NREL
Transforming ENERGY

Evaluation of Bifacial Modules and PV Technologies with Combined-Accelerated Stress Testing

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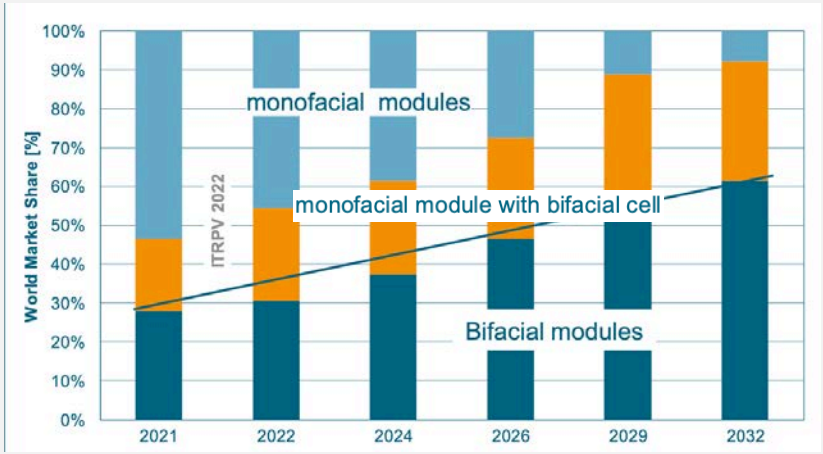
4. DuPont, Central Research and Development, Wilmington, USA

WCPEC-8 Milan
26-30 Sept 2022

Bifacial modules taking increased market share

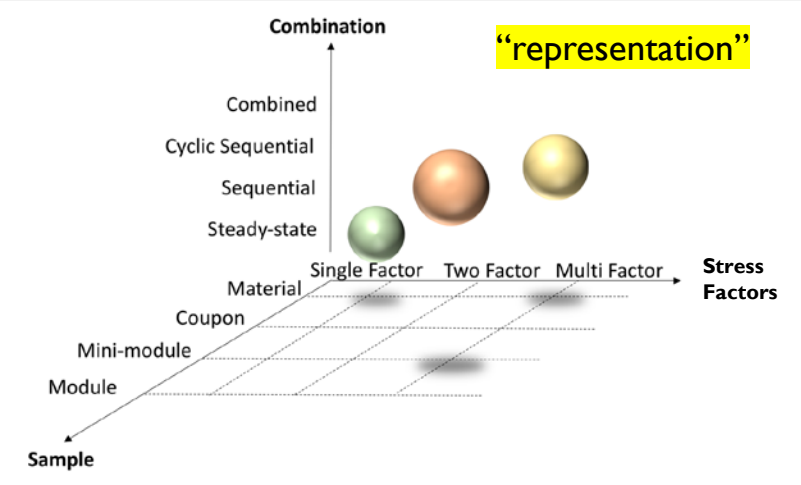


International Technology Roadmap for Photovoltaics (ITRPV 2021)

Need something transparent on the back

A-priori reliability concerns for bifacial module rear/substrate	
Glass	**Polymeric**
Delamination due to constrained outgassing	Discoloration and embrittlement→cracking
PID on back	
Delamination due to adhesion loss (non-EVA)	
Stress on cells & metallization	Stress on cells & metallization

Introduction to C-AST



C-AST Chamber

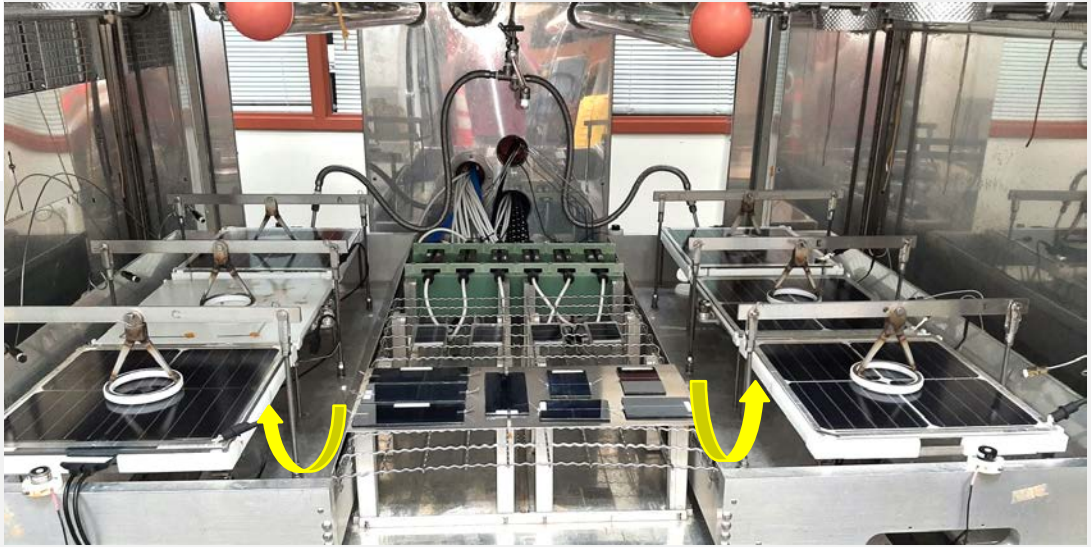
Applies five factors of the natural environment:

- Heat
- Light (filtered Xenon), ~7. 5 % albedo
- Humidity
  - Condensing
  - Non-condensing
- Mechanical pressure
- System voltage

Stress levels & combination: per maximum in nature

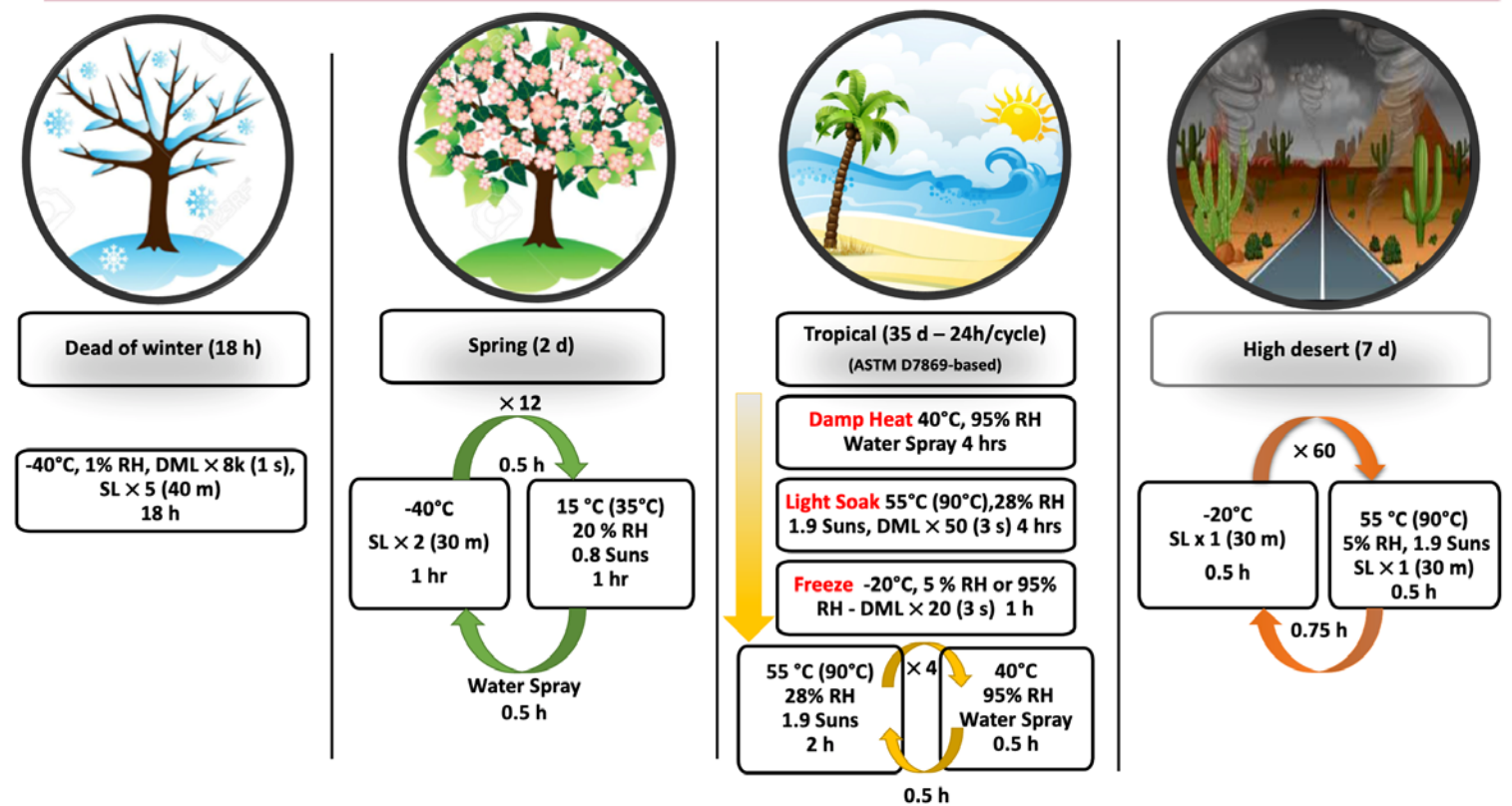
In-situ Metrology: *I-V*, EL

Degradation	Mean Acceleration Factor (Tropical/Florida)
Outer layer polymerics of backsheet (temperature/irradiance)	17.3
Backsheet inner PET (Temperature/humidity)	426
Electrochemical degradation (corrosion)	14.1
Thermomechanical fatigue (PbSn solder)	23.5



