A Comprehensive Database Approach to Track Industry Trends and Parameter Evolution in Photovoltaic Modules

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***Abstract*—Manufacturers of photovoltaic modules regularly update module specifications sheets throughout a product's commercial lifespan, making them dynamic documents, with each publication constituting a unique revision. However, consumers, researchers, and academics often treat these specification sheets as consistently representative of a given module, which they often are not. This work presents data and observations from our module specification sheet database, designed to track revisions over time, identify industry trends, and assess how changes impact system modeling, performance analysis, and experimental work that compares module behavior to published data. We have scraped over 9500 unique module specification sheets from various sources. This article discusses insights from the first 850 which resulted in 3438 entries from 134 manufacturers.**

Modules are becoming longer, wider, and thinner. The total glass thickness for single- and dual-glass modules remains stable, showing no industry-wide trends. The dimension ratio trend, a gross metric for module flexibility, is driven by length and width changes, primarily for single glass modules, and reduced frame thickness. Short-circuit current density (J_{SC}) estimates assume rectangular cells since precise cell area values are not documented. Although this simplification introduces some error, the cell-level J_{SC} vs. V_{OC} scatter plot shows consistent clustering by cell architecture, similar to published plots. The time series indicates improvements within each architecture. Temperature coefficients are stable or improving over time for each cell architecture. Updated distributions and statistics are provided.

Specification sheet revisions have been overlooked. Up to seven versions have been identified for some models, with 14.8% of modules having multiple published sheets. Major manufacturers are represented by up to six revisions. We emphasize including publication dates, not just version numbers, on specification sheets. Within the dataset, 67% indicate some form of date, while 33% lack any date, complicating contextual placement. Revision dates are crucial for contextualizing technical data and understanding impacts on modeling array behavior.

I. INTRODUCTION

In the 1970s and 1980s, the photovoltaic (PV) industry focused primarily on research and development, with limited commercial use in niche applications like space satellites and off-grid projects due to high costs. The 1990s marked a significant shift towards commercialization as advancements in manufacturing techniques led to lower costs and higher efficiencies. Since the 2000s, the industry has experienced substantial growth, with increasing efficiencies of silicon technologies, the introduction of thin-film technologies, and the establishment of large-scale grid-connected plants. As PV became mainstream, module costs decreased, making solar energy competitive with traditional energy sources in many regions. This attracted numerous companies to the commercial market, each offering unique advantages in efficiency, reliability, appearance, or specific technological improvements.

Manufacturers develop commercial specification sheets to market their products, present key metrics, enable product comparisons, and provide data necessary for modeling array performance. However, the sheer volume of available modules complicates comparisons; one database lists 45,195 module models from 12,162 series [1]. Consequently, system designers increasingly rely on online databases [1], [2] to narrow down the available models for modeling and estimating.

Manufacturers revise specification sheets due to changes in measured values, certifications, or correction of errors or omissions. Most include a stipulation that specifications are subject to change without notice. This poses problems for the industry, particularly when analyzing performance against published specification sheet values. Authors mostly treat specification sheets as static, and an initial literature review revealed no references to specific data sheet revision dates. A URL is insufficient to uniquely identify a data sheet revision, as manufacturers may update sheets without changing the URL. Databases like the California Energy Commission's [2] often provide a single entry per model, only a fraction of which indicate an insertion (44.4%) or update date (24.8%), and thus fail to adequately capture or track specification revisions. These shortcomings are not currently addressed.

Specification sheets may be updated due to changes in the bill-of-materials (BOM), non-technical details, or technical metrics (*e.g.*, STC I-V values, temperature coefficients), changes which potentially impact system reliability or performance over a typical plant's 20-30 year lifespan. Deceglie et al. [3] found different BOMs for the same make and model of module and stressed that interactions between BOM components often lead to reliability issues in the field. Mussard et al. [4] and Paudyal et al. [5] both found that temperature coefficients measured experimentally differed from those provided by the manufacturer in their specification sheet for the tested modules; in both, it was unclear if different specification sheet versions were consulted as no revision or date information was provided.

To understand how module specification sheets change over time and identify frequently revised parameters, Pordis implemented a database to store every identified unique specification sheet revision. Systems were developed to periodically scrape PDF specification sheets from live sites and obtain the most recent documents. The Internet Archive's Wayback Machine

[6] was used to access archived sheets. These documents were manually reviewed, entered, and validated. To date, we have scraped over 9500 unique module specification sheets from various sources. This article presents our methodology and discusses insights from the first 850 sheets, resulting in 3438 entries from 134 manufacturers. Although the data presented is limited, the database is growing, and efforts by Seigneur et al. aim to automate the process using deep learning models to detect and classify specification sheet elements.

