



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

DuraMAT SPARK project

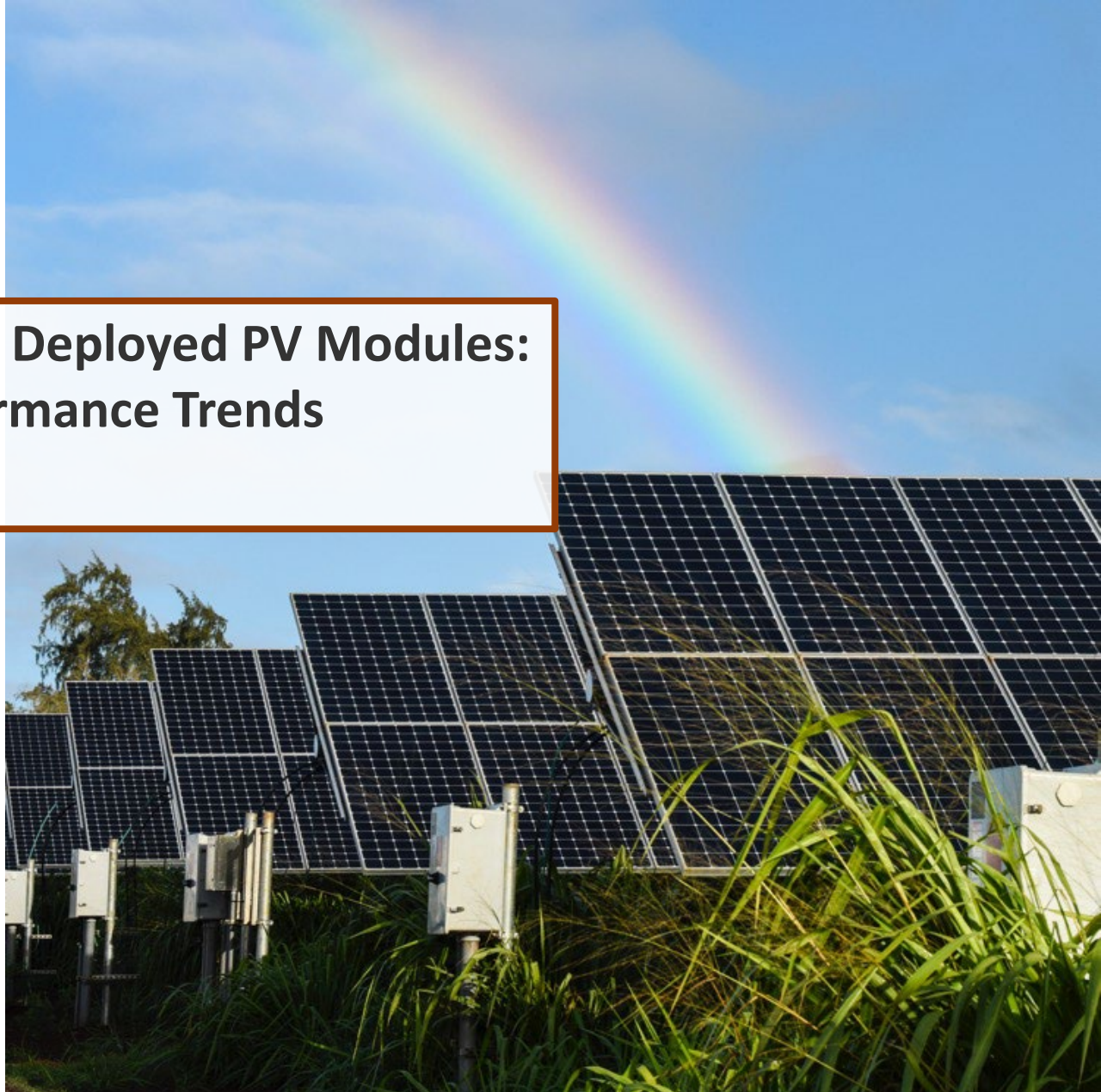
DuraMAT Fall Workshop

Albuquerque, NM

September 2023

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Understanding Trends in Failure Modes of Photovoltaic Modules and Materials

PI: Teresa Barnes (NREL), Jenya Meydbray (PVEL), Robert Flottemesch (Luminace) & Jim Rand (Core Energy Works)
Team: Joe Karas, Dirk Jordan, Teresa Barnes, Jenya Meydbray, Robert Flottemesch, Jim Rand, Max McPherson, Mason Reed, Mike Kempe

Fielded Module Forensics

Contributing to DuraMAT Consortium Goals

Identify bill of materials (BOM) and/or process control measures for photovoltaic modules with representative failure modes as informed by accelerated and field tests to guide next steps in module and material design.

Project Overview

- Project Goal: examine correlations between **module field performance and accelerated testing**
- Identify modules that have gone through partners' **accelerated testing programs AND are deployed in the field** in partners' fleets.
- Identify **BAD** field performance/failures, **GOOD** field performance, and mixed field performance. **BAD** performers are the easiest to find.
- Identify if **BAD performers** are due to **BOM changes, inadequate testing, or something else?**
- Identify modules that have **sharable accelerated test data**.

