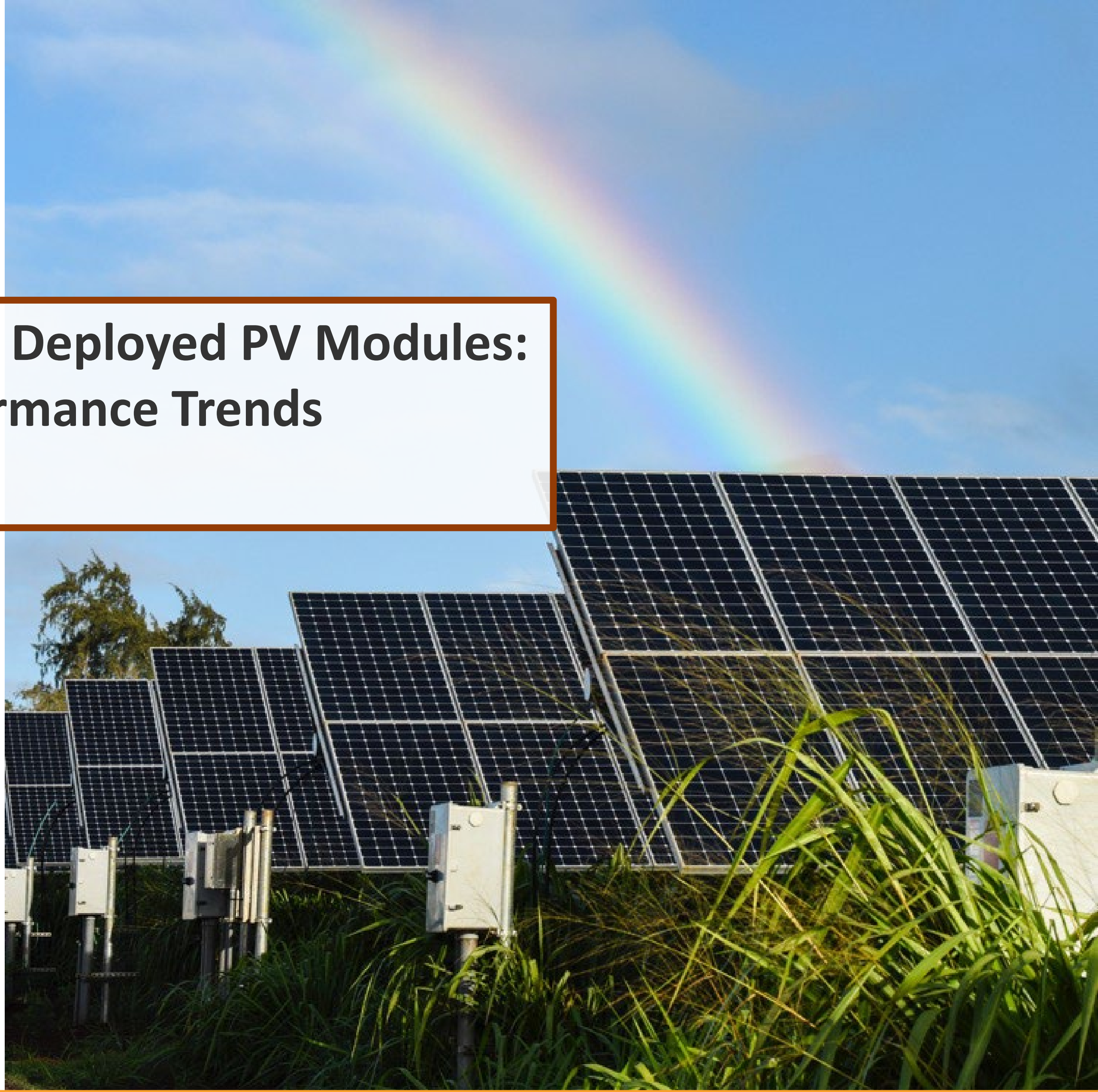
DuraMAT
Durable Module Materials Consortium

Benchmarking Bill-of-Materials of Recently Deployed PV Modules: Associating Specific BOMs with Field Performance Trends

DuraMAT SPARK project



DuraMAT Fall Workshop
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U.S. Department of Energy
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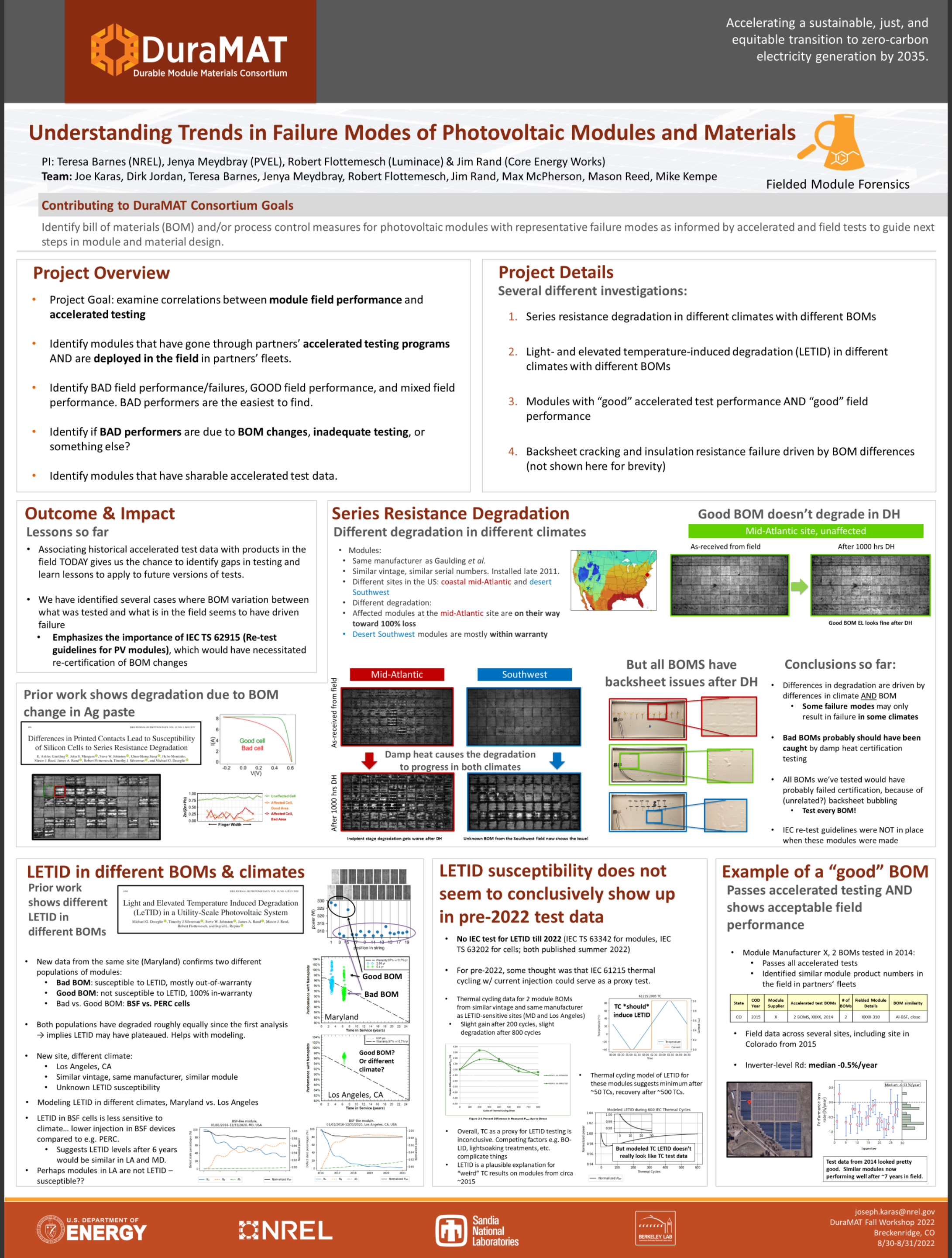


