degradation-research

This work was also authored in part by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Partial Funding provided by the U.S. Department of Energy (DOE)'s Office of Energy Efficiency and Renewable Energy (EERE) from the Solar Energy Technologies Office (SETO), under CPS Agreement 385258, and as part of the Durable Module Materials Consortium 2 (DuraMAT 2) funded by the U.S. DOE, Office of EERE, SETO, agreement number 38259. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

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