- *Spataru, S.; Hacke, P.; Owen-Bellini, M., (WCPEC-7) 2018*
- *Owen-Bellini, M. et. al. Progress in Photovoltaics: Research and Applications 29 (1), 2021*
- *Hacke, P. et al; Advanced Micro-and Nanomaterials for Photovoltaics (Elsevier) 2019*
- *Hacke, P. et al; Proc. Intl. Conf. Crystalline Silicon Photovoltaics, 2020.*

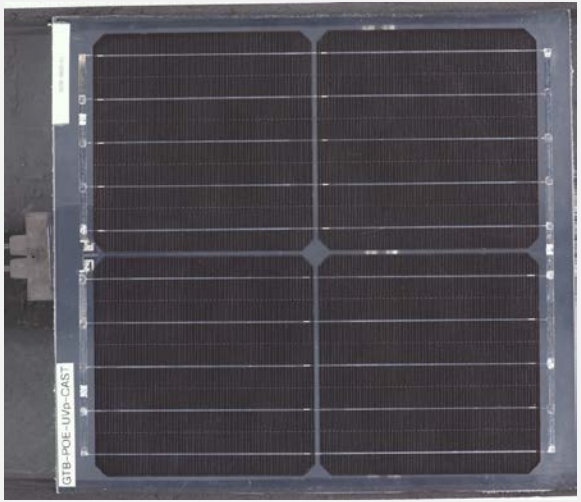
C-AST Cycle and its climate sequences



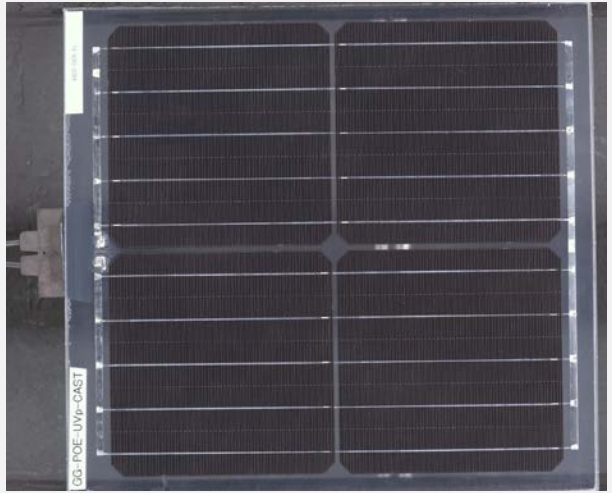
Notes: Temperatures indicated as $T_{chamber}$ (T_{module})
-1200 V System voltage applied to cell circuit only when irradiation is applied
DML = Cyclic Dynamic Loading 1000 Pa equivalent
SL = Static loading 2400 Pa equivalent

C-AST Experiment 1: Monofacial PERC: 2 encapsulants x 3 substrates

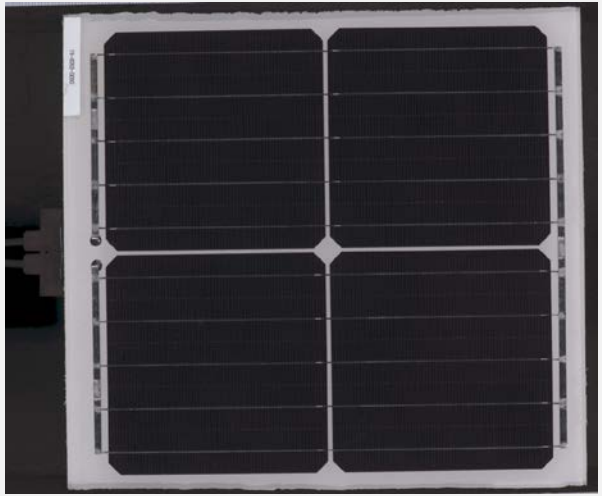
Cell type	No. samples	Encapsulant	Substrate	Cycles C-AST
Monofacial Mono-Si PERC	1	POE	transparent PVF	2
	1	POE	glass	2
	1	POE	white PVF	2
	1	EVA	glass	4
	1	EVA	white PVF	4
	1	EVA	transparent PVF	4



Substrate: transparent PVF

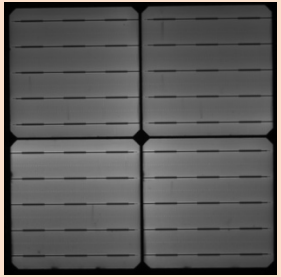
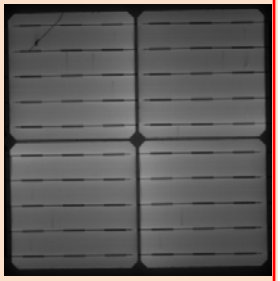
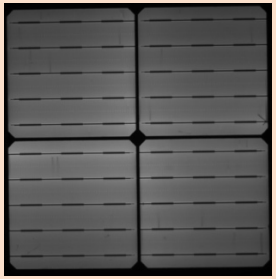
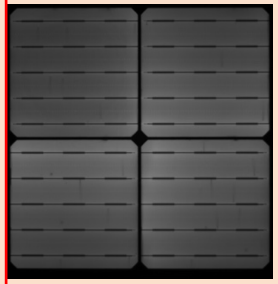
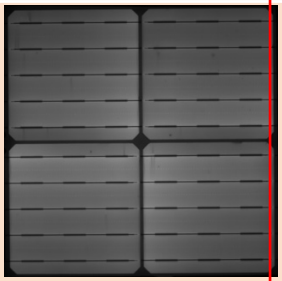
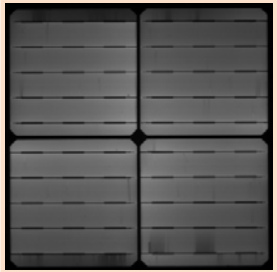


glass



white PVF

Sample set 1: Bifacial module constructions with monofacial PERC

	Encapsulant type: Substrate type Number of cycles in C-AST					
	POE: T-PVF	POE: W-PVF	POE: Glass	EVA: T-PVF	EVA: W-PVF	EVA: Glass
	4 cycles	4 cycles	4 cycles	2 cycles	2 cycles	2 cycles
Initial EL (I_{sc})						
Breaks	8	10	15	20	7	14
Final EL (I_{sc})						
Breaks	39	45	134	69	13	114