Follow on from FY2022 project "BOM Squad"

Goals/results of BOM Squad:

- **<u>Goal</u>**: examine correlations between historical accelerated testing data with specific fielded module BOMs and their field performance trends

- **<u>Results</u>**: it was challenging to associate accelerated test data with field performance, because *tested and fielded module BOMs were seemingly different*
  - Underscores the importance of BOM verification/ factory witnessing/ test every BOM, e.g. following IEC TS 62915 (IEC PV module re-test guidelines)
  - But, BOM variation drives different degradation in many cases (See also Deceglie *et al.*, *IEEE JPV*, doi: 10.1109/JPHOTOV.2022.3209610)
  - Establishing correlation requires enough field time to confidently measure Rd (5+ year old systems)

Benchmarking Bill-of-Materials of Recently Deployed PV Modules: Associating Specific BOMs with Field Performance Trends

PI: Joe Karas, NREL

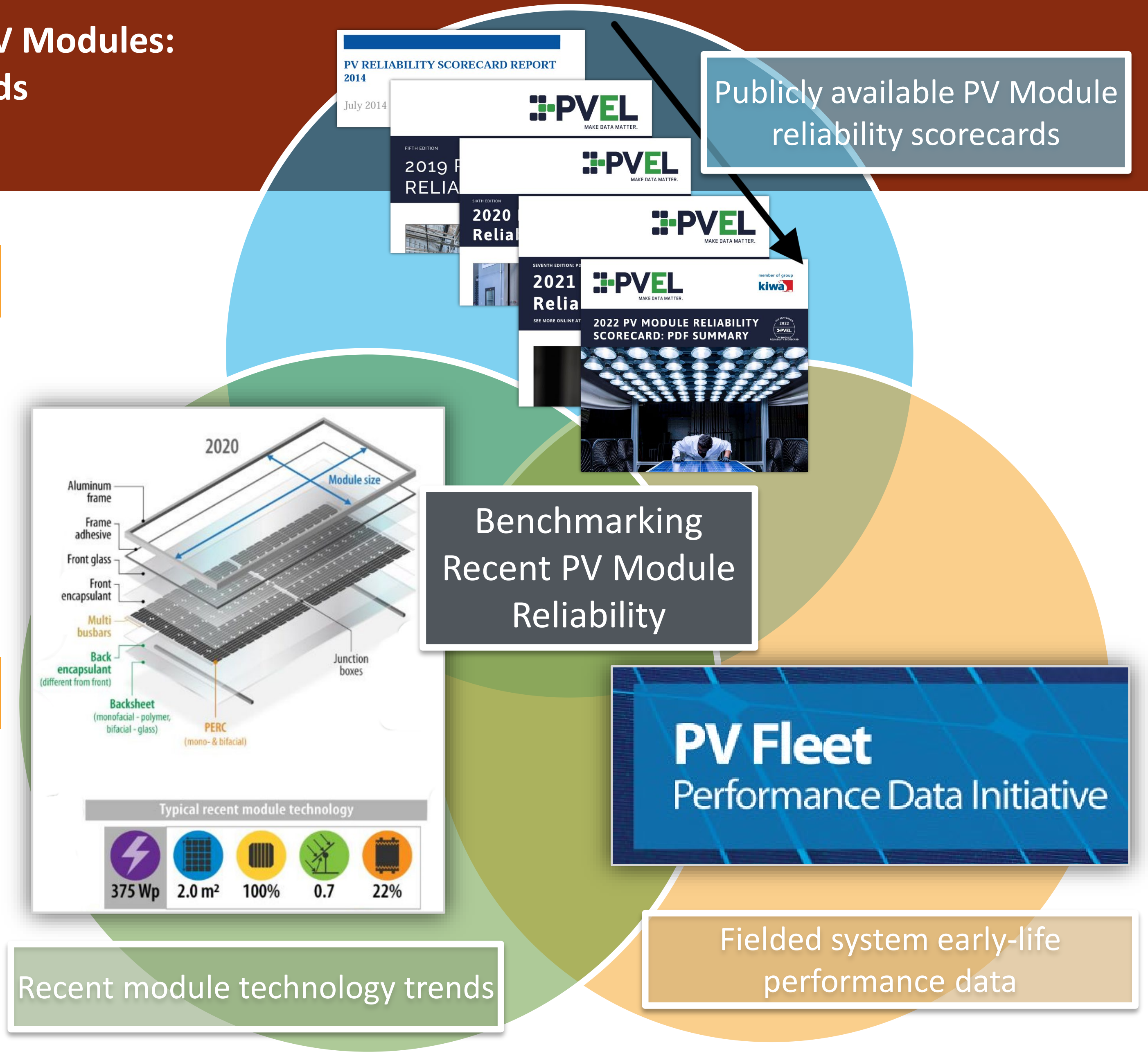
Key Results

- Database of module/technology features from publicly available sources and scorecards.
- Identify overlap of Model Names from Scorecards and fielded systems.
- Downselect systems with key trends and prepare data analysis pipeline for systems.

