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

DuraMAT SPARK Project FY 2023
Final Report
PI: Joe Karas, National Renewable Energy Laboratory (NREL)
joseph.karas@nrel.gov
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Growth in deployed solar photovoltaics (PV) has already been roughly exponential, and future deployment will dwarf currently deployed PV within a decade. This implies that global PV module manufacturing capacity will likely soon reach the terawatt level annually, which implies that billions of solar panels will be manufactured per year. At the same time, PV module technology is rapidly evolving. An ongoing DuraMAT effort to summarize PV technology trends has identified more than ten substantial changes in recent or near-future PV modules [1].

The consequence of enormous growth and evolving technology is that a substantial fraction of products deployed at a given time will lack a track record of field performance [2]. Changes in modern PV modules include increased size and new arrangements of cells and modules, physical and chemical changes to module materials, and new cell technology. Most of these changes have or will soon become mainstream while having, at most, a few years' worth of time-in-field. Any bill-of-material (BOM) or feature change has potential implications on long-term durability and reliability of the module, which are critical if PV is to play its intended role in a sustainable, just, and equitable transition to zero-carbon electricity.

In prior work, it is regularly found that PV module BOM components evolve, and may include several different options and evolutions for each component of a single PV module model name (e.g., glass, encapsulant, cells, etc.), perhaps leading to hundreds of possible variations for a single model. These differences can drive different degradation in the field [3]. Rigorous third-party testing and verification of specific BOMs is necessary to mitigate this risk.

This DuraMAT SPARK project intended to address some of this challenge. Widespread searchable data on PV module technology, features, and BOM components is not generally publicly available, which can leave module purchasers and PV system owners in the dark about precisely what materials are in their modules.

PV Evolution Labs (PVEL) is an independent PV module testing lab with headquarters in Napa, California, and publishes an annual PV Module Reliability Scorecard which designates "Top Performers" in a number of test categories. PVEL also performs factory-witnessed BOM verification of modules that it tests, which could potentially make the scorecards a valuable tool for associating field performance with test data on specific BOMs. This DuraMAT project began with an effort to comb historical scorecards and create a publicly available database of PVEL-tested PV modules, with notes on features and recent technological changes. This report details the findings of this effort.

Overview of PVEL Scorecards and Product Qualification Program

PVEL's PV Module Reliability Scorecards are an annual public report that details selected results of a testing program that PVEL calls its Product Qualification Program (PQP). The first scorecard was published in 2014, with a new edition every year since 2016. Over 500 unique PV module model names have appeared since the first Scorecard, made by approximately 60 different manufacturers. The test flow of PQP that appeared in the 2023 scorecard is shown in Figure 1.