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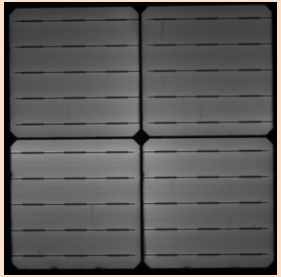
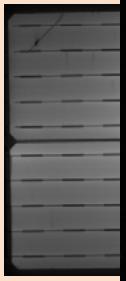
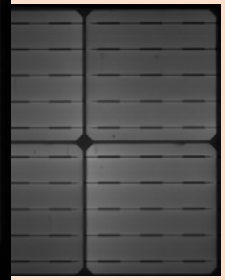
Initial EL (I_{sc})				
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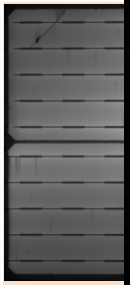
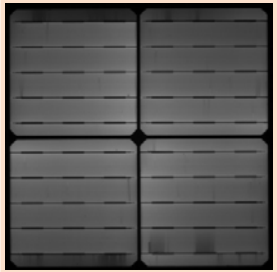
Final EL (I_{sc})				
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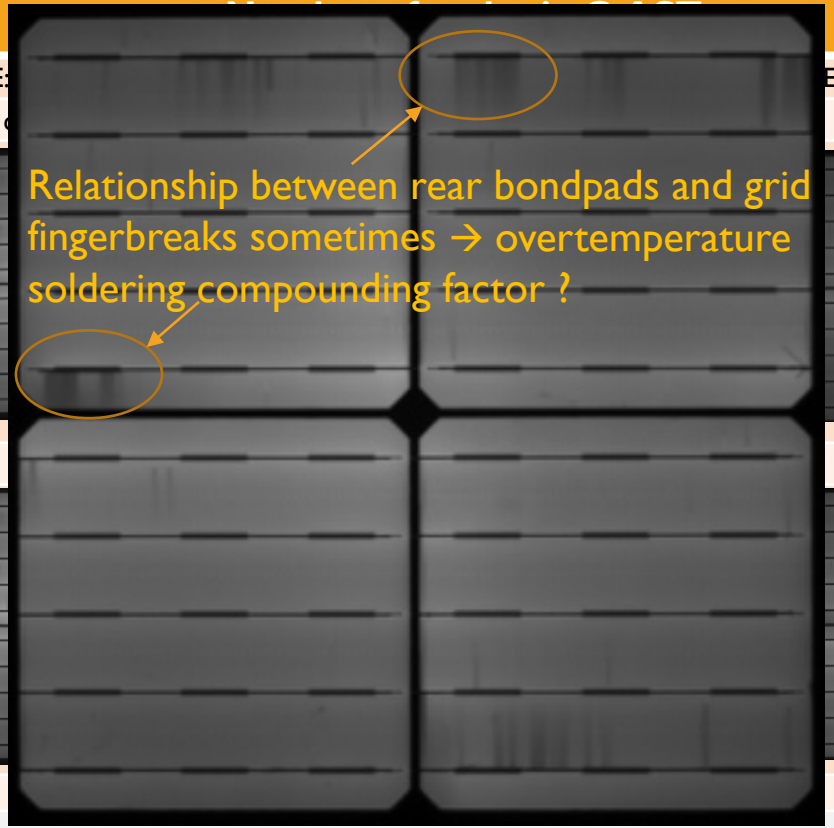
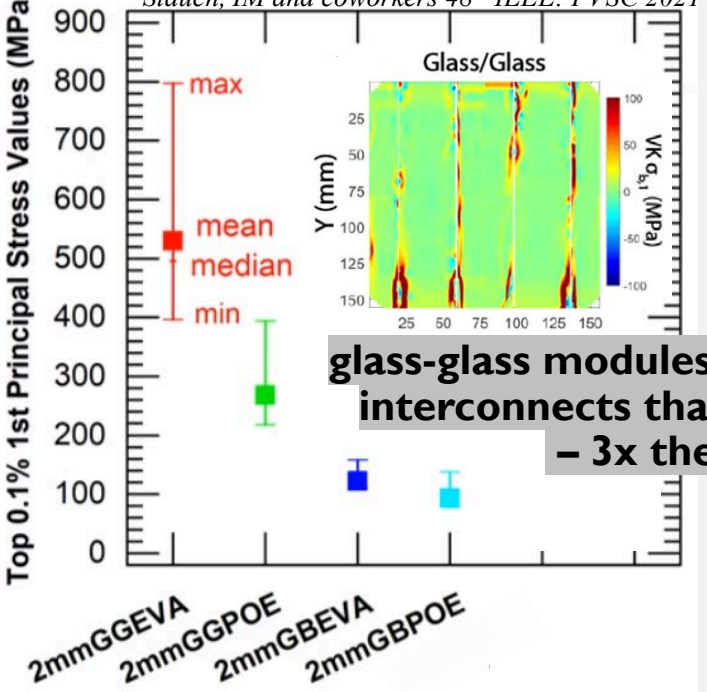


(Negligeable fill factor and power loss with the monofacial PERC)

Gridfinger breaks

X-Ray Topography, thin-plate theory and finite element analysis

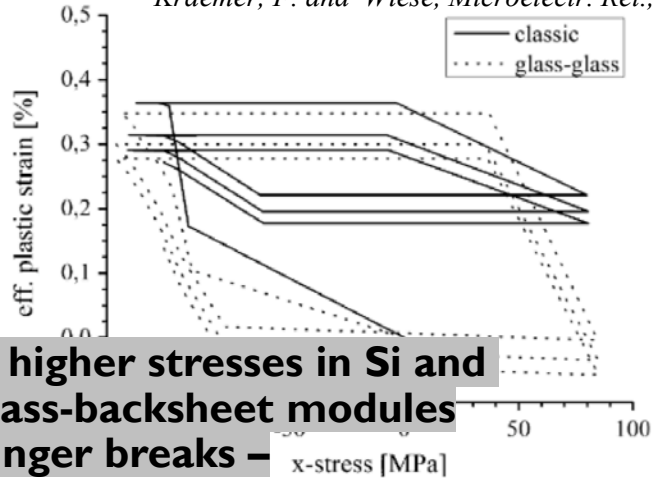
Slauch, IM and coworkers 48th IEEE: PVSC 2021



- 2 mm glass/glass have 200 % to 300 % higher stress than 2mm Glass/Backsheet modules
- Glass/glass exhibit higher bending induced cell stresses during module fabrication

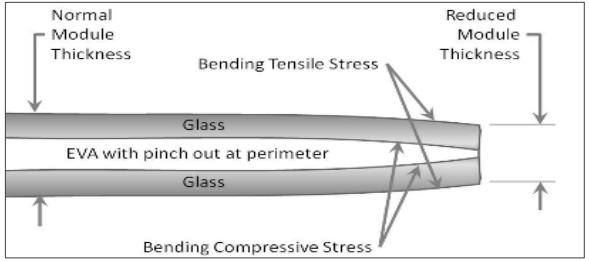
Finite element analysis of stress-strain in copper interconnects in -40 °C/85 °C temperature cycling

Kraemer, F. and Wiese, Microelectr. Rel., 55 (5) 2015



glass-glass modules show higher stresses in Si and interconnects than in glass-backsheet modules – 3x the gridfinger breaks –

- Highest mechanical loads appear in the glass–glass assembly
- The maximum accumulated plastic strain of some elements in glass-glass reaches double that of glass back sheet assembly



Cording, C. Proc. SPIE 7048 2008

C-AST Experiment 2: Bifacial PERC: 2 encapsulants x 2 substrates
Four cell mini modules

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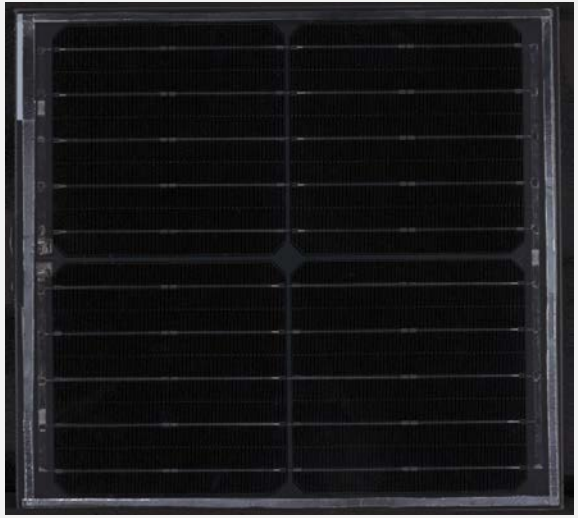
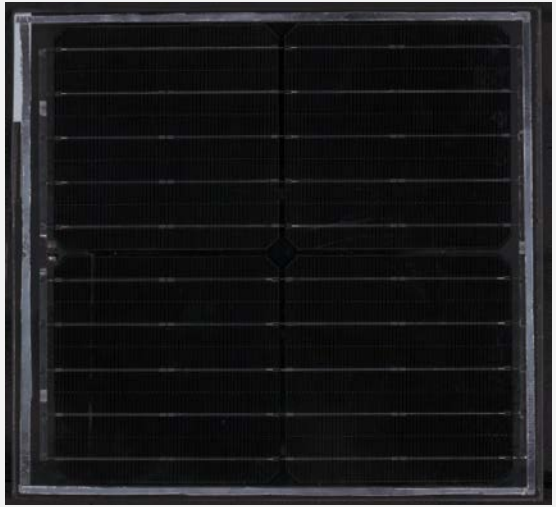
	1	POE	transparent PVF	3
	1	EVA	glass	3
	1	POE	glass	3
	1	POE	glass	n/a (ex-situ testing)