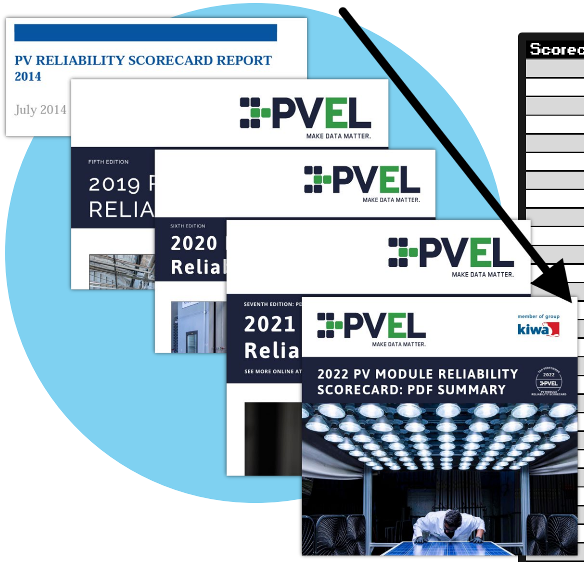
Core Objective & Teaming

Core Objective: Fielded Module Forensics

Team: Joe Karas, NREL



Publicly available PV Module reliability scorecards



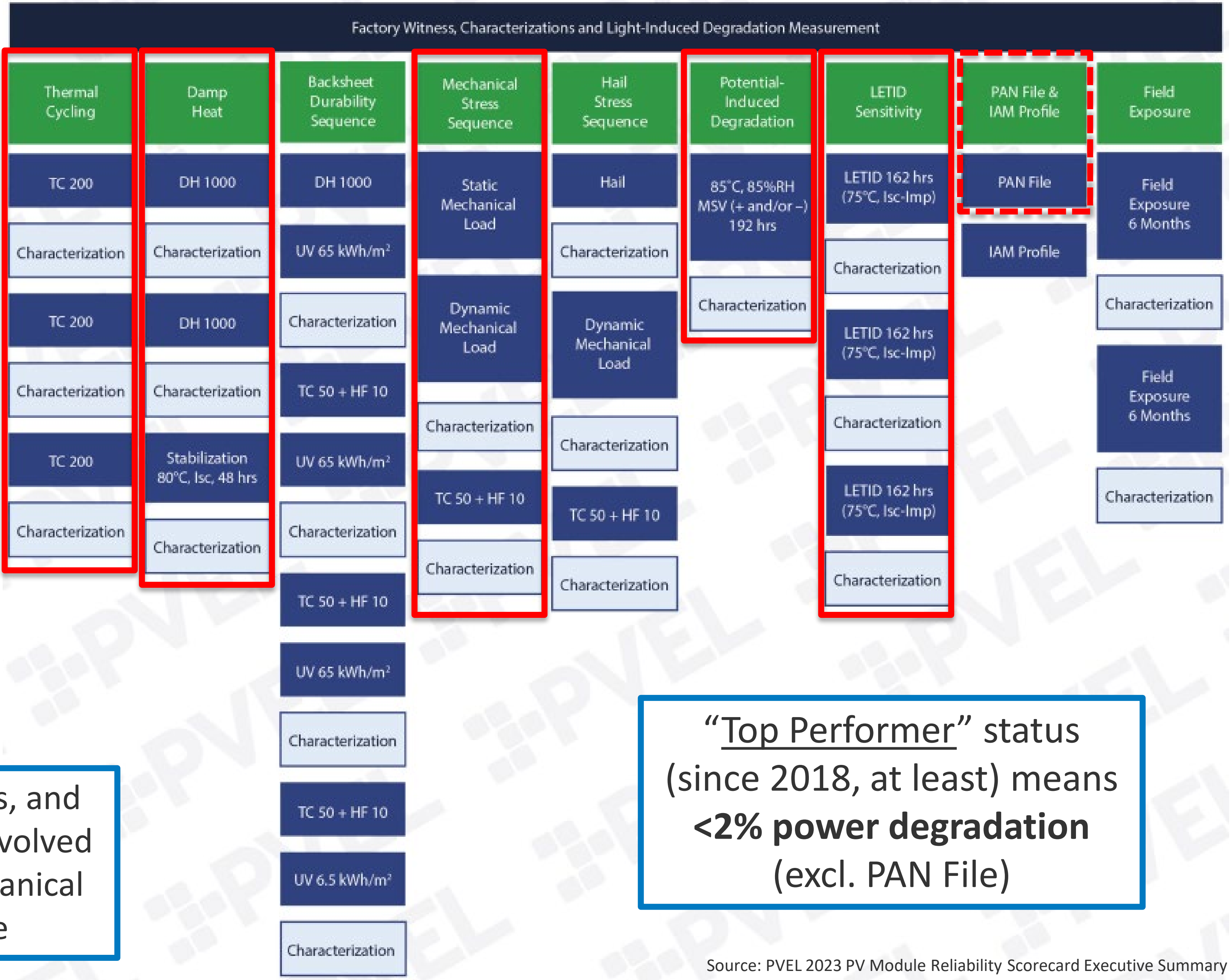
- 9 Module Scorecards (2014-2023)
- ~60 manufacturers
- > 500 Model Names