Project Details

Several different investigations:

- Series resistance degradation in different climates with different BOMs
- Light- and elevated temperature-induced degradation (LETID) in different climates with different BOMs
- Modules with "good" accelerated test performance AND "good" field performance
- Backsheet cracking and insulation resistance failure driven by BOM differences (not shown here for brevity)

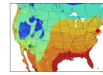
Outcome & Impact

- Lessons so far
- Associating historical accelerated test data with products in the field TODAY gives us the chance to identify gaps in testing and learn lessons to apply to future versions of tests.
- We have identified several cases where BOM variation between what was tested and what is in the field seems to have driven failure
- Emphasizes the importance of **IEC TS 62915 (Re-test guidelines for PV modules)**, which would have necessitated re-certification of BOM changes

Series Resistance Degradation

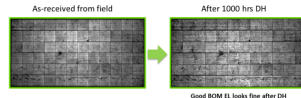
Different degradation in different climates

- Modules:
 - Same manufacturer as Gauding *et al.*
 - Similar vintage, similar serial numbers. Installed late 2011.
 - Different sites in the US: **coastal mid-Atlantic** and **desert Southwest**
- Different degradation:
 - Affected modules at the **mid-Atlantic** site are on their way toward 100% loss
 - Desert Southwest** modules are mostly within warranty

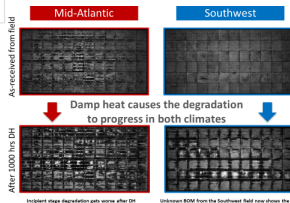
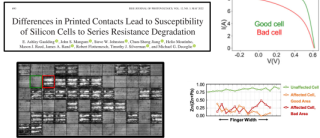


Good BOM doesn't degrade in DH

Mid-Atlantic site, unaffected



Prior work shows degradation due to BOM change in Ag paste



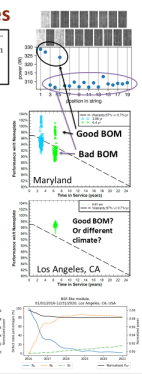
Conclusions so far:

- Differences in degradation are driven by differences in climate AND BOM
- Some failure modes may only result in failure in some climates
- Bad BOMs probably should have been caught by damp heat certification testing**
- All BOMs we've tested would have probably failed certification, because of (unrelated?) backsheet bubbling
- Test every BOM!
- IEC re-test guidelines were NOT in place when these modules were made

LETID in different BOMs & climates

Prior work shows different LETID in different BOMs

- New data from the same site (Maryland) confirms two different populations of modules:
 - Bad BOM:** susceptible to LETID, mostly out-of-warranty
 - Good BOM:** not susceptible to LETID, 100% in-warranty
 - Bad vs. Good BOM: **BSF vs. PERC cells**
- Both populations have degraded roughly equally since the first analysis → implies LETID may have plateaued. Helps with modeling.
- New site, different climate:
 - Los Angeles, CA
 - Similar vintage, same manufacturer, similar module
 - Unknown LETID susceptibility
- Modeling LETID in different climates, Maryland vs. Los Angeles
- LETID in BSF cells is less sensitive to climate... lower injection in BSF devices compared to e.g. PERC.
 - Suggests LETID levels after 6 years would be similar in LA and MD.
 - Perhaps modules in LA are not LETID-susceptible??

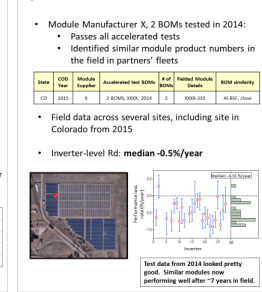


LETID susceptibility does not seem to conclusively show up in pre-2022 test data

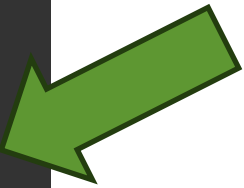
- No IEC test for LETID till 2022 (IEC TS 63342 for modules, IEC TS 63202 for cells; both published summer 2022)
- For pre-2022, some thought was that IEC 61215 thermal cycling w/ current injection could serve as a proxy test.
- Thermal cycling data for 2 module BOMs from similar vintage and same manufacturer at LETID-sensitive sites (MD and Los Angeles)
 - Slight gain after 200 cycles, slight degradation after 800 cycles
- Thermal cycling model of LETID for these modules suggests minimum after ~50 TCs, recovery after ~500 TCs.
- Overall, TC as a proxy for LETID testing is inconclusive. Competing factors e.g. BO-LUD, lightsoaking treatments, etc. complicate things.
- LETID is a plausible explanation for "weird" TC results on modules from circa ~2015

Example of a "good" BOM

- Module Manufacturer X, 2 BOMs tested in 2014:
 - Passes all accelerated tests
 - Identified similar module product numbers in the field in partners' fleets
- Field data across several sites, including site in Colorado from 2015
- Inverter-level Rd: **median ~0.5%/year**



Follow on from FY2022 project "BOM Squad"



Goals/results of BOM Squad:

- Goal:** examine correlations between historical accelerated testing data with specific fielded module BOMs and their field performance trends
- Results:** 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](https://doi.org/10.1109/JPHOTOV.2022.3209610))
 - Establishing correlation requires enough field time to confidently measure Rd (5+ year old systems)