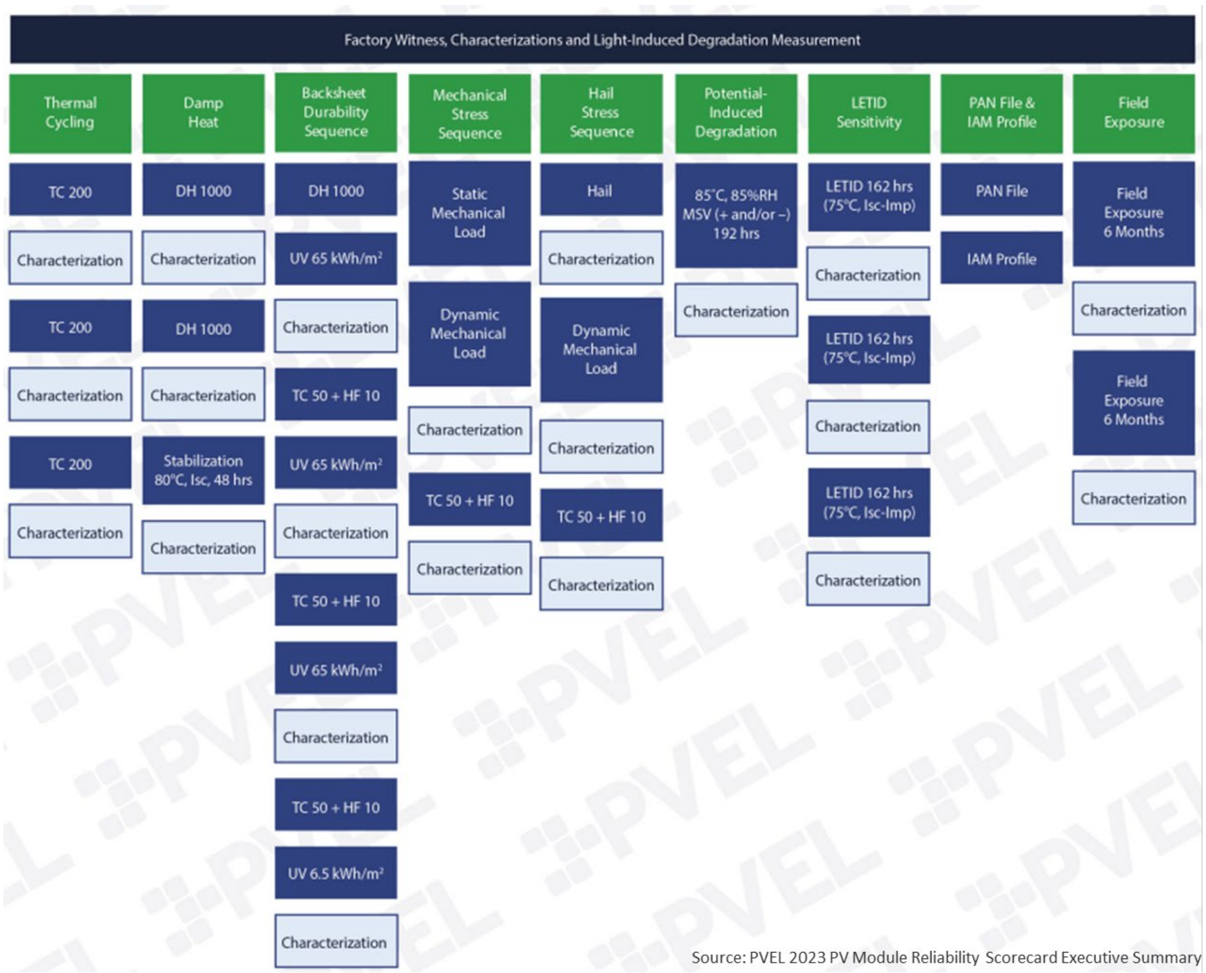

Figure 1. 2023 PVEL Product Qualification Program (PQP) testing flow.

It is important to note that the PQP test flow, some of the test procedures, and some test nomenclature has evolved over time. In general, PQP shares many of the same exposure conditions, procedures, and durations as the IEC 61215 PV module qualification standard and/or the IEC TS 63209-1 PV module extended-stress testing specification. However, a manufacturer's participation in the PQP program does not constitute product qualification as IEC 61215 testing would. On the other hand, anecdotally, a manufacturer's participation in PQP (or some other similar third-party extended testing regime) is often required or recommended by solar project financiers or independent engineers, in addition to IEC qualification.

The PQP test flow has been regularly updated since its inception, presumably due to new understanding of stressors and degradation and failure modes in PV modules. IEC standards have been revised several times in the last decade, so it is generally appropriate that the PQP test flow should also evolve. Every published scorecard details the precise test flow used in that edition. As an example, Figure 2 illustrates the evolution of the mechanical stress portion of the test since 2014. PVEL substantially updated the PQP test sequence in 2023, with the first results from that version of the program likely to appear in the forthcoming 2024 scorecard [4]. The implication of the evolving test flow is that results from different years may not be completely comparable.