Scorecard	Model Name	Manufacturer Name	PMAX	PMAX	PMAX	Module Design	Cell T	# of C	Cell F	Wafe	Thermal Cycl	Damp Hea	Mechanical S	PID (PID-1	LID+LETID (202	PAN Performance (2	Humidity
2023	ASB-M10-144-AAA (G2B)	Adani Solar	530-575	530	575	Bifacial - glass/backshee	p-type PI	144		182	x		x	x	x	x	
2023	ASB-M10-144-AAA (G2G)	Adani Solar	530-575	530	575	Bifacial - glass/glass	p-type PI	144		182					x		
2023	ASB-M10-144-AAA (G2WE	Adani Solar	530-575	530	575	Monofacial - glass/backsl	p-type PI	144		182	x			x	x		
2023	AExxxMD-108	AE Solar	380-425	380	425	Monofacial - glass/backsl	p-type PI	108		182	x		x		x		
2023	AExxxMD-108E	AE Solar	380-425	380	425	Monofacial - glass/backsl	p-type PI	108		182	x		x		x		
2023	AExxxMD-120	AE Solar	430-475	430	475	Monofacial - glass/backsl	p-type PI	120		182	x		x		x		
2023	AExxxMD-120E	AE Solar	480-525	480	525	Monofacial - glass/backsl	p-type PI	120		182	x		x		x		
2023	AExxxMD-132	AE Solar	480-525	480	525	Monofacial - glass/backsl	p-type PI	132		182	x		x		x		
2023	AExxxMD-132E	AE Solar	480-525	480	525	Monofacial - glass/backsl	p-type PI	132		182	x		x		x		
2023	AExxxMD-144	AE Solar	530-575	530	575	Monofacial - glass/backsl	p-type PI	144		182	x		x		x		
2023	AExxxMD-144E	AE Solar	530-575	530	575	Monofacial - glass/backsl	p-type PI	144		182	x		x		x		
2023	AIKO-Axxx-MAH54Mb	Aiko Solar	430-475	430	475	Monofacial - glass/backsl	n-type AI	108		182				x			
2023	AIKO-Axxx-MAH54Mw	Aiko Solar	430-475	430	475	Monofacial - glass/backsl	n-type AI	108		182			x	x			
2023	AIKO-Axxx-MAH72Mb	Aiko Solar	580-625	580	625	Monofacial - glass/backsl	n-type AI	144		182				x			
2023	AIKO-Axxx-MAH72Mw	Aiko Solar	580-625	580	625	Monofacial - glass/backsl	n-type AI	144		182			x	x			
2023	SKA508HDGDC	Akcome	380-425	380	425	Bifacial - glass/glass	n-type H	80		210	x	x		x	x		
2023	SKA509HDGDC	Akcome	430-475	430	475	Bifacial - glass/glass	n-type H	90		210	x	x		x	x		
2023	SKA510HDGDC	Akcome	480-525	480	525	Bifacial - glass/glass	n-type H	100		210	x	x		x	x		
2023	SKA511HDGDC	Akcome	530-575	530	575	Bifacial - glass/glass	n-type H	110		210	x	x		x	x		
2023	SKA610HDGDC	Akcome	630-675	630	675	Bifacial - glass/glass	n-type H	120		210	x	x	x	x	x		
2023	SKA611HDGDC	Akcome	675W	675		Bifacial - glass/glass	n-type H	132		210	x	x	x	x	x		
2023	CHSM54N(BL)-HC-xxx	Astronergy	380-425	380	425	Monofacial - glass/backsl	n-type T(	108		182					x		
2023	CHSM54N(DG)/F-BH-xxx	Astronergy	380-425	380	425	Bifacial - glass/glass	n-type T(	108		182		x	x		x		
2023	CHSM54N(DG)/F-HC-xxx	Astronergy	380-425	380	425	Monofacial - glass/glass	n-type T(	108		182		x			x		
2023	CHSM54N(DGT)/F-BH-xxx	Astronergy	380-425	380	425	Bifacial - glass/glass	n-type T(	108		182		x			x		
2023	CHSM54N-HC-xxx	Astronergy	380-425	380	425	Monofacial - glass/backsl	n-type T(	108		182					x		
2023	CHSM60M(DG)/F-BH-xxx	Astronergy	580-625	580	625	Bifacial - glass/glass	p-type PI	120		210	x		x	x	x		
2023	CHSM60M-HC-xxx	Astronergy	580-625	580	625	Monofacial - glass/backsl	p-type PI	120		210					x		
2023	CHSM60N(DG)/F-BH-xxx	Astronergy	430-475	430	475	Bifacial - glass/glass	n-type T(	120		182		x	x		x		
2023	CHSM60N(DG)/F-HC-xxx	Astronergy	430-475	430	475	Monofacial - glass/glass	n-type T(	120		182		x			x		
2023	CHSM60N-HC-xxx	Astronergy	430-475	430	475	Monofacial - glass/backsl	n-type T(	120		182					x		
2023	CHSM66M(DG)/F-BH-xxx	Astronergy	630-675	630	675	Bifacial - glass/glass	p-type PI	132		210	x		x	x	x		
2023	CHSM66M-HC-xxx	Astronergy	630-675	630	675	Monofacial - glass/backsl	p-type PI	132		210					x		
2023	CHSM72N(DG)/F-BH-xxx	Astronergy	530-575	530	575	Bifacial - glass/glass	n-type T(	144		182		x	x		x	x	
2023	CHSM72N-HC-xxx	Astronergy	530-575	530	575	Monofacial - glass/backsl	n-type T(	144		182					x		
2023	CHSM78N(DG)/F-BH-xxx	Astronergy	580-625	580	625	Bifacial - glass/glass	n-type T(	156		182		x	x		x		
2023	CHSM78N-HC-xxx	Astronergy	580-625	580	625	Monofacial - glass/backsl	n-type T(	156		182					x		
2023	BVM6610M-xxxS-H-HC-BI	Boviet Solar	330-375	330	375	Bifacial - glass/glass	p-type PI	120		166				x			
2023	BVM6612M-xxxS-H-HC-BI	Boviet Solar	430-475	430	475	Bifacial - glass/glass	p-type PI	144		166				x			
2023	BVM7609M-xxx-H-HC	Boviet Solar	380-425	380	425	Monofacial - glass/backsl	p-type PI	108		182			x	x			
2023	BVM7609M-xxx-H-HC-BF	Boviet Solar	380-425	380	425	Bifacial - glass/glass	p-type PI	108		182			x	x			
2023	BVM7610M-xxx-H-HC	Boviet Solar	430-475	430	475	Monofacial - glass/backsl	p-type PI	120		182			x	x			
2023	BVM7610M-xxx-H-HC-BF	Boviet Solar	430-475	430	475	Bifacial - glass/backshee	p-type PI	120		182			x	x			
2023	BVM7610M-xxx-H-HC-BF-	Boviet Solar	430-475	430	475	Bifacial - glass/glass	p-type PI	120		182			x	x			
2023	BVM7612M-xxx-H-HC	Boviet Solar	530-575	530	575	Monofacial - glass/backsl	p-type PI	144		182			x	x			
2023	BVM7612M-xxx-H-HC-BF	Boviet Solar	530-575	530	575	Bifacial - glass/backshee	p-type PI	144		182			x	x			
2023	BVM7612M-xxx-H-HC-BF-	Boviet Solar	530-575	530	575	Bifacial - glass/glass	p-type PI	144		182			x	x			
2023	CS3N-xxxMS	Canadian Solar	380-425	380	425	Monofacial - glass/backsl	p-type PI	132		166	x	x	x	x	x		