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PI: Joe Karas, NREL

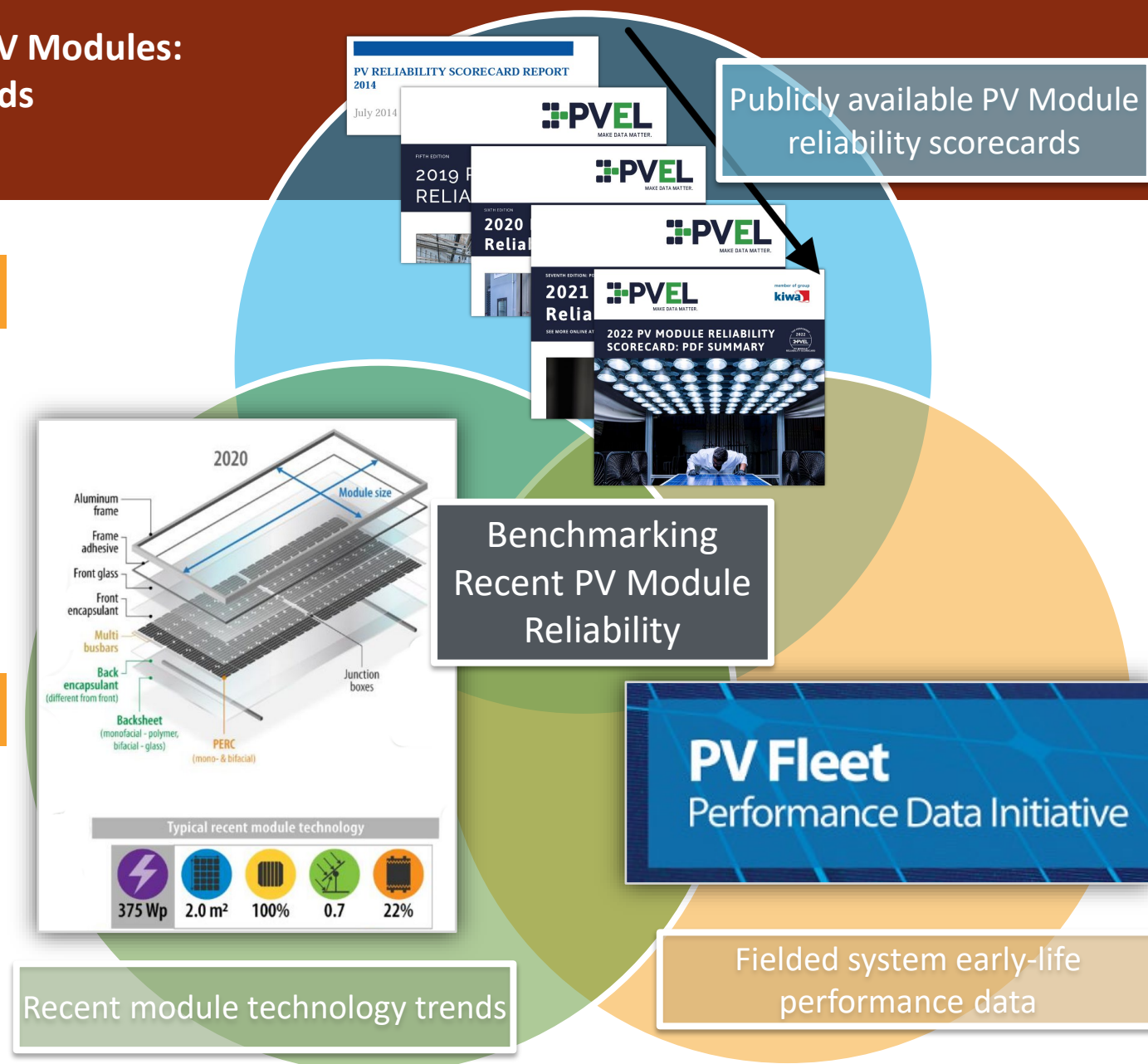
Key Results

- 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.