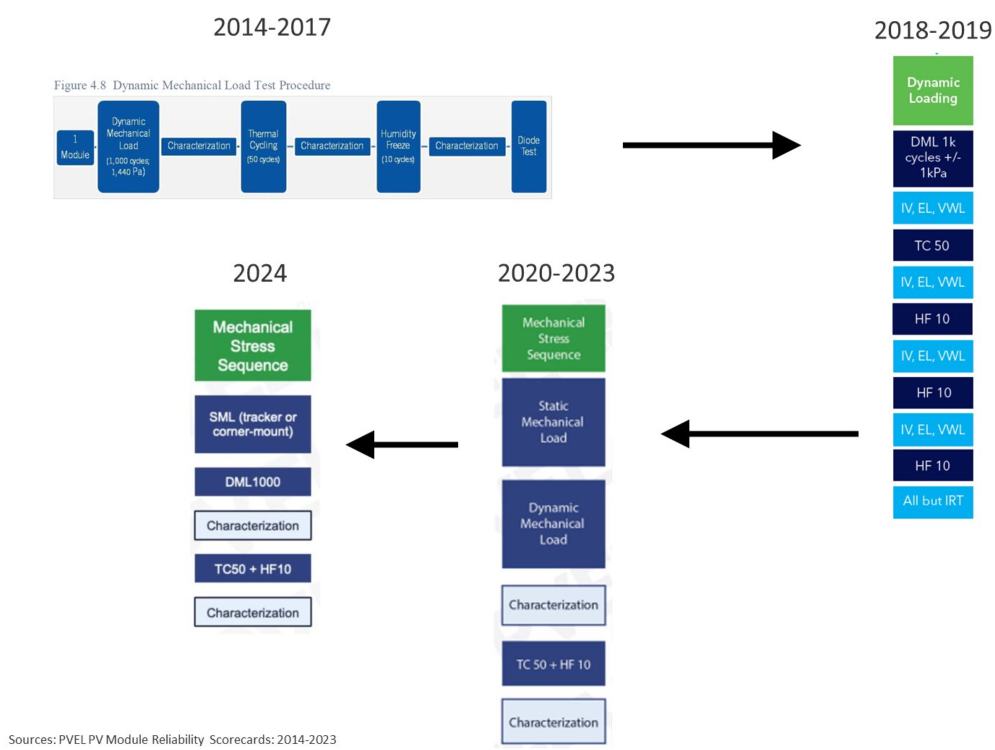

Figure 2. Evolution of mechanical stress testing protocol in PVEL PQP.

PVEL scorecards designate models as “Top Performers” in selected test sequences. Top Performer designation has typically been given to modules that undergo less than 2% maximum power degradation in a test, which is different from the 5% maximum power degradation threshold that is used most frequently in IEC qualification. Scorecards do not designate modules with Pass/Fail criteria or quantified test performance, only Top Performer or no appearance in the scorecard. Additionally, not all sequences of the PQP test flow appear in every scorecard. For example, for the 2023 PQP flow depicted in Figure 1, Top Performer status was only given for six of the nine test sequences: Thermal Cycling, Damp Heat, Mechanical Stress Sequence, Potential-Induced Degradation, LETID Sensitivity, and PAN File & IAM Profile. For the first five of these sequences, the Top Performer threshold is <2% maximum power loss, whereas for the PAN file sequence, which is not a degradation test, Top Performer status is given to the top quartile of all modules tested after performing energy yield simulations.

The data that appears in scorecards and the criteria for scorecard inclusion has evolved over time. The first two editions (2014 and 2016) only listed module manufacturer names. Since 2017, the results are ascribed to specific module model names. Also since 2017 the scorecards have included a list of each manufacturer's factory locations, but not every model name can be mapped to a single factory with the public scorecard data.

Since 2022, the scorecards have included limited BOM information: module design (bifacial or monofacial, and glass/backsheet or glass/glass construction), cell technology, number of cells, and wafer width.

According to PVEL, a model name may be listed in a year's scorecard if it was factory-witnessed in the prior 18 months. That implies that one factory-witnessed batch of modules could potentially appear in two consecutive scorecards. Every witnessed module model must submit two samples per test sequence, and a manufacturer must participate in every test in PQP; i.e., no selective testing. Sometimes, a testing sequence is not complete at the time of scorecard publication. This implies that one must consider multiple year's scorecards to ensure full Top Performer information for a given model.

Scorecards list either tested models or "representative variants", which have different model names than the tested model but for which the Top Performer status still applies. Presumably, these representative variants have trivial changes with regard to test performance, for example, frame color or cable length, but PVEL has not publicly detailed its guidelines for precisely determining how representative variants are determined to qualify for Top Performer status.

Finally, the public scorecard data compiled and presented here is presumably only part of the data that is made available to PVEL's commercial customers. The data in the public scorecards is useful, but limited. For example, commercial customers likely have access to more detailed BOM information, quantified test performance (rather than binary Top Performer designations), factory witness information, etc.

Scorecard data typically appears in tables embedded in publicly available, downloadable PDF files on PVEL's website, although beginning in 2023 the data was also downloadable in CSV format. This effort aimed to compile the data from these separate files into a single sortable spreadsheet, which is now available for download from the DuraMAT Datahub [5] .