✓ Historical Scorecard data entry complete

➢ Currently: <u>**understand research value** of historical public Scorecard data</u>, identify trends & systems of interest

PQP Tests



Denotes test data appears in 2023 Scorecard results

Test flow, procedures, and nomenclature have evolved over time, e.g. Mechanical Stress Sequence

"Top Performer" status (since 2018, at least) means **<2% power degradation** (excl. PAN File)

Source: PVEL 2023 PV Module Reliability Scorecard Executive Summary

User’s guide to historical PVEL Reliability Scorecard Data

- Scorecard data has evolved over time
  - 2014 & 2016, only manufacturer names were listed
  - Since 2017, product names, and factory locations.
    - But factory locations are not always mappable to Model Names…. could be multiple.
  - Since 2022, limited BOM information (bifacial vs. monofacial, g/g vs. g/bs, power, # cells, cell size/format)
  - Since 2023, downloadable as .CSV (thank you!)

- According to PVEL, a module Model Name may be listed in a Scorecard if:
  - Factory witness in the prior 18 months with BOM verification.
    - ➢ Implies that one witnessed Model Name may appear in two consecutive Scorecards
  - Submitted at least 2 factory-witnessed modules per test sequence. No picking and choosing tests.

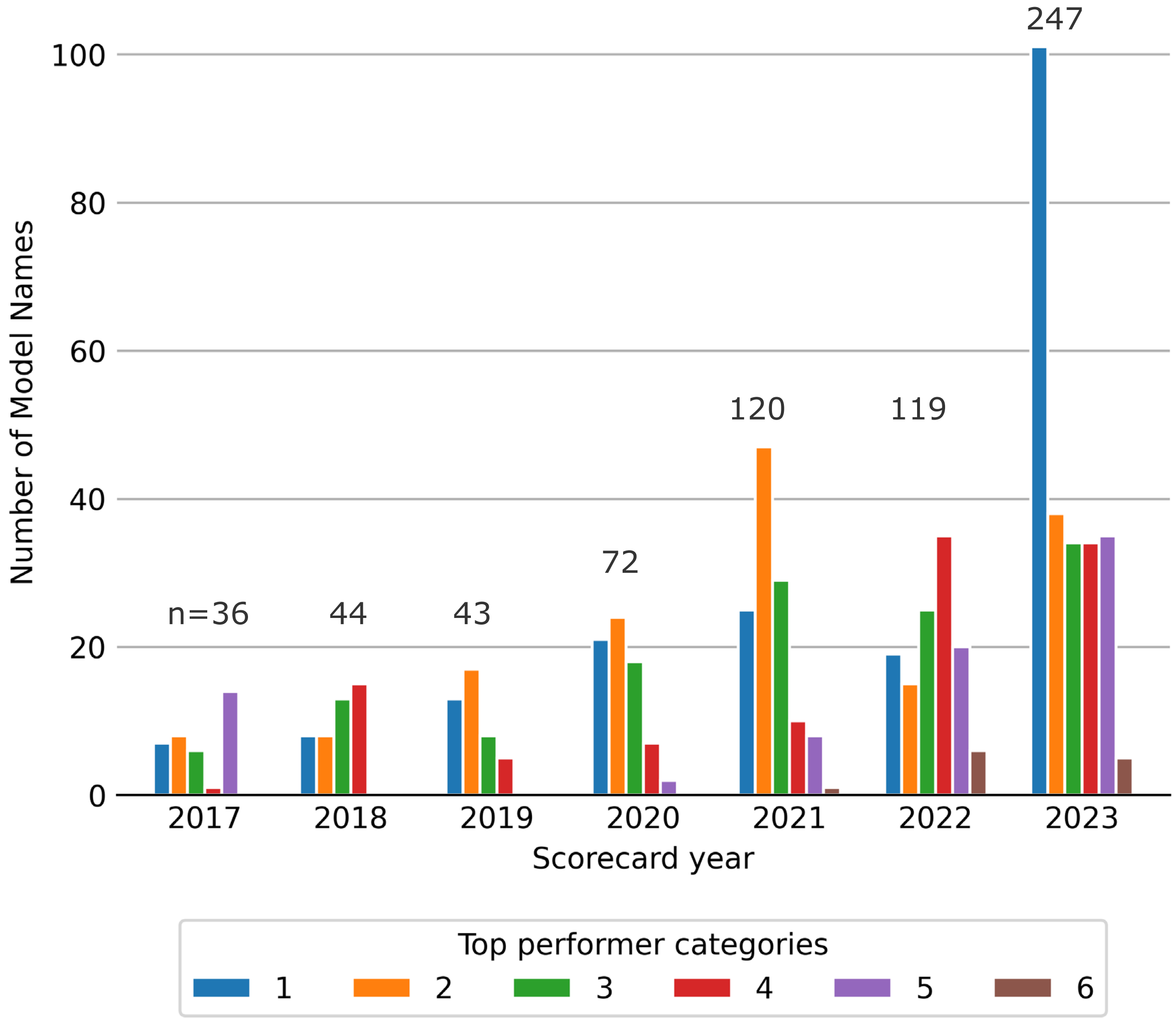
- Sometimes, testing is not complete at Scorecard publication date.
  - ➢ Important to look at multiple years for complete Scorecard data for a given Model Name!