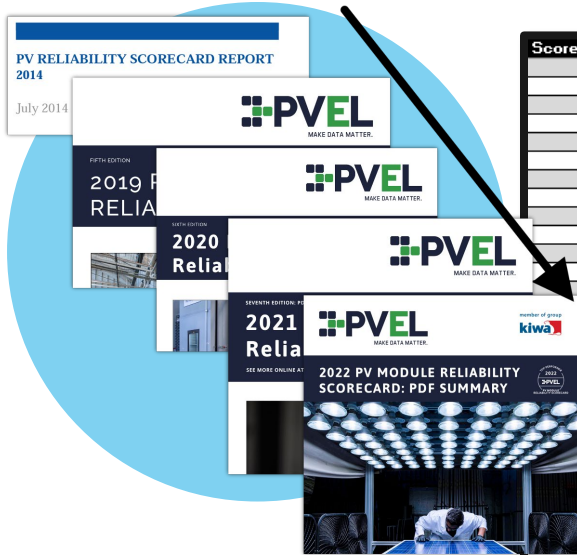
Core Objective & Teaming

Core Objective: Fielded Module Forensics

Team: Joe Karas, NREL



Publicly available PV Module reliability scorecards



Scorecard	Model Name	Manufacturer Name	PMA	PMA	PMA	Module Design	Cell	# of	Cell	Wafer	Thermal Cyclic	Damp Heat	Mechanical Shock	PID (PID)	LID+LETID (20%)	PAN Performance (20%)	Humidity
2023	ASB-M10-144-AAA (G2B)	Adani Solar	530-575	530	575	Bifacial - glass/backsheet	p-type Pi	144		182	x			x			x
2023	ASB-M10-144-AAA (G2G)	Adani Solar	530-575	530	575	Bifacial - glass/glass	p-type Pi	144		182							
2023	ASB-M10-144-AAA (G2WE)	Adani Solar	530-575	530	575	Monofacial - glass/backsheet	p-type Pi	144		182	x			x			
2023	AExxxxMD-108	AE Solar	380-425	380	425	Monofacial - glass/backsheet	p-type Pi	108		182	x						x
2023	AExxxxMD-108E	AE Solar	380-425	380	425	Monofacial - glass/glass	p-type Pi	108		182	x						x
2023	AExxxxMD-120	AE Solar	430-475	430	475	Monofacial - glass/backsheet	p-type Pi	120		182	x						x
2023	AExxxxMD-120E	AE Solar	480-525	480	525	Monofacial - glass/backsheet	p-type Pi	120		182	x						x
2023	AExxxxMD-132	AE Solar	480-525	480	525	Monofacial - glass/backsheet	p-type Pi	132		182	x						x
2023	AExxxxMD-132E	AE Solar	480-525	480	525	Monofacial - glass/backsheet	p-type Pi	132		182	x						x
2023	AExxxxMD-144	AE Solar	530-575	530	575	Monofacial - glass/backsheet	p-type Pi	144		182	x						x
2023	AExxxxMD-144E	AE Solar	530-575	530	575	Monofacial - glass/backsheet	p-type Pi	144		182	x						x
2023	AIKO-Axxxx-MAH54M	Aiko Solar	430-475	430	475	Monofacial - glass/backsheet	n-type Al	108		182				x			
2023	AIKO-Axxxx-MAH54Mw	Aiko Solar	430-475	430	475	Monofacial - glass/backsheet	n-type Al	108		182				x			
2023	AIKO-Axxxx-MAH72M	Aiko Solar	580-625	580	625	Monofacial - glass/backsheet	n-type Al	144		182				x			
2023	AIKO-Axxxx-MAH72Mw	Aiko Solar	580-625	580	625	Monofacial - glass/backsheet	n-type Al	144		182				x			
2023	SKA508HDGDC	Akcome	380-425	380	425	Bifacial - glass/glass	n-type H	80		210	x	x					x
2023	SKA509HDGDC	Akcome	430-475	430	475	Bifacial - glass/glass	n-type H	90		210	x	x					x
2023	SKA510HDGDC	Akcome	480-525	480	525	Bifacial - glass/glass	n-type H	100		210	x	x					x
2023	SKA511HDGDC	Akcome	530-575	530	575	Bifacial - glass/glass	n-type H	110		210	x	x					x
2023	SKA610HDGDC	Akcome	630-675	630	675	Bifacial - glass/glass	n-type H	120		210	x	x					x
2023	SKA611HDGDC	Akcome	675w	675		Bifacial - glass/glass	n-type H	132		210	x	x					x
2023	CHSM54N(BL)-HC-xxxx	Astronergy	380-425	380	425	Monofacial - glass/backsheet	n-type Tt	108		182							x
2023	CHSM54NDGJF-BH-xxxx	Astronergy	380-425	380	425	Bifacial - glass/glass	n-type Tt	108		182							x
2023	CHSM54NDGJF-HC-xxxx	Astronergy	380-425	380	425	Monofacial - glass/glass	n-type Tt	108		182							x
2023	CHSM54NDGTJF-BH-xxxx	Astronergy	380-425	380	425	Bifacial - glass/glass	n-type Tt	108		182							x
2023	CHSM54N-HC-xxxx	Astronergy	380-425	380	425	Monofacial - glass/backsheet	n-type Tt	108		182							x
2023	CHSM60M(DG)JF-BH-xxxx	Astronergy	580-625	580	625	Bifacial - glass/glass	p-type Pi	120		210	x			x			x
2023	CHSM60M-HC-xxxx	Astronergy	580-625	580	625	Monofacial - glass/backsheet	p-type Pi	120		210							x
2023	CHSM60NDGJF-BH-xxxx	Astronergy	430-475	430	475	Bifacial - glass/glass	n-type Tt	120		182				x			x
2023	CHSM60NDGJF-HC-xxxx	Astronergy	430-475	430	475	Monofacial - glass/glass	n-type Tt	120		182				x			x
2023	CHSM60N-HC-xxxx	Astronergy	430-475	430	475	Monofacial - glass/backsheet	n-type Tt	120		182							x
2023	CHSM66M(DG)JF-BH-xxxx	Astronergy	630-675	630	675	Bifacial - glass/glass	p-type Pi	132		210	x			x			x
2023	CHSM66M-HC-xxxx	Astronergy	630-675	630	675	Monofacial - glass/backsheet	p-type Pi	132		210							x
2023	CHSM72NDGJF-BH-xxxx	Astronergy	530-575	530	575	Bifacial - glass/glass	n-type Tt	144		182				x			x
2023	CHSM72N-HC-xxxx	Astronergy	530-575	530	575	Monofacial - glass/backsheet	n-type Tt	144		182							x
2023	CHSM78NDGJF-BH-xxxx	Astronergy	580-625	580	625	Bifacial - glass/glass	n-type Tt	156		182				x			x
2023	CHSM78N-HC-xxxx	Astronergy	580-625	580	625	Monofacial - glass/backsheet	n-type Tt	156		182							x
2023	BVM6610M-xxxx-S-H-HC-BI	Boviet Solar	330-375	330	375	Bifacial - glass/glass	p-type Pi	120		166							x
2023	BVM6612M-xxxx-S-H-HC-BI	Boviet Solar	430-475	430	475	Bifacial - glass/glass	p-type Pi	144		166							x
2023	BVM7609M-xxxx-H-HC	Boviet Solar	380-425	380	425	Monofacial - glass/backsheet	p-type Pi	108		182				x			x
2023	BVM7609M-xxxx-H-HC-BF	Boviet Solar	380-425	380	425	Bifacial - glass/glass	p-type Pi	108		182				x			x
2023	BVM7610M-xxxx-H-HC	Boviet Solar	430-475	430	475	Monofacial - glass/backsheet	p-type Pi	120		182				x			x
2023	BVM7610M-xxxx-H-HC-BF	Boviet Solar	430-475	430	475	Bifacial - glass/backsheet	p-type Pi	120		182				x			x
2023	BVM7610M-xxxx-H-HC-BF	Boviet Solar	430-475	430	475	Bifacial - glass/glass	p-type Pi	120		182				x			x
2023	BVM7612M-xxxx-H-HC	Boviet Solar	530-575	530	575	Monofacial - glass/backsheet	p-type Pi	144		182				x			x
2023	BVM7612M-xxxx-H-HC-BF	Boviet Solar	530-575	530	575	Bifacial - glass/backsheet	p-type Pi	144		182				x			x
2023	BVM7612M-xxxx-H-HC-BF	Boviet Solar	530-575	530	575	Bifacial - glass/glass	p-type Pi	144		182				x			x
2023	BVM7612M-xxxx-H-HC-BF	Boviet Solar	530-575	530	575	Bifacial - glass/glass	p-type Pi	144		182				x			x
2023	CS3N-xxxxMS	Canadian Solar	380-425	380	425	Monofacial - glass/backsheet	p-type Pi	132		166	x			x			x