II. METHODOLOGY

Web scraping tools are employed for various purposes, and their development is relatively straightforward. The authors developed a Python-based tool to scrape multiple live websites and download published PDF module specification sheets. Recognizing that these activities can be disruptive if not properly managed, we implemented rate limiting to minimize impact. Specifically, we limited our scraping to one site over a 24-hour period, thereby avoiding excessive load on any single site. This tool is run periodically to obtain the latest published specification sheets, ensuring our database remains up-to-date without overburdening the source websites.

Historical specification sheets were collected from archived resources using the Internet Archive's Wayback Machine, which provides public access to archived versions of websites. We began our search for modules from the 1990s, with the earliest entry in our database being an ASE Americas module from November 1996. During this period, the PDF format was in its infancy, so most entries from the 1990s were in HTML or a simple text format. From the early 2000s onward, most specification sheets were documented in PDF format and became more standardized. Utilizing the archive, we were able to track industry mergers, the emergence and collapse of manufacturers, and obtain historical module specification sheets. The authors did not target makes and models with known multiple revisions, but aimed to develop a comprehensive and unbiased dataset from all available specification sheets.

To eliminate duplicate entries in the database, it was necessary to develop a test for document uniqueness. In this context, uniqueness is defined as any unique combination of specification sheet checksum and module model number. The primary test uses the SHA-512 checksum, a cryptographic hash function that generates a unique 512-bit signature for a given input. When a specification sheet is first added to the database, its SHA-512 hash value is computed and stored. For subsequent documents, the SHA-512 hash is calculated and compared to all stored hash values. If the new document's hash matches any existing hash, it is identified as a duplicate. If it does not match any existing hash, it is considered unique and added to the database with its hash value.

As a secondary check, the MD5 checksum, another cryptographic hash, is also stored. However, it is important to note that the MD5 checksum is not collision-resistant, meaning that it is possible for two different documents to produce the same hash value, although this is relatively rare. Through this dual checksum methodology, we effectively manage and verify the uniqueness of specification sheets, ensuring that each revision is accurately tracked and recorded. To date, we have not experienced any instances of duplication using this approach.

General rules were established for entering technical and non-technical data. Due to the varied methods manufacturers use to indicate document versioning, rules for revision dates were developed. For numeric values, manufacturers may provide both metric (e.g., mm, kg, Pa) and Imperial units (e.g., inch, pound, psf). When both units are provided, the metric unit is stored; otherwise, the provided unit is stored. However, analysis always was performed using metric units. Additionally, many specification sheets have incomplete cell size or cell architecture information, requiring the determination of likely cell size and architecture from the available numeric data. Cell size was inferred by correlating module layout, module dimensions, and known cell sizes and cuts. When not stated outright, cell architecture was determined using calculated cell-level short-circuit current density (J_{SC}), open-circuit voltage (V_{OC}), and provided temperature coefficients of power (γ) and voltage (β). Sufficient data is available to discern statistics for Aluminum Back Surface Field (Al-BSF), Interdigitated Back Contact (IBC), Heterojunction (HJT), Passivated Emitter Rear Cell (PERC), and Tunnel Oxide Passivated Contact (TOPCon) cell architectures.

Analyses were conducted along two parallel paths: 1) to identify industry trends over time from dated specification sheets, and 2) to gather statistics on the parameters changing between specification sheet revisions and examine how those parameters may impact PV system modeling.

III. RESULTS & DISCUSSION

The objectives of this study are to: 1) analyze industry trends over time and technology, 2) determine the prevalence of revised specification sheets, 3) identify which parameters are revised and, along the way, 4) develop methodologies to determine cell architecture and size from provided data for modules lacking this detail.

Two subsections present initial insights derived from our dataset, which comprises 850 unique specification sheets from 134 manufacturers, totaling 3438 entries. First, industry trends become observable only when specification sheet revisions are arranged chronologically. Of the specification sheets entered, 67% indicate some form of publication date — either complete, month-year, or year only — while 33% lack any indication of publication date, complicating contextual placement. Industry trends and time-bound parameter distributions from dated specification sheets are presented. Second, the evolution if parameters between specification sheet revisions is discussed. Finally, this section concludes with general observations and statements on module specification sheet uniqueness and the potential impact on parameter distributions.

A. *Industry Trends*

Numerous publications and industry guides discuss trends in the PV module sector, highlighting developments such as increasing module sizes, rising efficiencies, and the introduction of thinner glass. These well-documented trends do not require our database for observation. However, for completeness and comparison, we present some of this information. More importantly, we delve into less commonly examined aspects, such as the evolution of temperature coefficients over time within different cell technologies and the recent distributions of normalized current density and open-circuit voltage. These subtler trends are not easily discernible from existing databases and represent a key area of interest in our study.