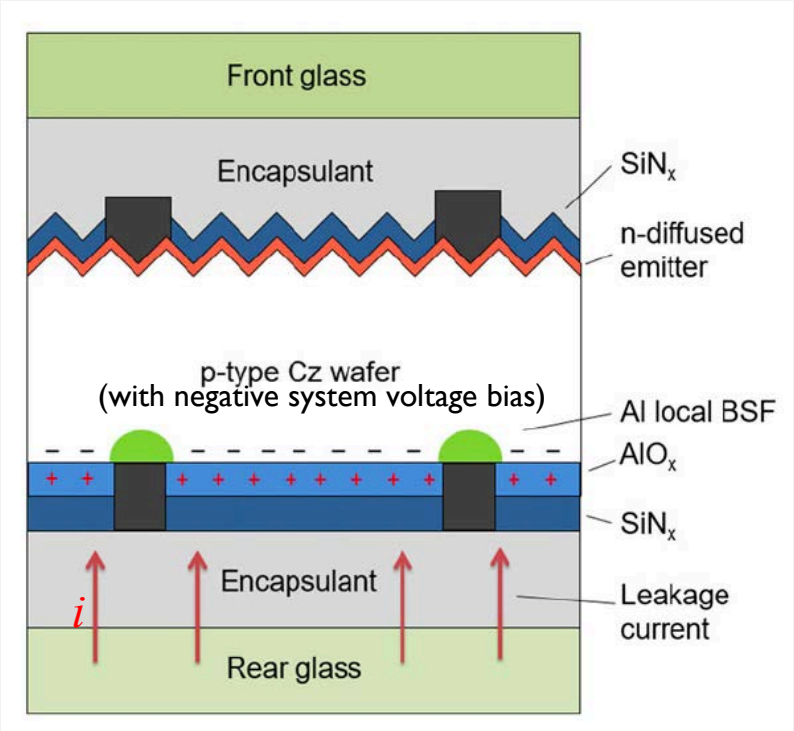


Substrate: transparent PVF glass

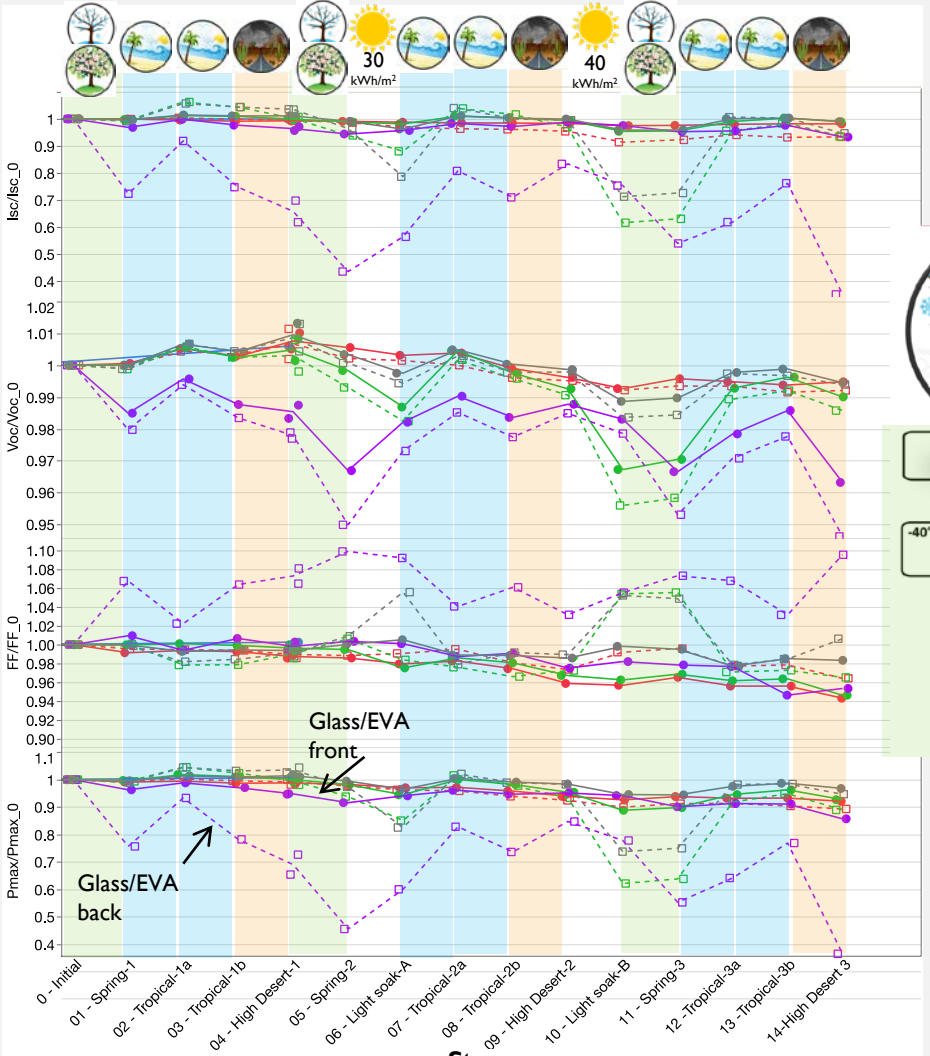
Overview of potential-induced degradation polarization (PID-p) on rear of bifacial PERC

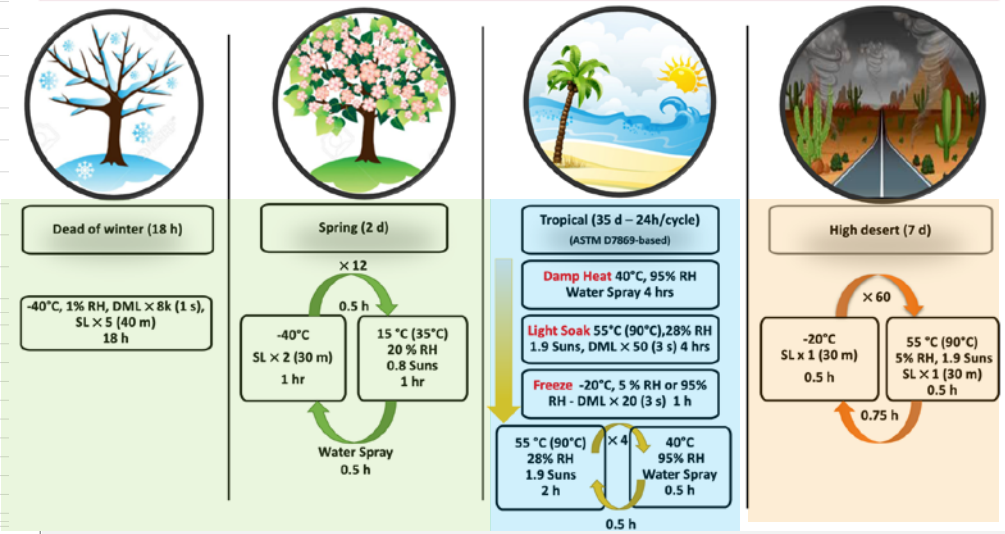
When and where does it happen

- Rear of bifacial PERC (undoped, sensitive to dielectric charge state) [1]
- Occurs most in EVA-glass back modules[1]
- Negative system voltage (builds up + charge in dielectric)[2]
- Generally correlated to high leakage current[1]
- Degradation greater under low light or dark[3]
- Recovery under light soak because of SiNx photoconductivity and annihilation of charge[2-4]
- Recovery under opposite system voltage polarity[5]



1 *Luo, W and coworkers, Progress in Photovoltaics: Research and Applications 2018, 26 (10), 859-867.*
2 *Luo, W and coworkers, IEEE Journal of Photovoltaics 2018, 8 (5), 1168-1173.*
3 *Habersberger, B. M.; Hacke Progress in Photovoltaics: Research and Applications 2022, 30 (5), 455-463.*
4 *Hacke, P. and coworkers, IEEE Journal of Photovoltaics, vol. 5, no. 1, pp. 94-101, Jan. 2015*
5 *Swanson and coworkers, proceedings 15th International PVSEC, 2005.*

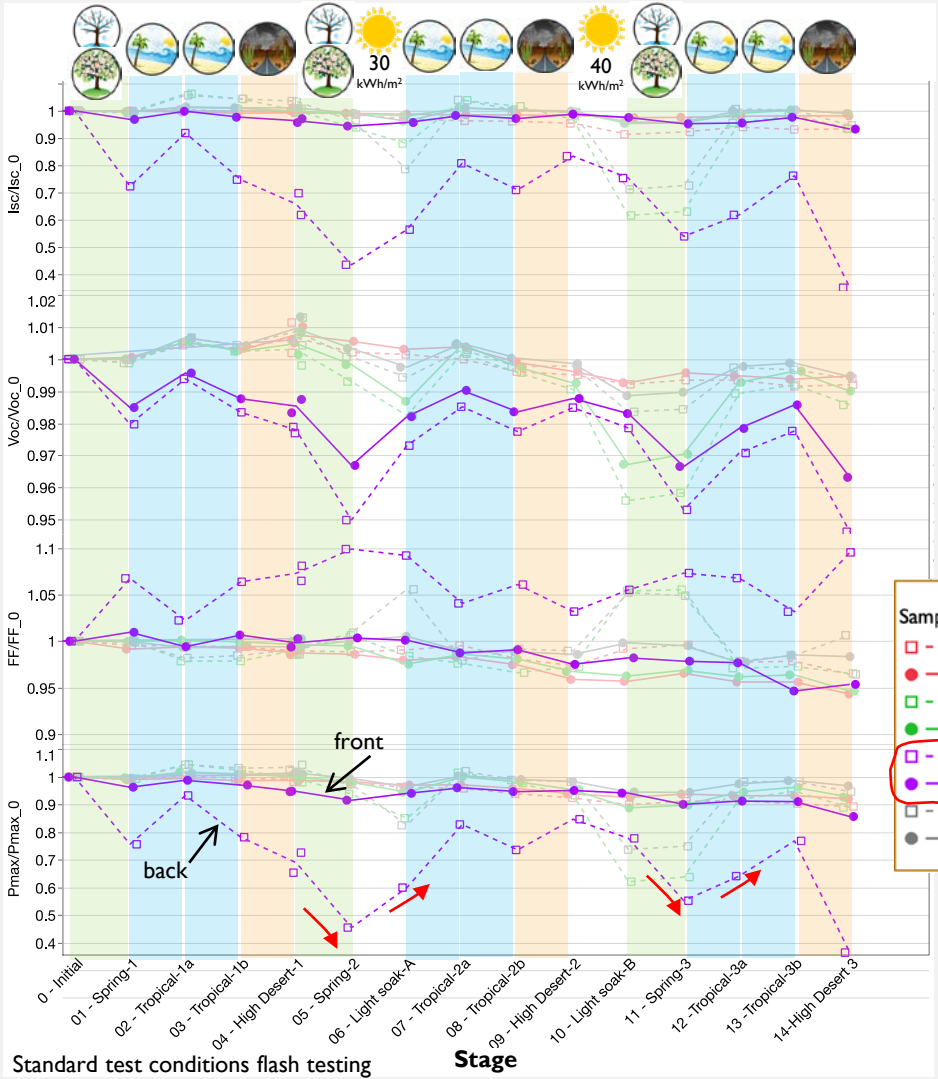




Standard test conditions flash testing

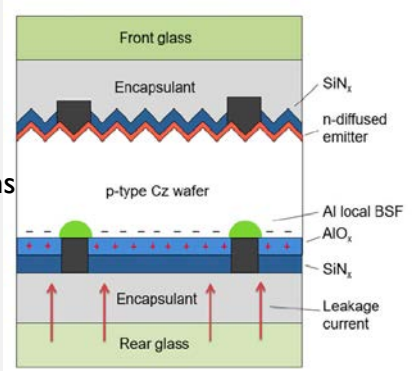
PID results

Glass back with EVA encapsulant sample shows most significant loss in I_{sc} and V_{oc} from the rear in bifacial PERC