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

- ✓ Historical Scorecard data entry complete
- Currently: understand research value of historical public Scorecard data, identify trends & systems of interest

PQP Tests

Factory Witness, Characterizations and Light-Induced Degradation Measurement								
Thermal Cycling	Damp Heat	Backsheet Durability Sequence	Mechanical Stress Sequence	Hail Stress Sequence	Potential-Induced Degradation	LETID Sensitivity	PAN File & IAM Profile	Field Exposure
TC 200	DH 1000	DH 1000	Static Mechanical Load	Hail	85°C, 85%RH MSV (+ and/or -) 192 hrs	LETID 162 hrs (75°C, Isc-Imp)	PAN File	Field Exposure 6 Months
Characterization	Characterization	UV 65 kWh/m ²		Characterization		Characterization	IAM Profile	Characterization
TC 200	DH 1000	Characterization	Dynamic Mechanical Load	Dynamic Mechanical Load	Characterization	LETID 162 hrs (75°C, Isc-Imp)		Field Exposure 6 Months
Characterization	Characterization	TC 50 + HF 10	Characterization	Characterization		Characterization		Characterization
TC 200	Stabilization 80°C, Isc, 48 hrs	UV 65 kWh/m ²	TC 50 + HF 10	TC 50 + HF 10		LETID 162 hrs (75°C, Isc-Imp)		Characterization
Characterization	Characterization	Characterization	Characterization	Characterization		Characterization		
		TC 50 + HF 10						
		UV 65 kWh/m ²						
		Characterization						
		TC 50 + HF 10						
		UV 6.5 kWh/m ²						
		Characterization						