- Tested Model Names vs. “representative variants”
  - Could understand better which tests allow for what changes for variants to qualify (i.e., frame color, 60 vs. 72 cells…). Are these IEC TS 62915 guidelines or other?

- Some of these questions might be answerable if you are a “Downstream Partner”

Some summary data

- Model names per year has gone up and up
  - 2017: 36
  - 2018: 44
  - 2019: 43
  - 2020: 72
  - 2021: 120
  - 2022: 119
  - 2023: 247



<u>But most models don't achieve "Top Performer" in all (or even most) categories</u>

- Median number of "Top Performer" categories per model name:
- 2017: 3 (out of 5)
- 2018: 3 (out of 5)
- 2019: 3 (out of 5)
- 2020: 2 (out of 5)
- 2021: 2 (out of 6)
- 2022: 4 (out of 6)
- 2023: 2 (out of 6)

An example:

One Model Name, four consecutive Scorecards, but some opacity

			Top Performer Categories				
Scorecard year	**Model Name**	**Manufacturer**	**Thermal Cycling**	**Damp Heat**	**Mechanical Stress Sequence**	**PID**	**LID+LETID (since 2021)**
2019	Q.PEAK DUO L-G5.2	Qcells	x		x	x	N/A
2020	Q.PEAK DUO L-G5.2	Qcells	x				N/A
2021	Q.PEAK DUO L-G5.2	Qcells	x	x	x	x	x
2022	Q.PEAK DUO L-G5.2	Qcells	x		x	x	x

<u>Q.PEAK DUO L-G5.2</u>
- 355-400W
- Monofacial - glass/backsheet
- p-type PERC
- 144 cells
- Half-cell
- 156.75mm wafer width

Unclear from public Scorecards…
- How many times was this BOM factory-witnessed and tested? At least 2, or as many as 4
- Did it “fail” Mechanical Stress and PID in 2020?
- Did this module “fail” Damp Heat prior to 2021? Did it subsequently “fail” in 2022?

<u>Many questions like this start to appear as one starts sifting through public Scorecards</u>

Another example:

One Model Name, Four consecutive Scorecards, but several BOM changes

			Top Performer Categories				
Scorecard year	Model Name	Manufacturer	Thermal Cycling	Damp Heat	Mechanical Stress Sequence	PID	LID+LETID (since 2021)
2020	CHSM60M-HC-xxx	Astronergy	x	x		x	N/A
2021	CHSM60M-HC-xxx	Astronergy	x				x
2022	CHSM60M-HC-xxx	Astronergy	x		x	x	x
2023	CHSM60M-HC-xxx	Astronergy					x

Astronergy CHSM60M-HC-xxx

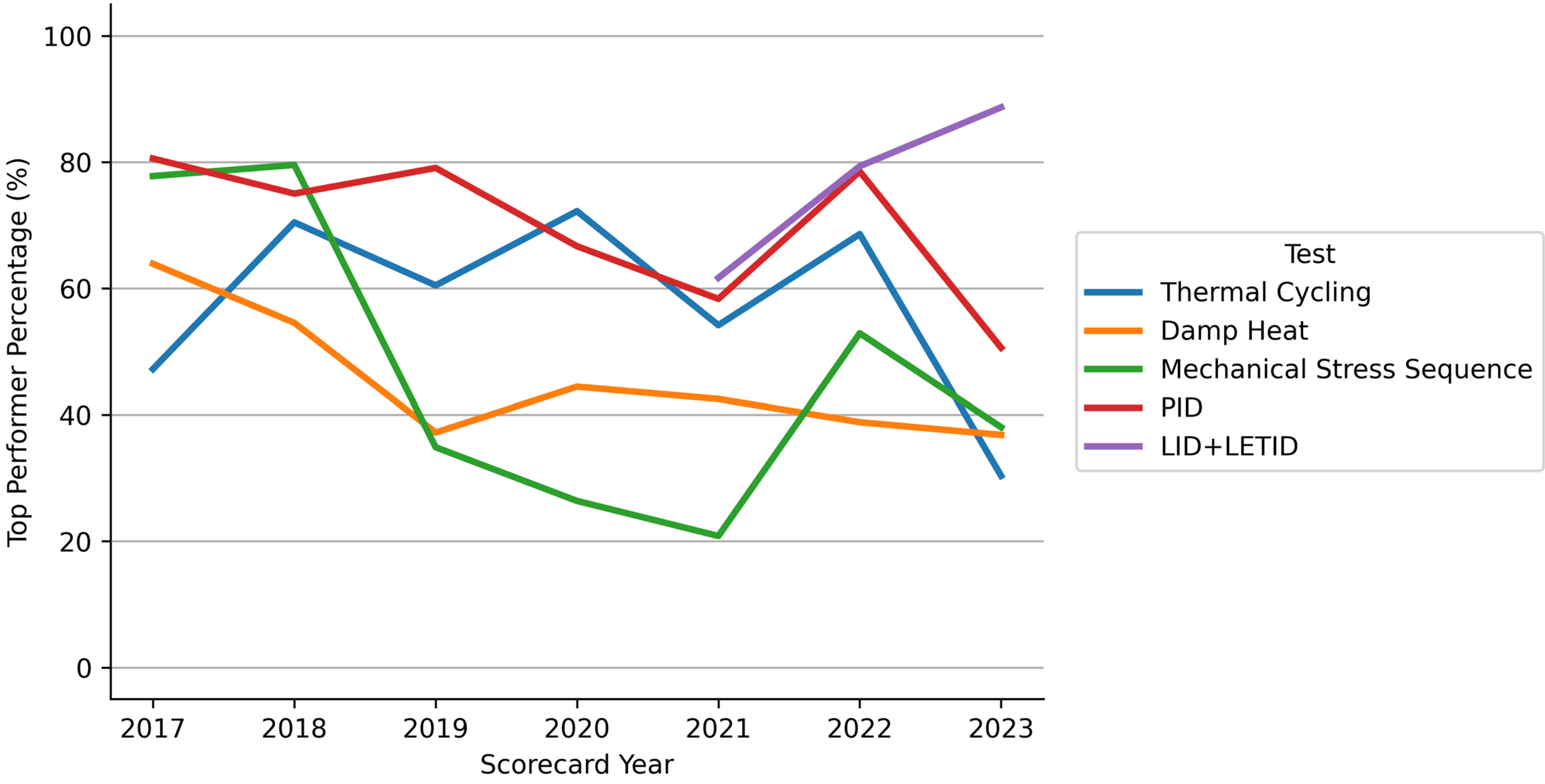
- ~335W → ~350W → ~380W
- Monofacial - glass/backsheet
- p-type PERC
- 120 cells
- Half-cell
- 156.75 → 158.75 → 166 mm wafer width
- 5BB → 9BB