Summary of conclusions from compiled data

Figure 3 shows a histogram of scorecard data from 2017-2023. One clear trend is that the number of models that appear in the scorecards has steadily increased over time; the first scorecard to include model names (2017) listed 36 unique models, and the most recent 2023 scorecard listed 247. Also obvious from this data is that most models do not achieve Top Performer status in all categories.

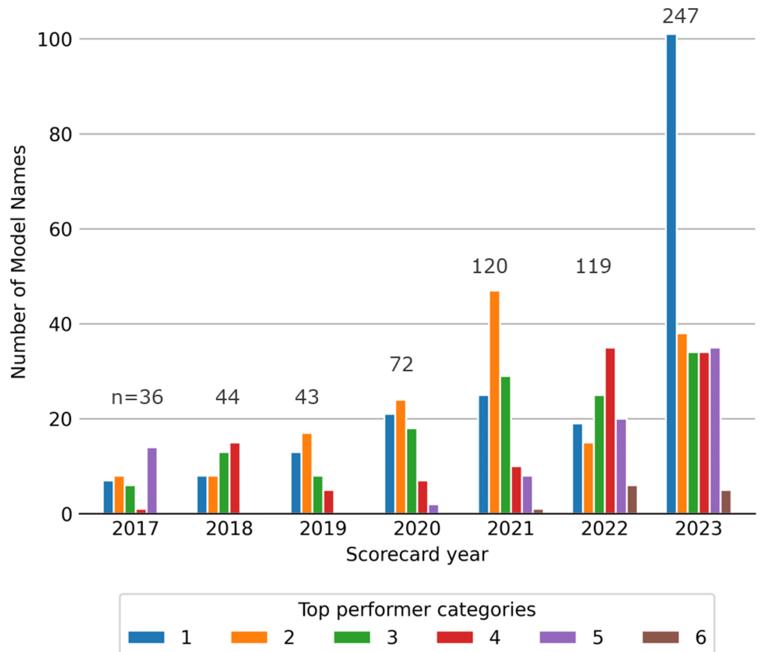

Figure 3. PVEL scorecard data 2017-2023. "n" indicates the number of unique model names that appeared that year, and colored bars indicate the number of tests passed by each model.

Scorecards from 2017-2020 awarded Top Performer status in five test categories, and 2021-2023 awarded it in six test categories. The median number of Top Performer categories per model name is as follows:

- 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)

Figure 3 and the yearly median Top Performer data demonstrate that the number of models that achieve Top Performer status in all (or even most) categories in a given year is only a small fraction of the total number of models tested. Some of this could be due to a testing sequence not being complete at the time of scorecard publication, and subsequent scorecards might need to be considered for complete information.

Figure 4 shows the percentage of model names that appear in each scorecard that achieve Top Performer status in each test sequence (this excludes the PAN file testing, where the top 25% are awarded Top Performer). We might reasonably expect the Top Performer percentage to increase over time, as manufacturers gain experience in designing modules capable of undergoing each testing sequence with minimal degradation. This does not appear to be the case, except for the LID+LETID test sequence. However, recall that some of the test sequences have evolved over this time as demonstrated in Figure 2; for example, the Mechanical Stress Sequence performed in 2017 was not same as the one performed in more recent years. This may explain some of the year-to-year fluctuation in Top Performer percentage. Otherwise, we conclude that manufacturers do not obviously appear to be getting better at making better-performing models over time. Typically, no more than ~80% of models tested in a given year achieve Top Performer in any given test sequence.