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

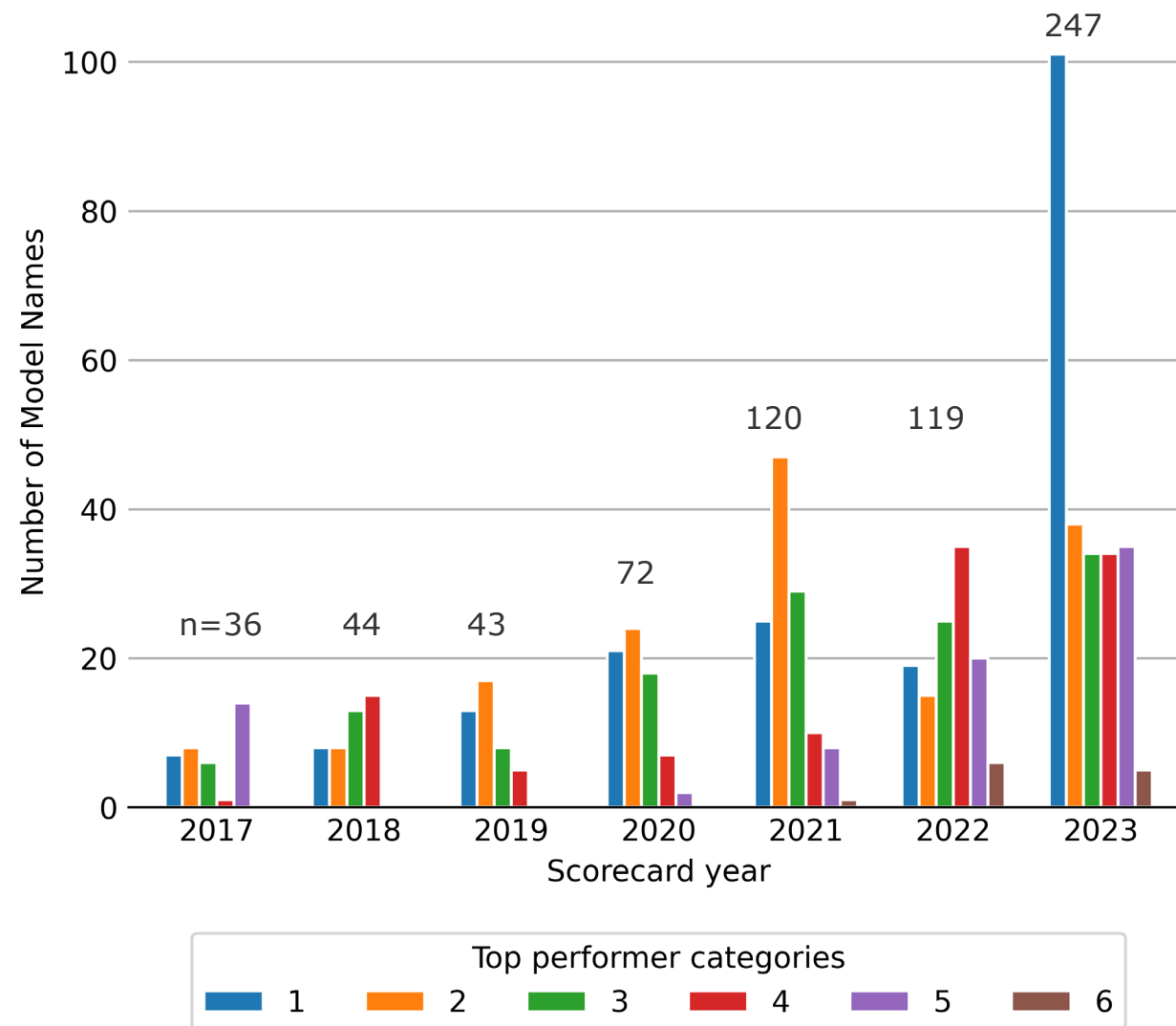
- Scorecard data has evolved over time
 - 2014 & 2016, only manufacturer names were listed
 - Since 2017, product names, and factory locations.
 - But factory locations are not always mappable to Model Names.... could be multiple.
 - Since 2022, limited BOM information (bifacial vs. monofacial, g/g vs. 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

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

- 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

Q.PEAK DUO L-G5.2

- 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?

Many questions like this start to appear as one starts sifting through public Scorecards

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

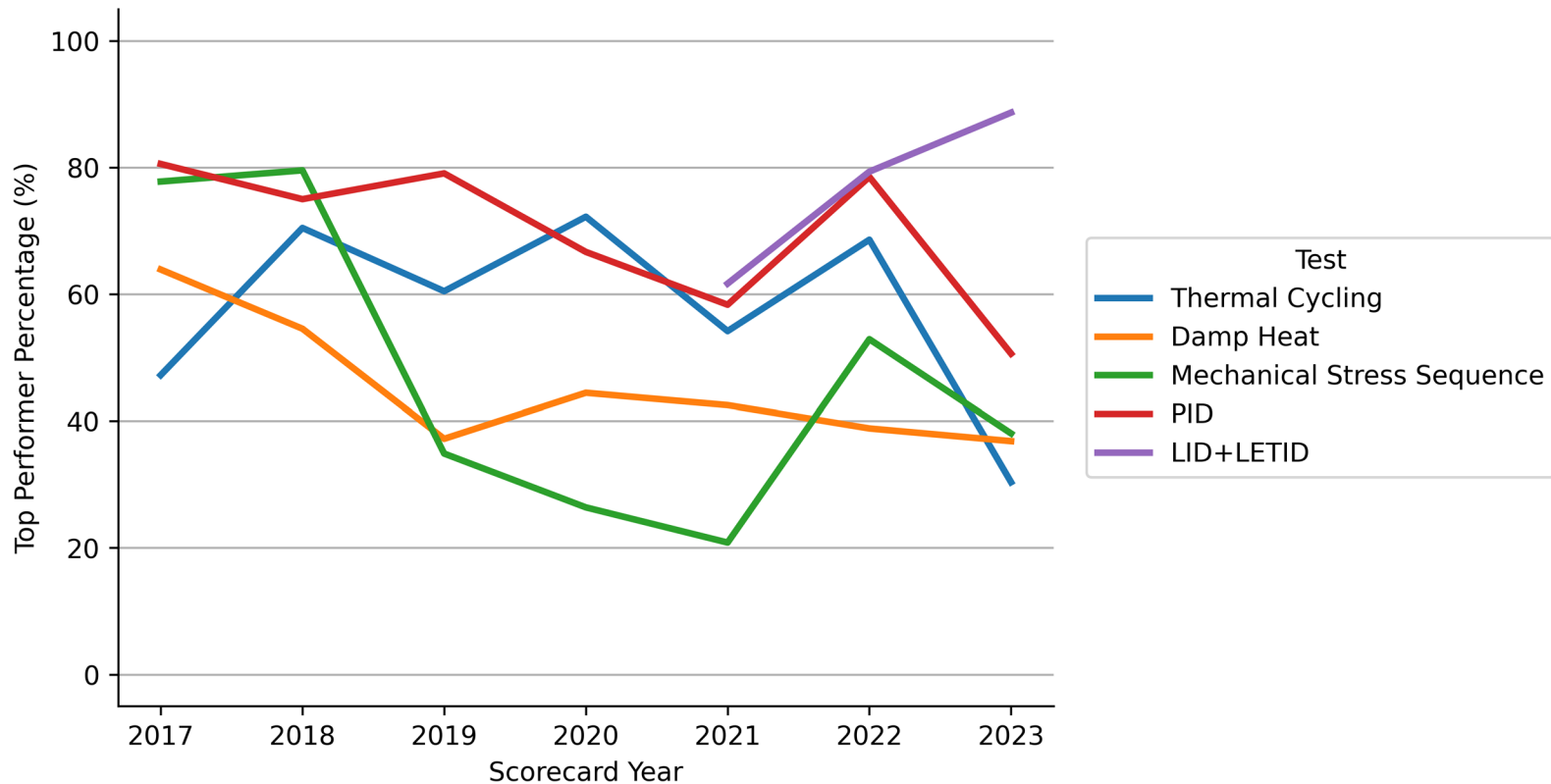
- ~335W → ~350W → ~380W
- Monofacial - glass/backsheet
- p-type PERC
- 120 cells
- Half-cell
- 156.75 → 158.75 → 166 mm wafer width
- 5BB → 9BB