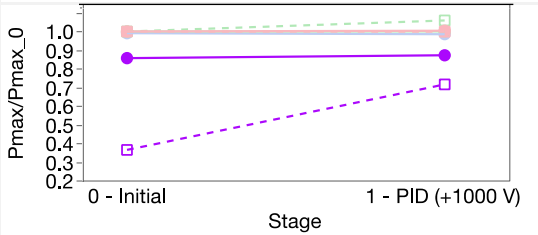
Standard test conditions flash testing

- ✓ Glass/EVA module construction
- ✓ -1200 V system voltage applied
- ✓ Seen with highest leakage current
- ✓ Degradation under low light conditions (Spring: 800 W/m² 35 °C)
- ✓ Recovery with elevated irradiation
- ✓ Recovery under opposite polarity



Sample	Substrate	Encapsulant	Coulombs/cycle
39B	T-PVF	EVA	1.37
39F	T-PVF	EVA	
40B	T-PVF	POE	0.35
40F	T-PVF	POE	
41B	Glass	EVA	2.15
41F	Glass	EVA	
42B	Glass	POE	0.19
42F	Glass	POE	

+1000 V 60°C 96 h (faces grounded)
→PID recovery



From IEC 61215 : 2021 series
PV Module design qualification and type approval

4 Modules
Sequence F

MQT 21
PID test

85 °C, 85 % relative humidity, 96 h ± Vsys (dark)

MQT 19.2
Final stabilization

Standard calls for 2 kWh/m^2 on rear to eliminate “polarization artifacts”

MQT 06.1
Performance at STC

Flash test

PID-polarization seen in C-AST Spring, so polarization may not be an “artifact”

PID results

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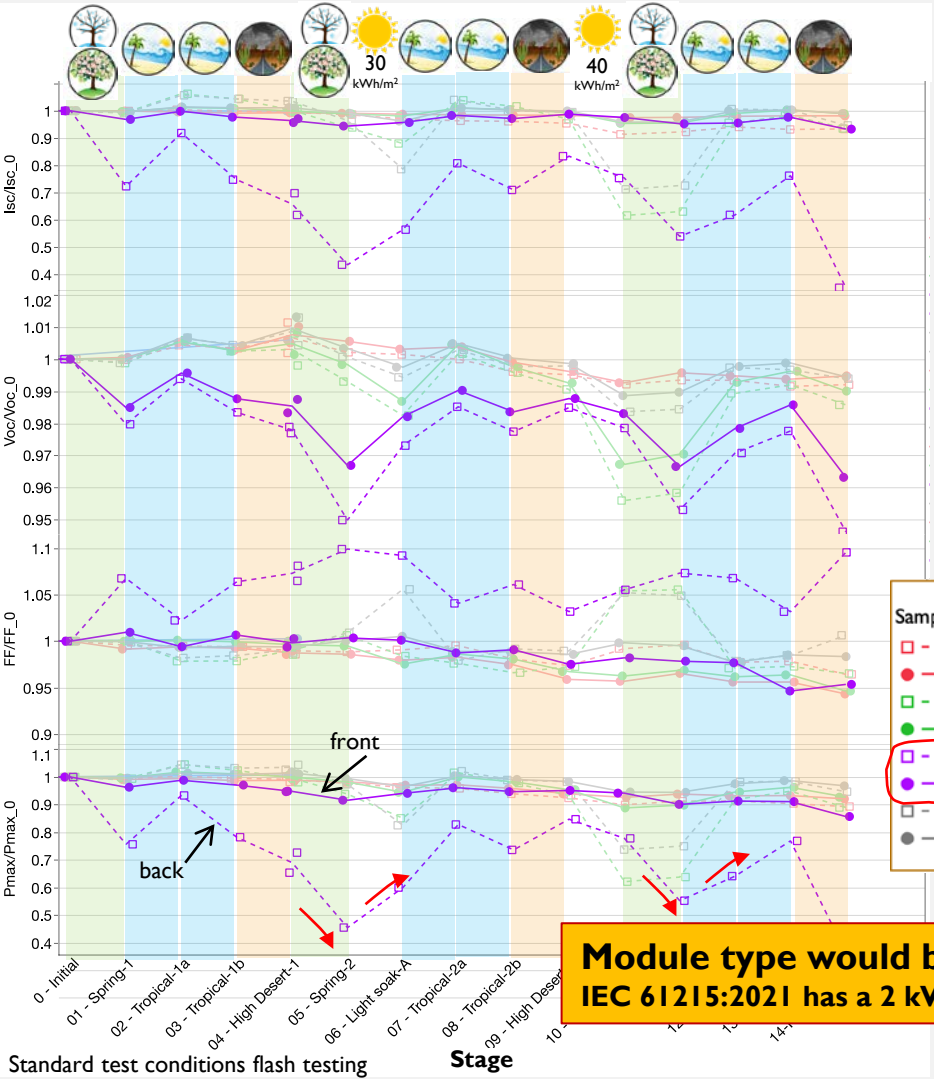

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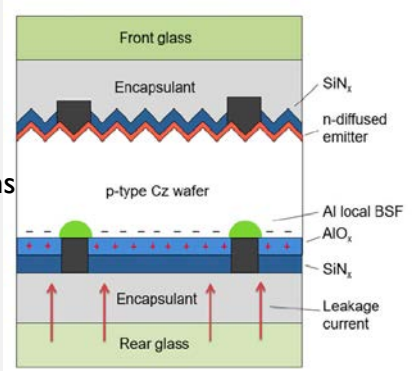

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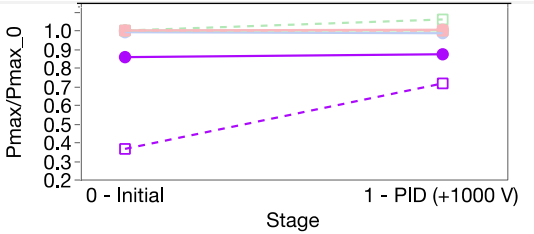
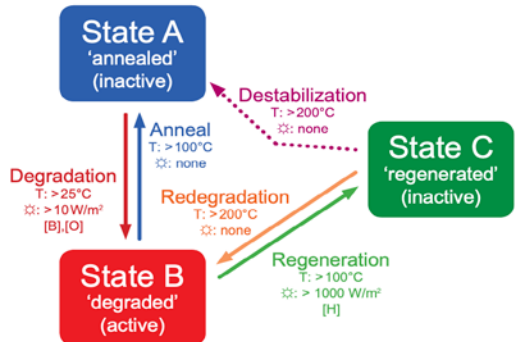


Module type would be susceptible to PID in the field (Spring conditions)
IEC 61215:2021 has a 2 kWh/m² rear light soak that may hide PID-p in PERC

Light-induced degradation (B-O complex) basics



Herguth, A. 33rd EU PVSEC (2017)