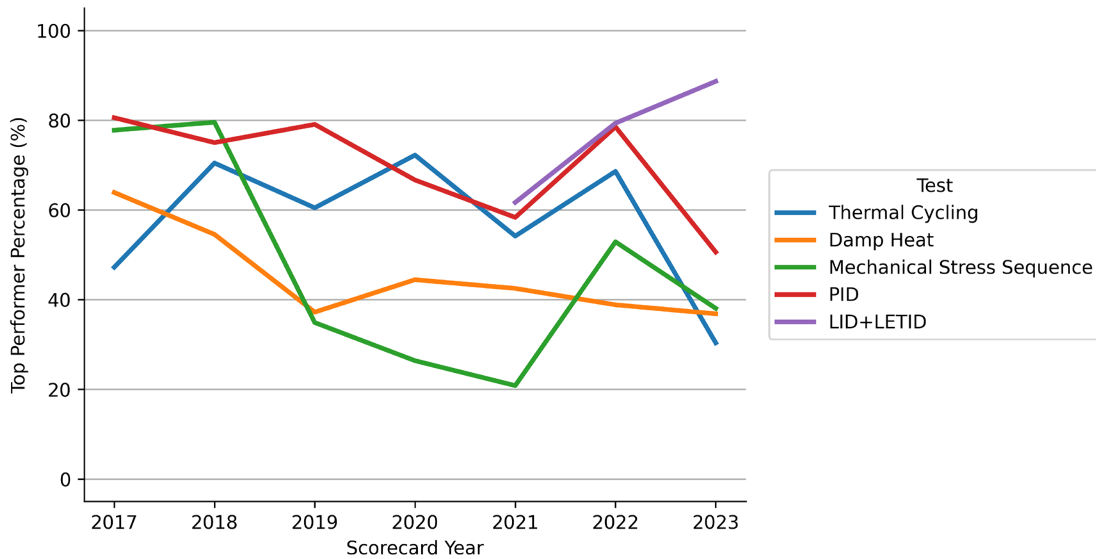

Figure 4. Percentage of models that appear in a scorecard that achieve Top Performer in each test sequence.

Figure 5 attempts to classify manufacturers by Top Performer "score", essentially the fraction of Top Performer designations a manufacturer's models have received out of the total number of tests we assume it submitted modules for.

$$Top\ Performer\ score = \frac{Top\ Performer\ Designations \times Scorecard\ Participation\ Years}{Tests\ \times Scorecard\ Participation\ Years} \tag{1}$$

Data bubbles in Figure 5 are sized by the number of scorecards a manufacturer has participated in out of the nine scorecards 2014-2023. Bubbles are colored by the number of unique model names a manufacturer has submitted across all scorecards. In general, a higher Top Performer score and a larger bubble would indicate a manufacturer has consistently high-performing models in PVEL's testing.

Most manufacturers achieve a Top Performer score of approximately 0.4-0.6. Manufacturers at the upper and lower tails of the distribution have mostly only participated in one or two scorecards, and submitted small numbers of models. The best Top Performer score from a 9-time participating manufacturer is Jinko, with a score of 0.57. Among manufacturers with at least five years of scorecard participation, the highest score is the 0.65 of First Solar, and the lowest score is the 0.35 of Vikram Solar. The bulk of manufacturers representing the great majority of the historical models tested by PVEL lie between these numbers.