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 m²
 - 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"

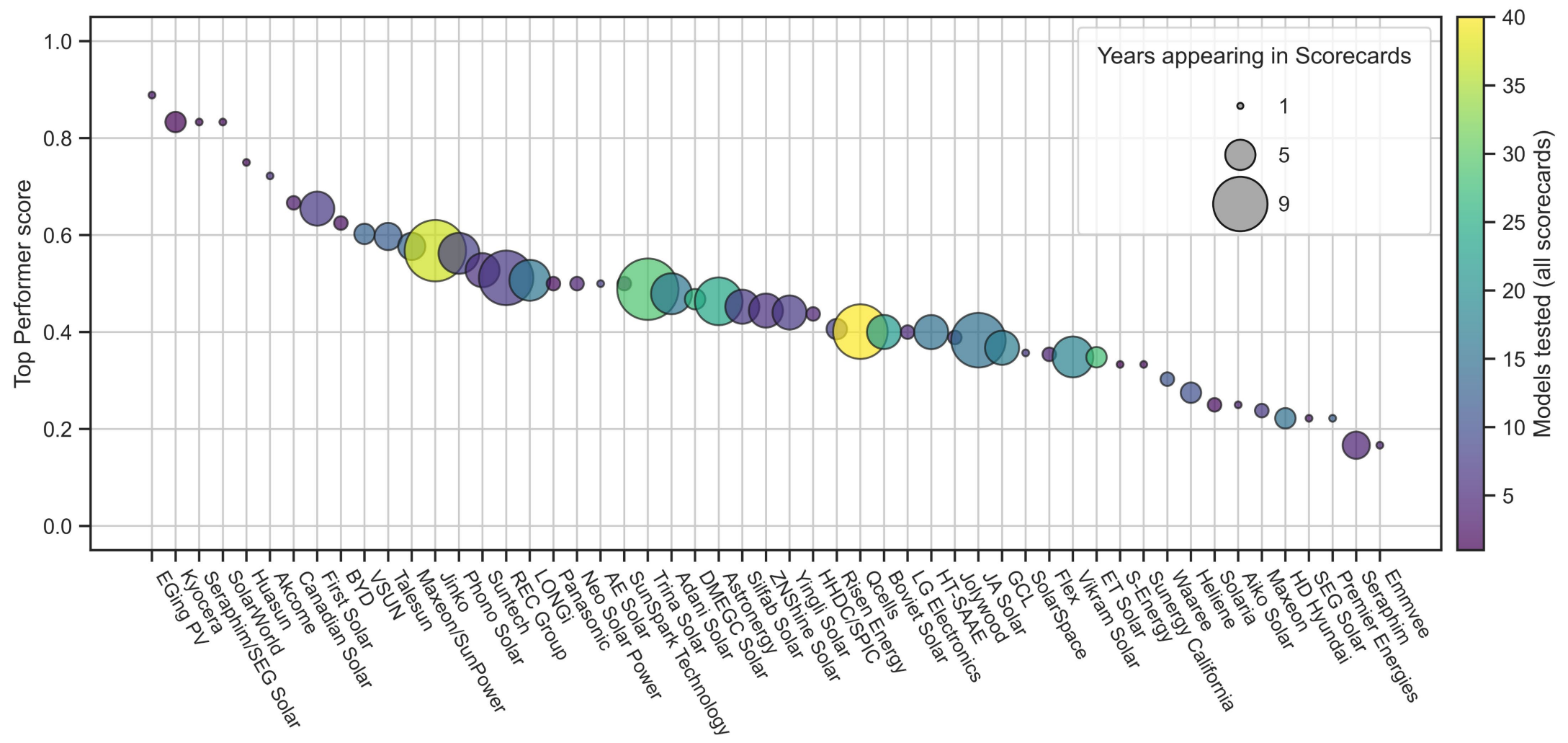


Which tests are the easiest and hardest for achieving Top Performer Status?