Datasheets dated 10-2019, 5-2020, and 7-2020

- Same Model Name, but obvious BOM changes when you look at datasheets:
  - 156.75 → 158.75 → 166 mm wafer width, and 5BB → 9BB interconnects
  - Larger module ~1.66 → 1.84 m^2
  - BOM data not included in 2020 and 2021 Public Scorecards, so we're in the dark

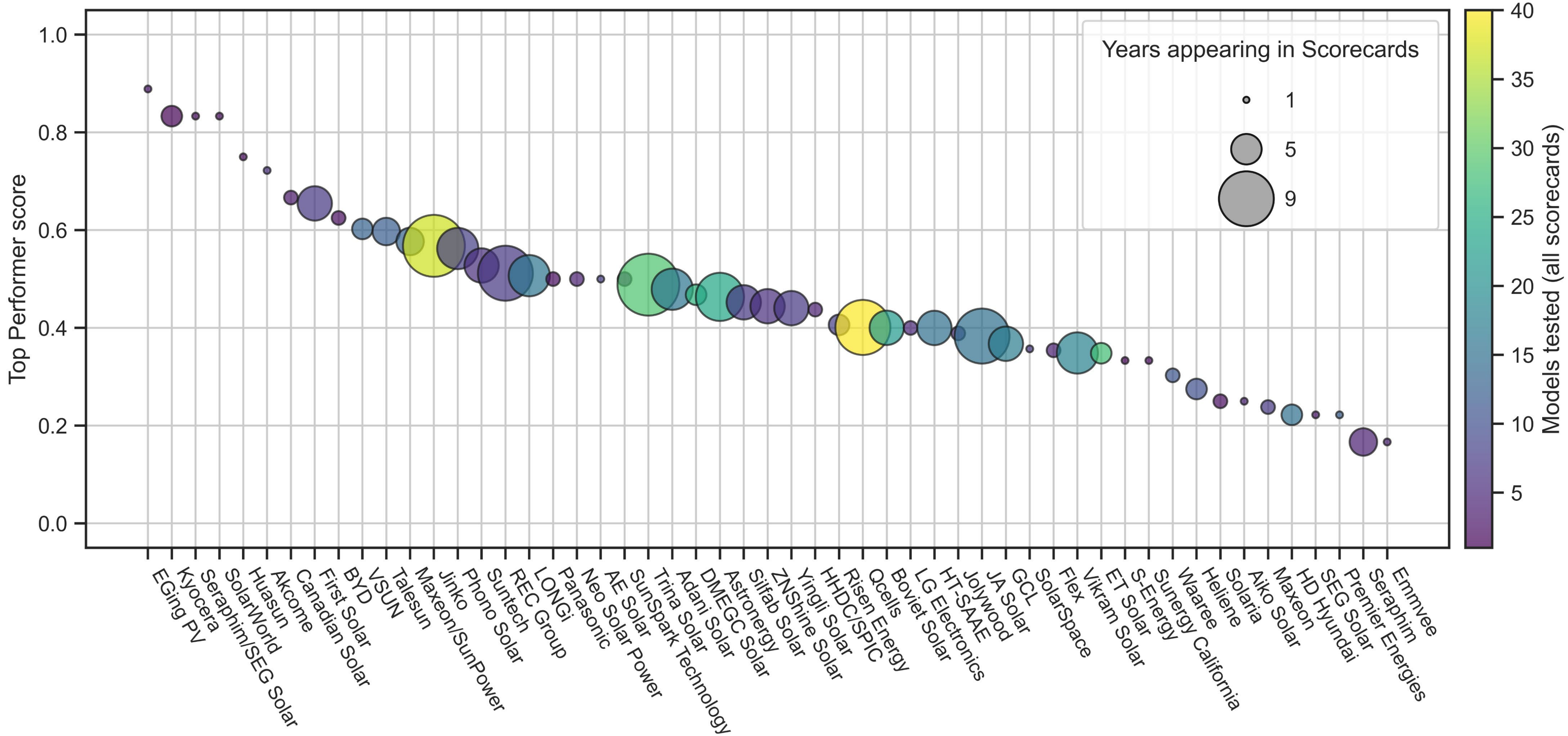
- Which BOM was factory-witnessed and tested for each test?
- This model seems to have not been tested for every test, and instead was a "representative variant"

Which tests are the easiest and hardest for achieving Top Performer Status?



- Since 2017*, it appears like modules are not getting demonstrably better at earning Top Performer status at:
  - TC, DH, MSS, PID
- LID+LETID is on a good trajectory, though (219 out of 247 in 2023)
- Some mitigating factors:
  - Tests have evolved over time:
    - e.g. mechanical stress sequence; DH duration
  - *For 2023, test duration + PVEL facility move. LID+LETID is relatively short compared to other tests

Do any manufacturers stand out from the rest?