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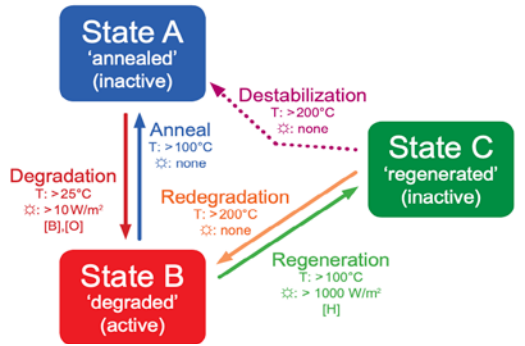
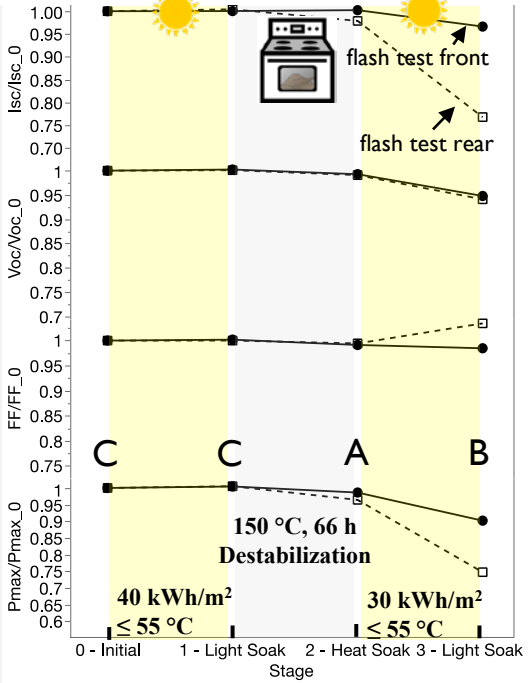
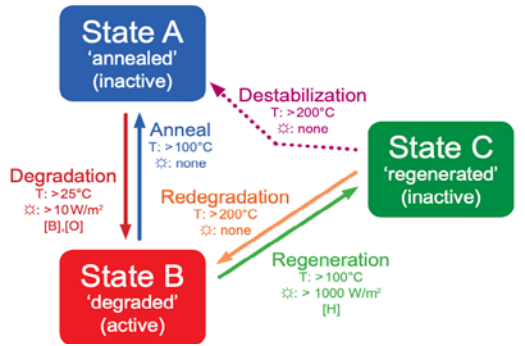


A new POE/glass module under sun→dark heat→sun





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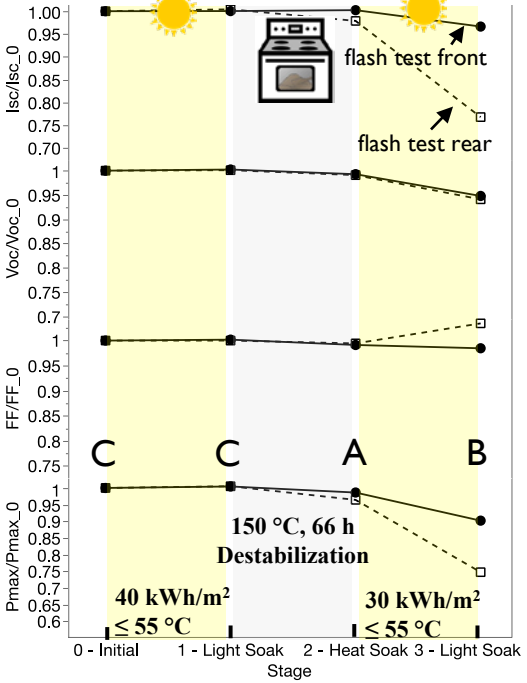

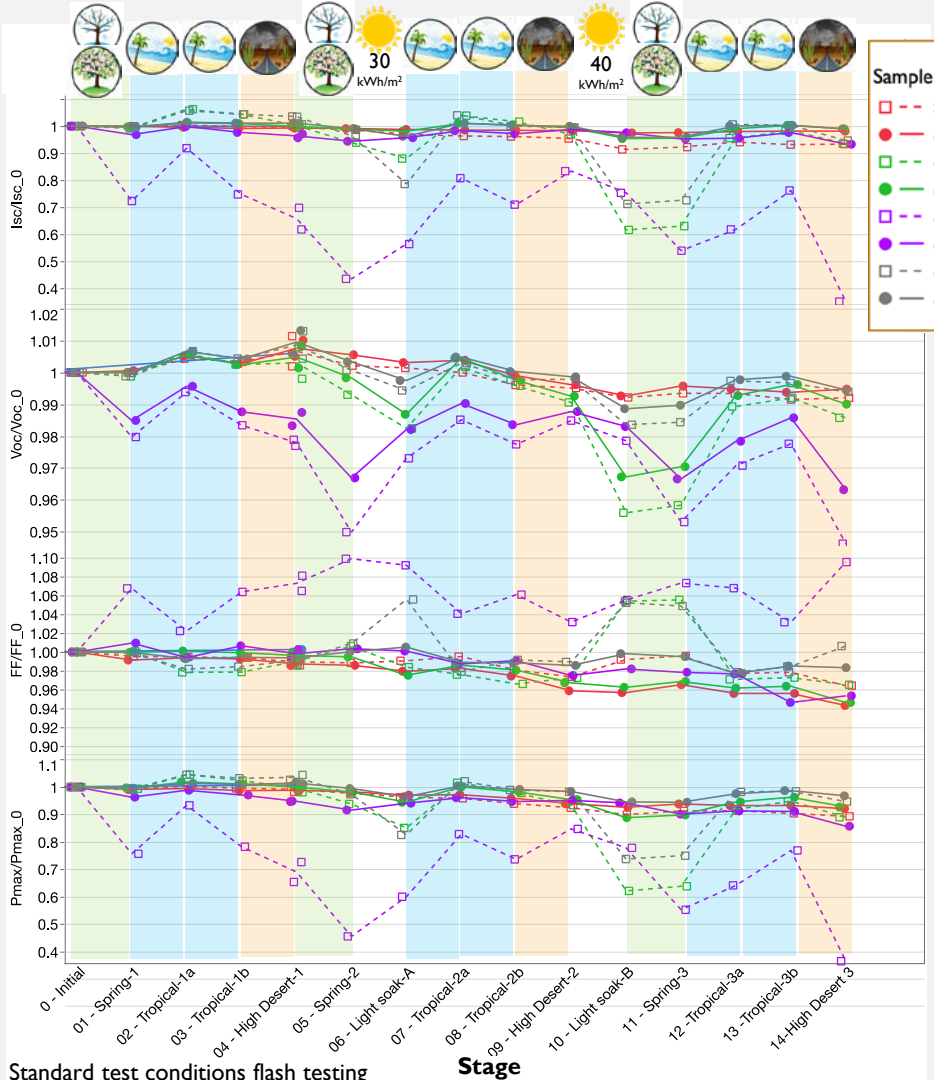

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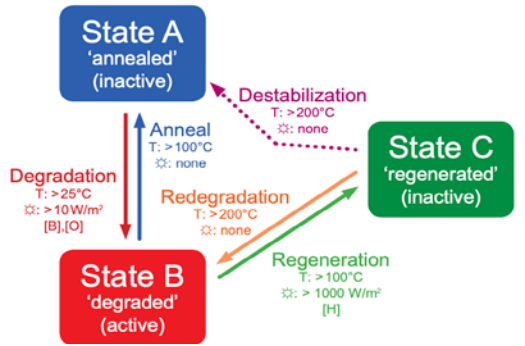

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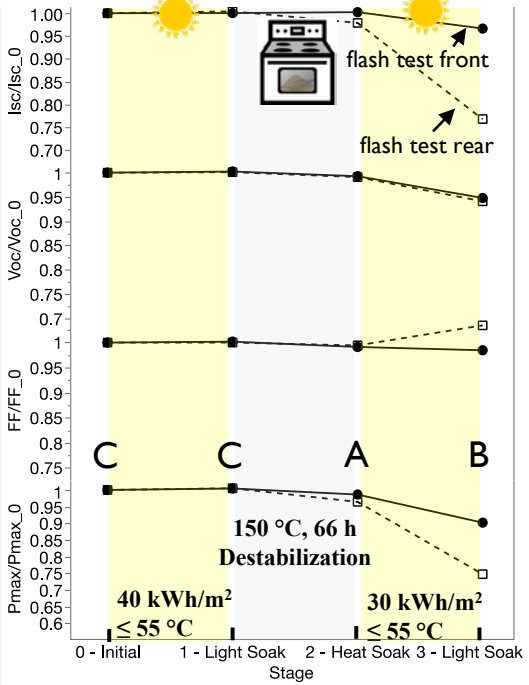