- 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?

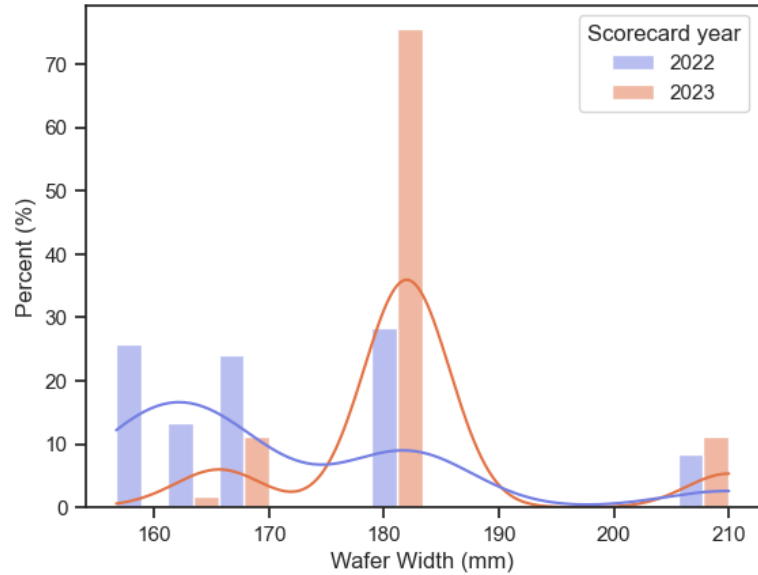


$$\text{Top Performer score} = \frac{\text{Top Performer Designations} \times \text{Scorecard Participation Years}}{\text{Tests} \times \text{Scorecard Participation Years}}$$

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

Recent trends (2022 → 2023)

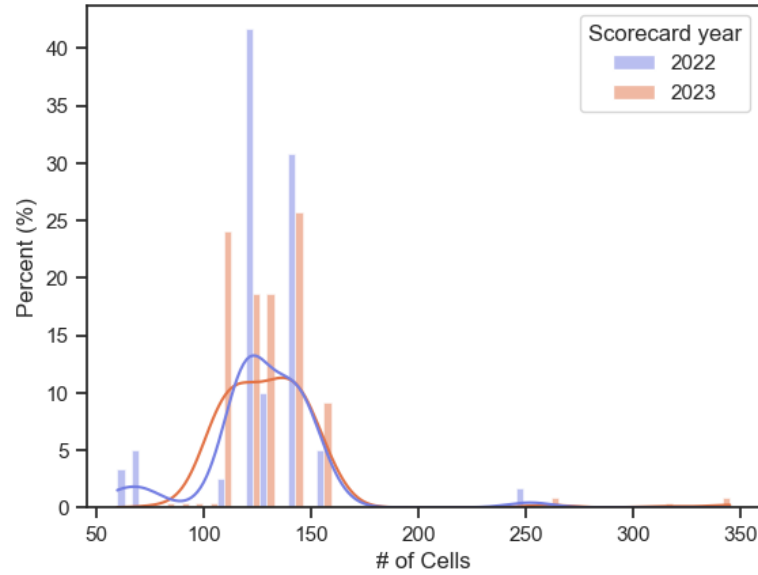
Wafer Sizes



Obvious consolidation/increase in wafer size:

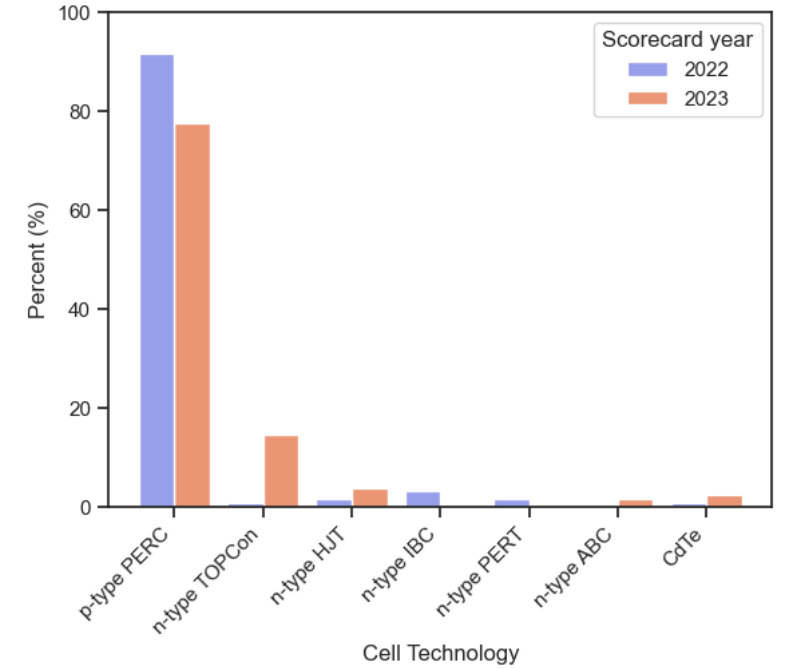
- 2022: Roughly equal M2/G1/M4/M6/M10
- 2023: Predominantly M10 (182mm)

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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This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided as part of the Durable Module Materials Consortium 2 (DuraMAT 2) funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Solar Energy Technologies Office, agreement number 38259. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.