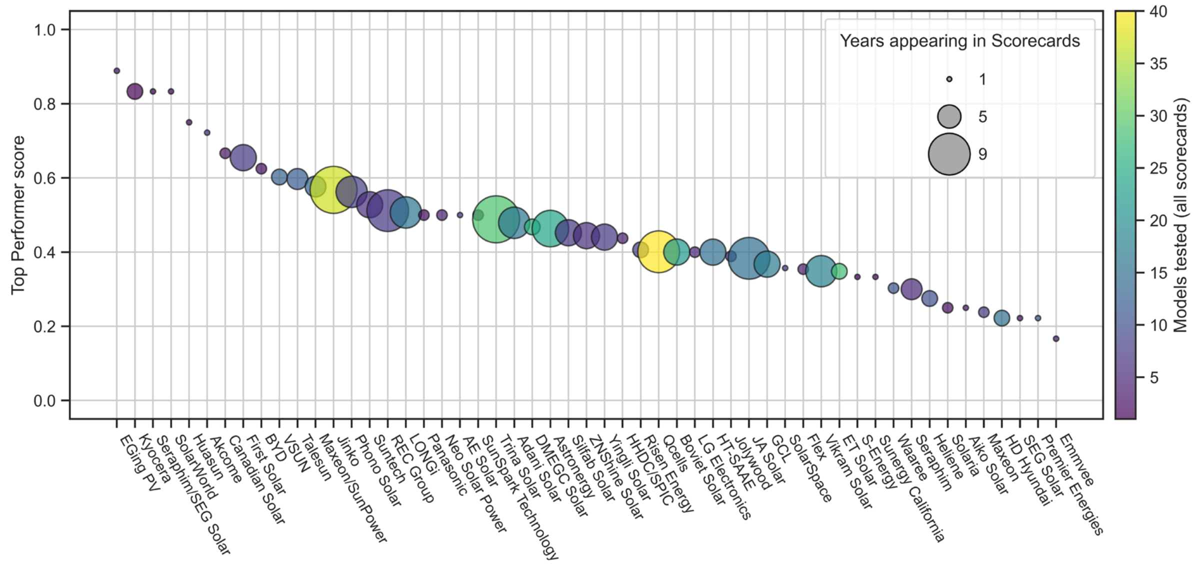

Figure 5. Top Performer score by manufacturer. See Equation 1 for definition. Bubble size indicates the number of scorecards the manufacturer appeared in from 2014-2023 (maximum 9). Bubble color indicates the number of unique model names that have appeared from that manufacturer.

While data may indicate small differences in test performance by different manufacturers, it may also simply represent the limits of statistical control and natural variation in test performance. This data does not seem to obviously suggest that any manufacturer inherently makes more reliable modules than its competitors. A deeper look at individual manufacturers and individual models' test performance, as well as quantified test data, BOM verification, and quality assurance and auditing are necessary when selecting module manufacturers.

BOM Evolution

Since 2022, the scorecards have included limited information about the module bill-of-materials. Four features are noted: module design (bifacial or monofacial, and glass/backsheet or glass/glass construction), cell technology, number of cells, and wafer width. Figure 6 shows distribution of this BOM information for 2022 and 2023.

There are several notable features of this data. The distribution of wafer width shows a clear evolution toward 182mm wide wafers (a wafer size standard known as M10) in 2023, while the distribution of the number of cells per module has not substantially evolved. This implies that module dimensions are growing to accommodate larger wafers. The trends toward larger wafers and larger modules are both well-documented [1].

The changes in cell technology and module design as evidenced by PVEL scorecards have been more modest. Approximately 90% of products tested in the 2022 scorecard contained p-type PERC cells, this decreased to ~80% in 2023. The evolution of the silicon PV industry to n-type cell technologies (TOPCon and HJT) has been well-documented, however, so the forthcoming 2024 scorecard should be expected to show a much greater fraction of these technologies [1]. PVEL has tested roughly equal fractions of bifacial and monofacial modules the past two years. However, within bifacial modules, there has been a small shift in favor of glass/glass construction and away from glass/backsheet construction.