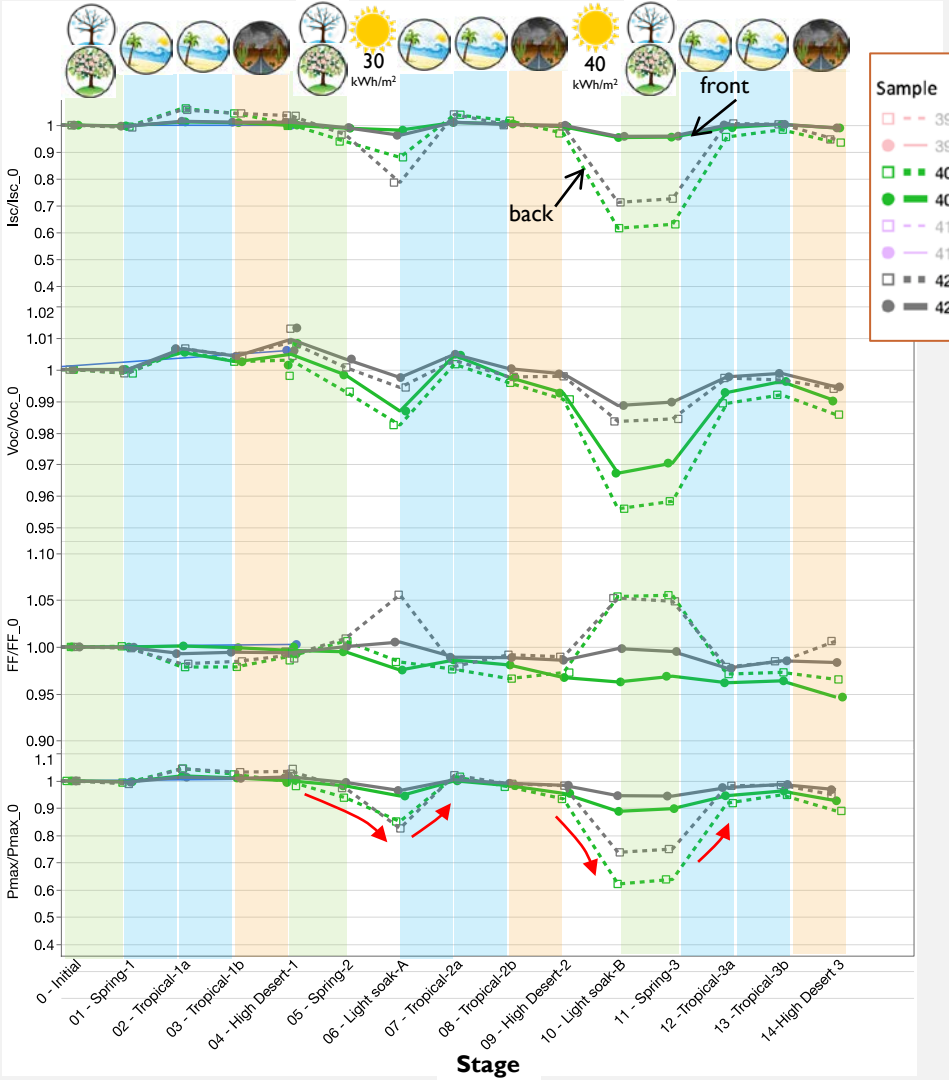

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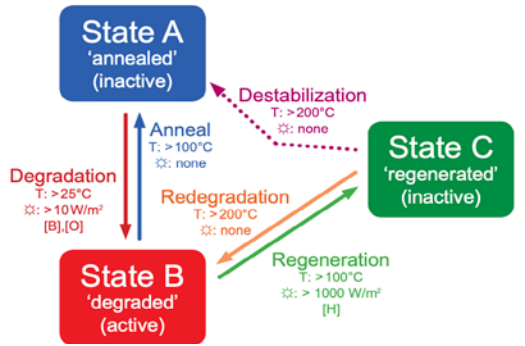
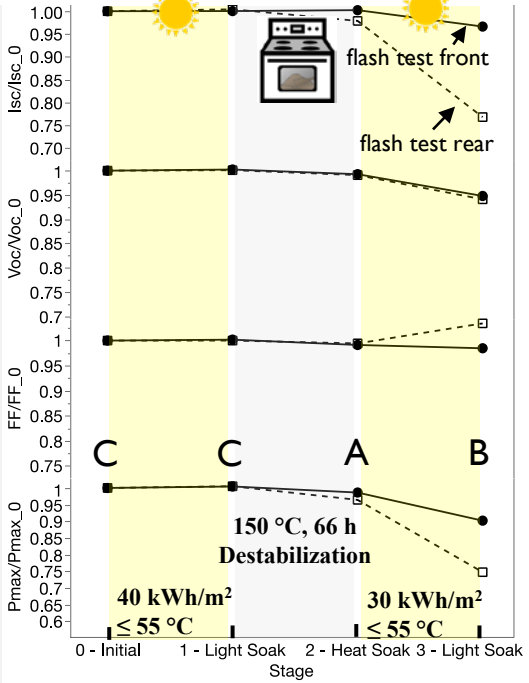
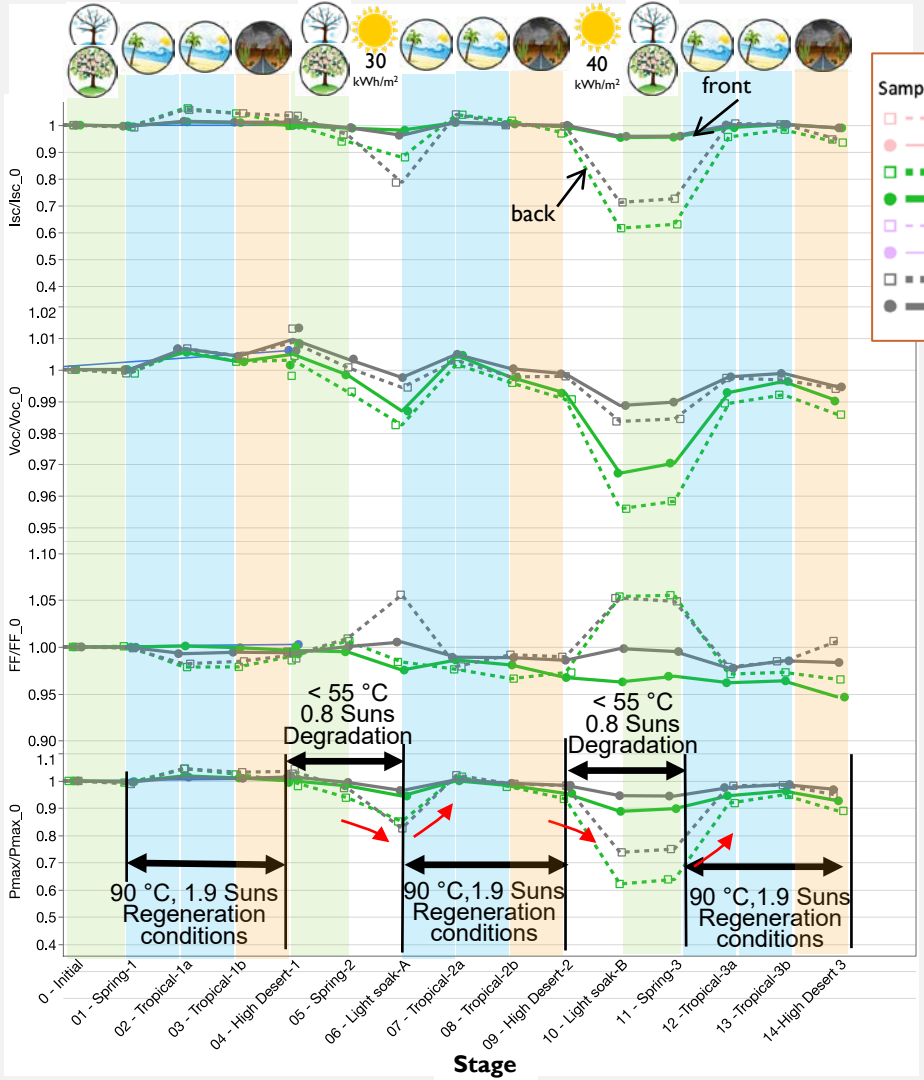
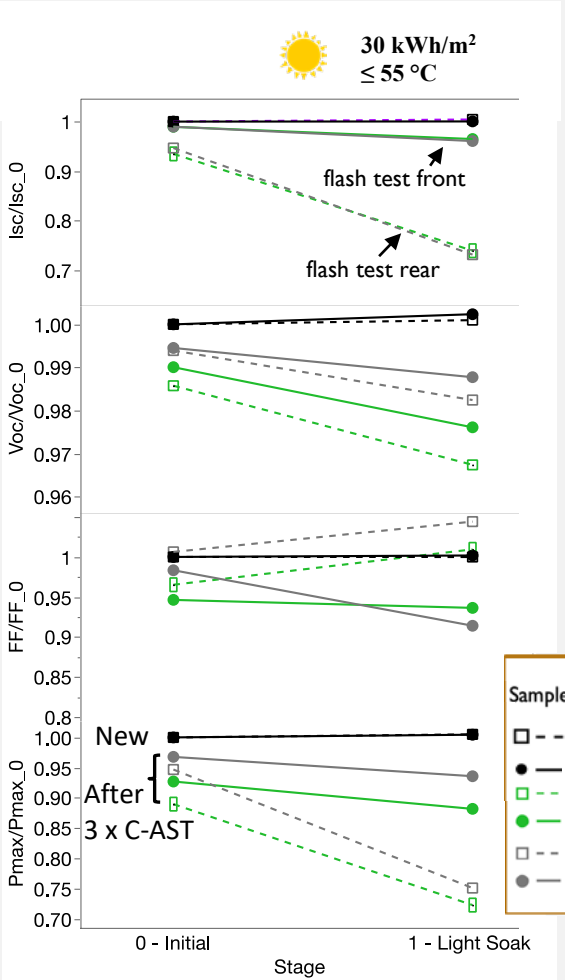