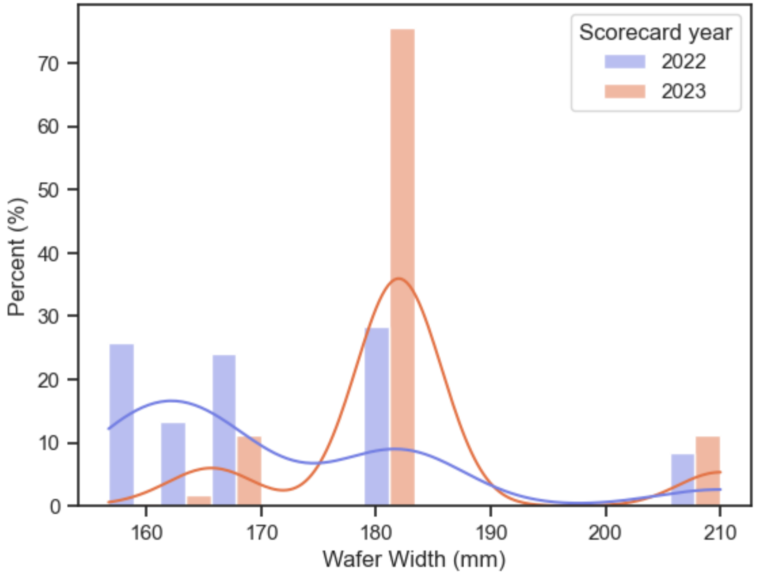


$$Top\ Performer\ score = \frac{Top\ Performer\ Designations \times Scorecard\ Participation\ Years}{Tests\ \times Scorecard\ Participation\ Years}$$

A high Top Performer score and a big bubble is better.

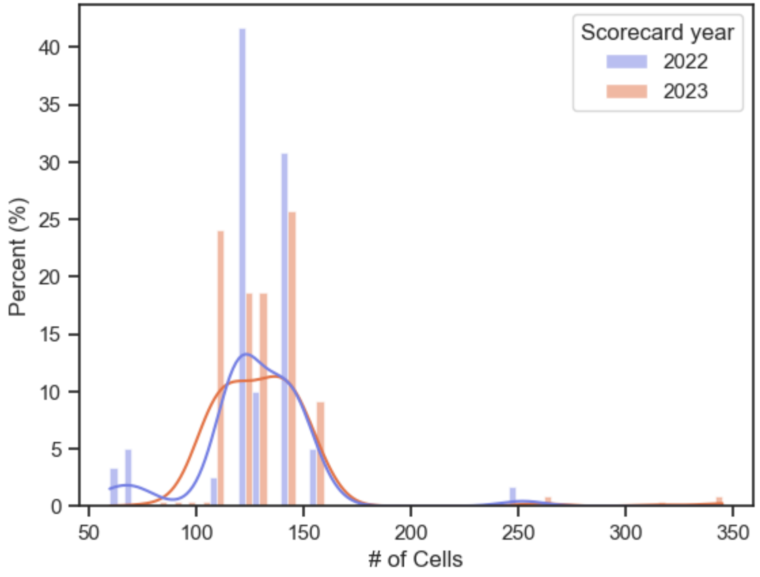
Recent trends (2022 → 2023)

Wafer Sizes



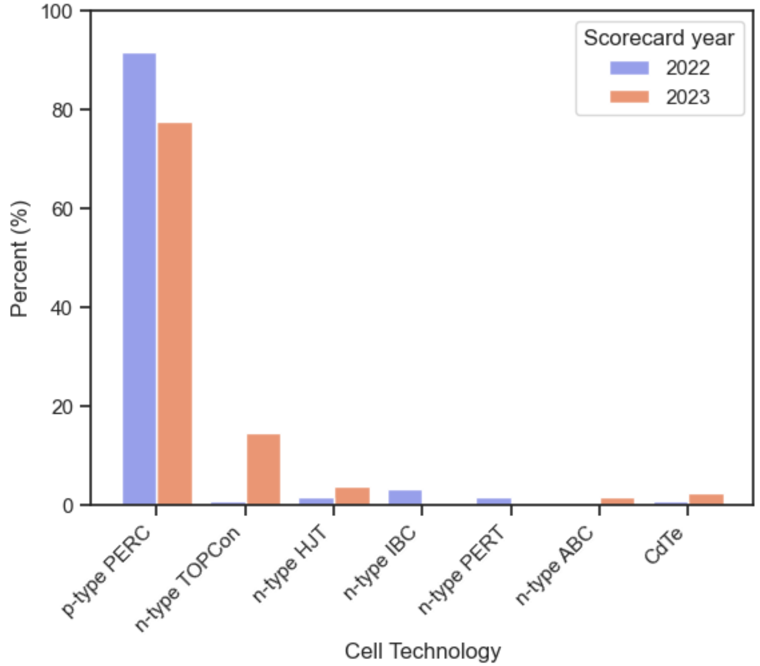
Obvious consolidation/increase in wafer size:
- 2022: Roughly equal M2/G1/M4/M6/M10
- 2023: Predominantly M10 (182mm)

of Cells



No obvious change in cells per module; implies half-cell format is still predominant

Cell Technology



Only a slight transition to n-type TOPCon/HJT, p-type PERC still predominant

Summary

- All historical PVEL Scorecard data has been entered
  - Most models don't achieve Top Performer status in all tests
  - Public Scorecard data leaves some unanswered questions regarding model testing/retesting, and BOM changes

  - The fraction of modules that achieve Top Performer status in most tests seems to be going down over time, LID/LETID is the exception

  - Tough to differentiate between manufacturers based on Scorecard results
    - Most manufacturers achieve Top Performer status ~40%-60% of the time on a per-module basis

  - Recent trends: substantial evolution in wafer size; transition to n-type is underway

- Next steps
  - DuraMAT datahub
  - ✓ Identified overlap of several fielded systems and Scorecard data, continue look for systems of interest

Thank you!

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