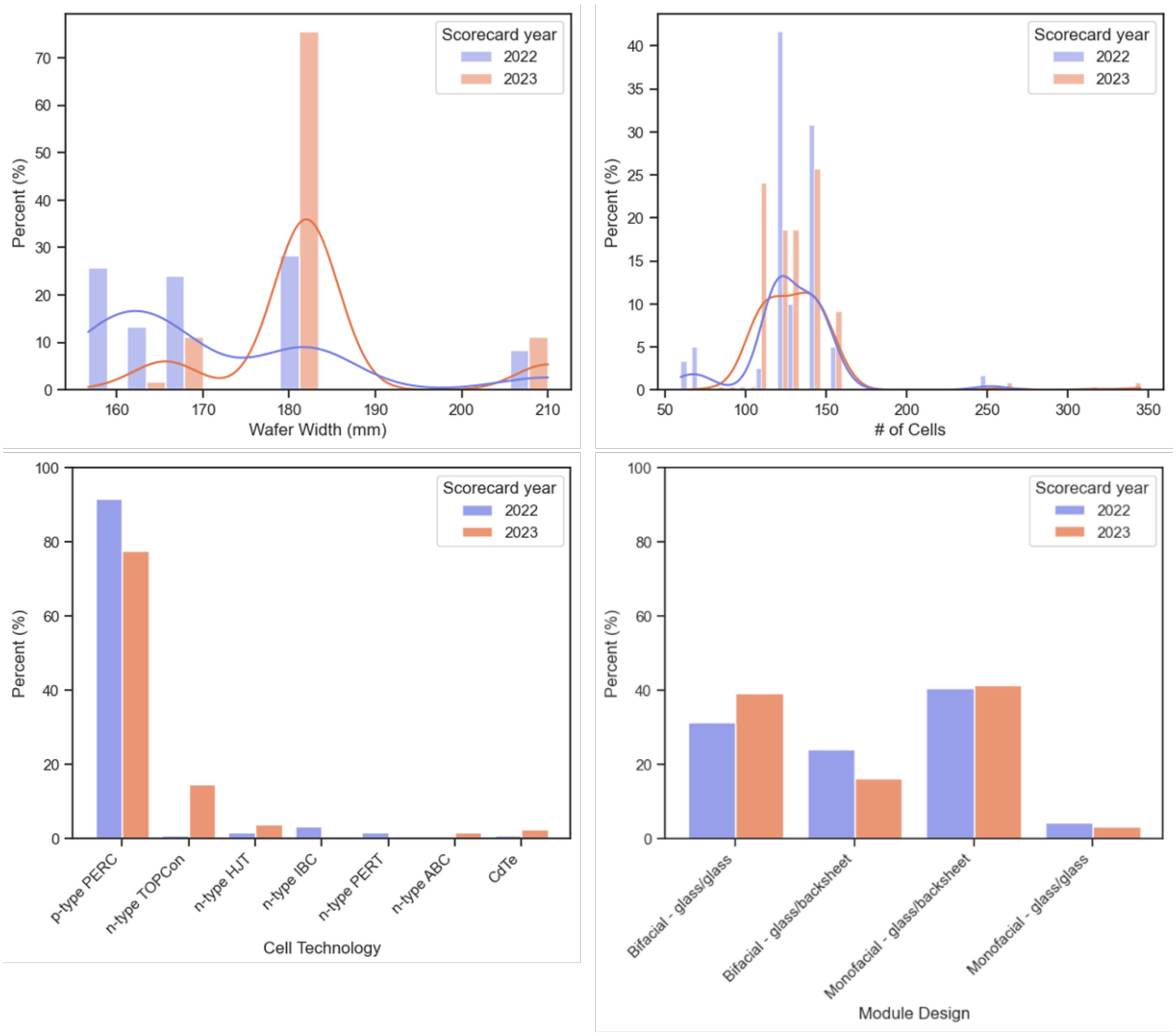

Figure 6. BOM information from the 2022 and 2023 scorecards.

Overall, this BOM information is important, but limited in its usefulness at this point. Long-term evaluations of different BOM choices are not possible, as the requisite BOM information has only been provided in the public scorecards since 2022. For example, with only two years of data it is too early to suggest whether a particular module design choice (i.e. glass/glass vs. glass/backsheet) results in more Top Performer designations in a given test sequence. It could be possible to incorporate historical BOM information on tested models (from, e.g., historical module datasheets) which would provide a longer history. However, this would ideally be supplemented with verification from PVEL. Future scorecards should also be incorporated into this dataset.

Outlook and opportunities for follow-on work

The aim of this project was to compile PVEL scorecard data and assemble a database of PVEL-tested products with notes on features and technological changes. Using this information, it was proposed to identify the overlap between these products and systems of interest in the field, e.g., using the PV Fleet Performance Data Initiative, and lay the groundwork for actively monitoring degradation in these systems of interest. NREL researchers are presently investigating several systems of interest with module model names that appear in PVEL scorecards, and therefore appear in this assembled dataset. Follow-on work could include incorporating more (non-public) module data (e.g., audit reports, extended BOM information or lists of BOM components, quantified test performance, etc.), performance data analysis of selected systems, and field and lab characterization of selected systems or on unfielded spare modules.

The aim of making the assembled PVEL scorecard data available on the DuraMAT Datahub is to make it easier for PV industry stakeholders to know if a given model name has been tested previously by PVEL. For a given model to appear in a scorecard implies that a specific BOM was factory-witnessed and tested, which may make it possible to identify BOM variation that leads to premature degradation. It could also aid in the proactive identification of degradation risks in recently deployed products.

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[2] D. C. Jordan, N. Haegel, and T. M. Barnes, "Photovoltaics module reliability for the terawatt age," *Prog. Energy*, vol. 4, no. 2, p. 022002, Apr. 2022, doi: 10.1088/2516-1083/ac6111.
[3] M. G. Deceglie *et al.*, "Correspondence: Bill of Materials Variation and Module Degradation in Utility-Scale PV Systems," *IEEE J. Photovolt.*, pp. 1–5, 2022, doi: 10.1109/JPHOTOV.2022.3209610.
[4] K. Gibson, "The Latest Improvements in Extended Module Reliability Testing: PVEL's Updated PQP." [Online]. Available: https://www.pvel.com/PQPv11/
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