A new POE/glass module under sun→dark heat→sun

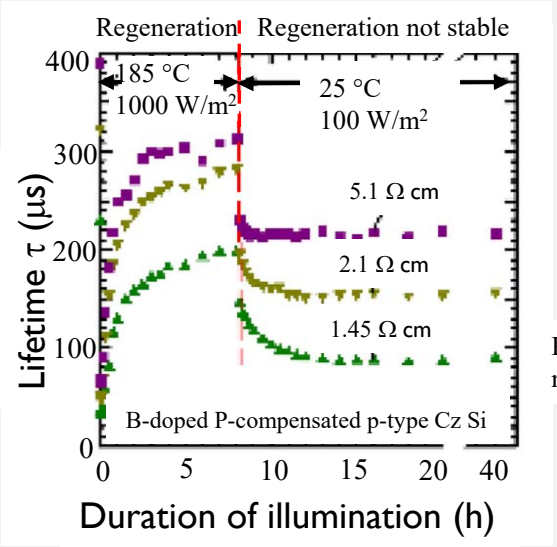




Sample	Substrate	Encapsulant	Coulombs/cycle
39B	T-PVF	EVA	1.37
39F	T-PVF	EVA	
40B	T-PVF	POE	0.35
40F	T-PVF	POE	
41B	Glass	EVA	2.15
41F	Glass	EVA	
42B	Glass	POE	0.19
42F	Glass	POE	



Sample	Substrate	Encapsulant
25B	Glass	POE
25F	Glass	POE
40B	T-PVF	POE
40F	T-PVF	POE
42B	Glass	POE
42F	Glass	POE



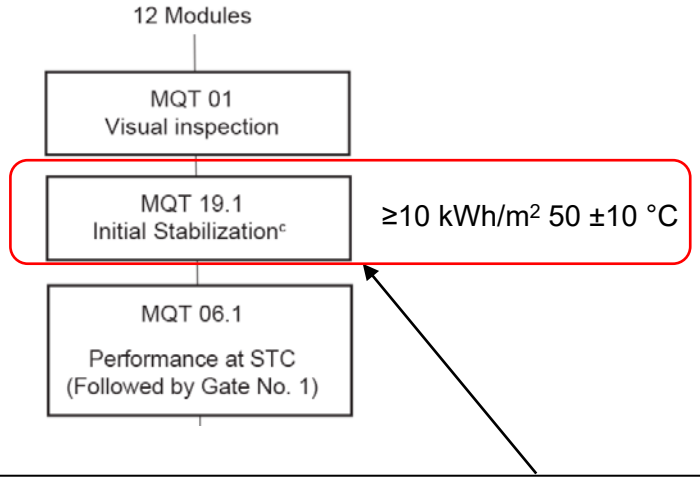
Lim, B
PhD Thesis. U Hanover (2011)

"prolonged illumination at elevated temperature always resulted in renewed degradation"

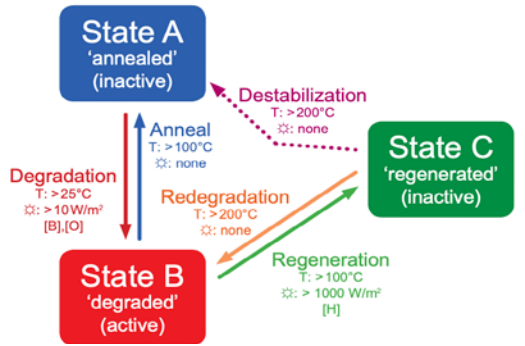
Regeneration not stable

From IEC 61215 : 2021series PV Module design qualification and type approval

Front-end characterization



Higher temperature, longer light exposures as with C-AST Tropical and High Desert might lead to LID destabilization, which won't be seen in IEC 61215



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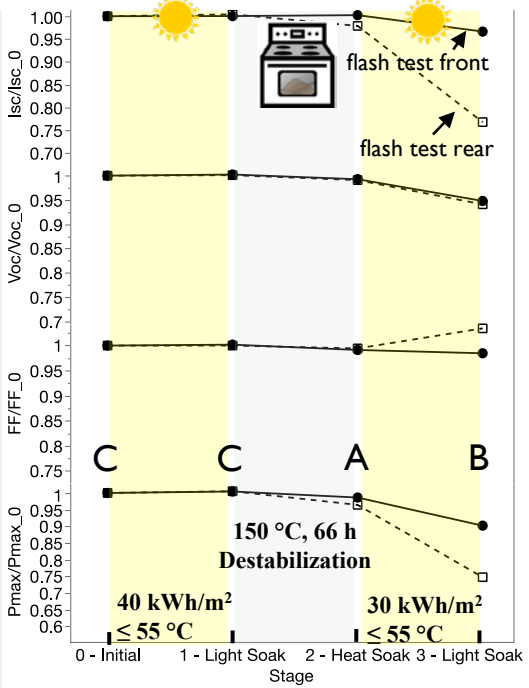

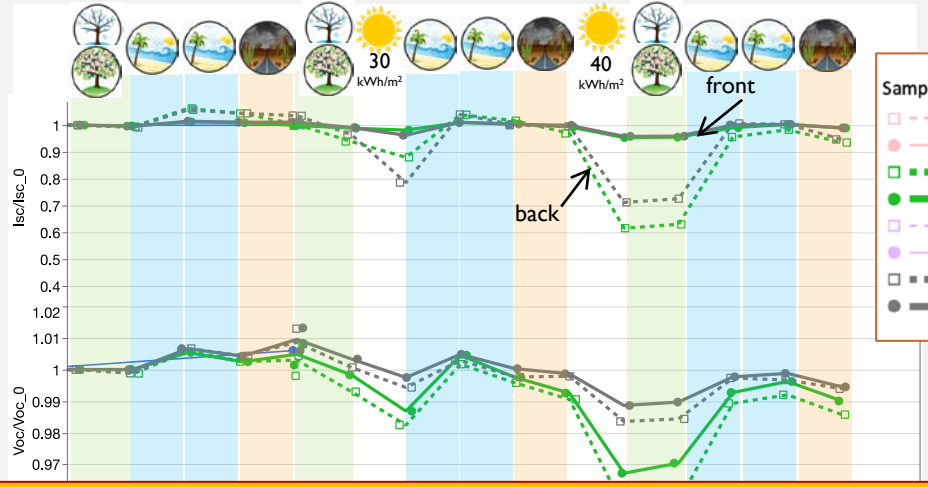

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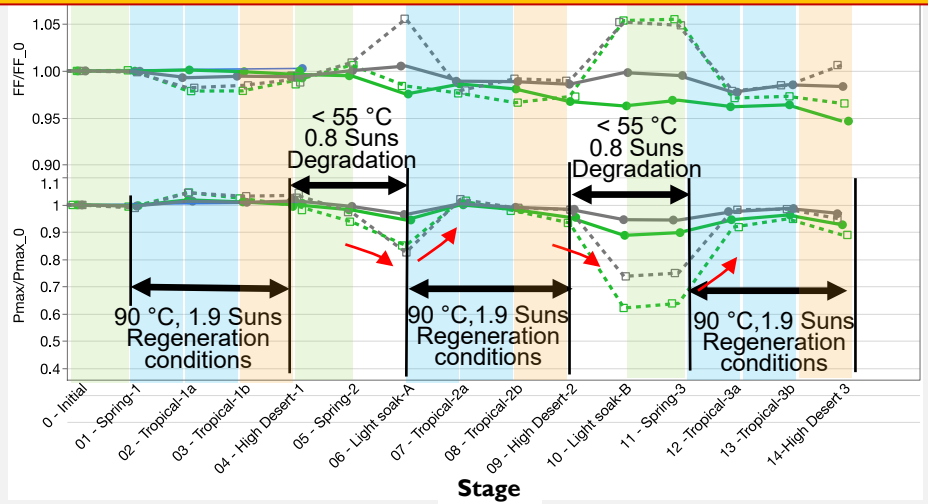
41B	Glass	EVA	2.15
41F	Glass	EVA	
42B	Glass	POE	0.19
42F	Glass	POE	

Module type would be susceptible to LID in the field
in high temperature operation. Issue would not be seen in IEC 61215:2021



Summary of Results

Reliability concerns for bifacial module rear/substrate Up to 4 rounds combined-accelerated stress	
Glass	**Polymeric**
No delamination due to constrained outgassing	No discoloration and embrittlement → cracking (with polyvinyl fluoride)
PID on back	No PID on back
No delamination due to adhesion loss (non-EVA)	No delamination due to adhesion loss (non-EVA)
Stress on cells & metallization	Stress on cells & metallization

- also -

- C-AST Spring showed PID-polarization
  - -The 2 kWh/m^2 after the PID test per the IEC 61215 qualification test masks it
  - -Installed modules in the field do not necessarily get rear light soaks
- C-AST found destabilization of LID-regenerated, inactive state cells leading to power loss in the Spring cycle and ex-situ light soaks;
  - -Likely not findable in IEC 61215

Thank you

NREL/PR-5K00-84177

US Dept of Energy Awards

08565 – Reliability Evaluation of Bifacial and Monofacial Glass/Glass Modules with EVA and non-EVA Encapsulants

38259 – DuraMAT

38263 – PV Reliability R&D to Ensure a Scientific Basis of Qualification Test and Standards

Hosted at: **Swiss NSF/ École Polytechnique Fédérale de Lausanne**

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