1) Physical Dimensions: Placed in the context of specification sheet publication date, trends in modules dimension show increasing module lengths and widths, and decreasing module thickness, as shown in Fig. 1. Distributions indicate that physical dimensions trends are not restricted to either single- or dual-glass modules, but are relevant to both categories. Module height trends show consistent reduction over the past 30 years. The most represented module in the database measures 1722 x 1134 x 30mm, a size common to the 108 half-cut (182 x 91mm) cell layout. Dual-glass has become increasingly common in the industry as system designers attempt to take advantage of bifacial gain available with newer cell architectures, but Fig. 2 shows that total glass thickness within both designs has remained consistent.

To assess the propensity for modules to flex, particularly since most modules use similarly designed aluminum frame components, we calculated two different dimension ratios accounting for the length, width, and thickness of the frame, potentially including total glass thickness. We investigated both a simple frame size ratio, $(L{\cdot}\mathrm{W})/\mathrm{h}$, and one that includes a derating term, t, to account for the total thickness of the laminate glass, $(L{\cdot}\mathrm{W})/(\mathrm{h}{\cdot}\mathrm{t})$. Both methods produced similar results, although the latter more logically responds to changes in overall laminate glass thickness: thicker glass results in a stiffer module and a lower ratio value. Therefore, for two modules that differ only in total glass thickness, the thicker glass will result in a lower ratio, suggesting a less flexible module. The results of this calculation are shown in Fig. 3. Given that single-glass modules typically have a glass thickness of 3.2 mm and dual-glass modules are predominantly constructed to a total thickness of 4.0 mm (Fig. 2), the increase in ratio values is driven by the increasing length and width and decreasing height of modules over time.

2) Temperature Coefficients: Temperature coefficients for current (α), voltage (β), and power (γ) were reported for nearly all analyzed module specification sheets. Parameter trends must be analyzed within the confines of each cell architecture and not as an aggregate, although at a high level there exist more favorable temperature coefficients in modern cell architectures compared to earlier ones. Within specific cell architectures, trends in the temperature coefficients of voltage and power are similar between architectures: Al-BSF, IBC, and PERC indicate a clear historical improvement trend while HJT remains flat. The temperature coefficient of current indicates improvement within Al-BSF and HJT while IBC and PERC remain flat. At this time there is insufficient TOPCon data to state with confidence that any trends exist.

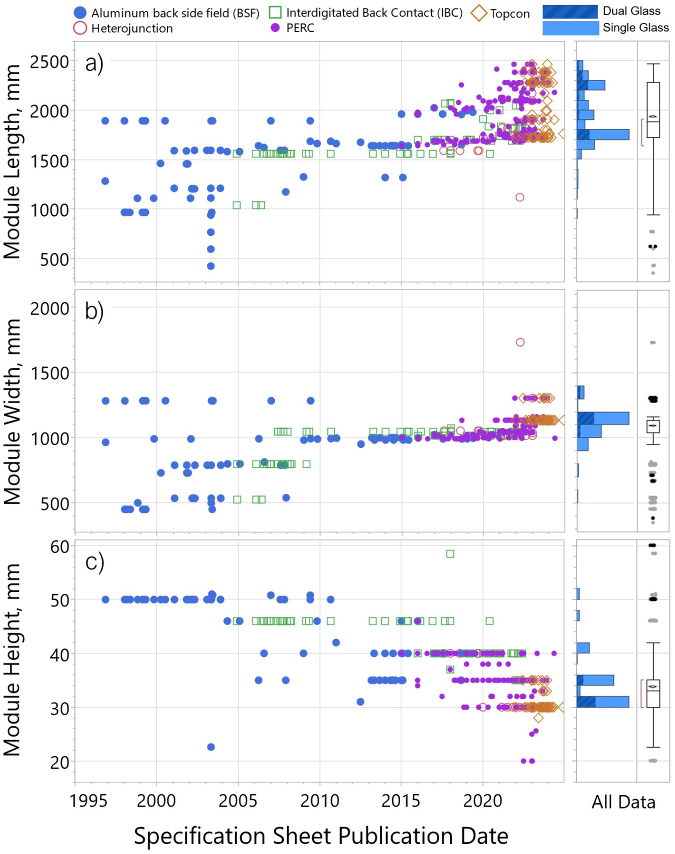

Fig. 1. Trends in module physical dimensions: a) length, b) width, and c) height based on data from dated module specification sheets. Modules are becoming longer, wider, and thinner in both single- and dual-glass configurations. Distributions are shown for each parameter, including both dated and undated specification sheets, with dual-glass configurations shaded and single-glass configurations unshaded.

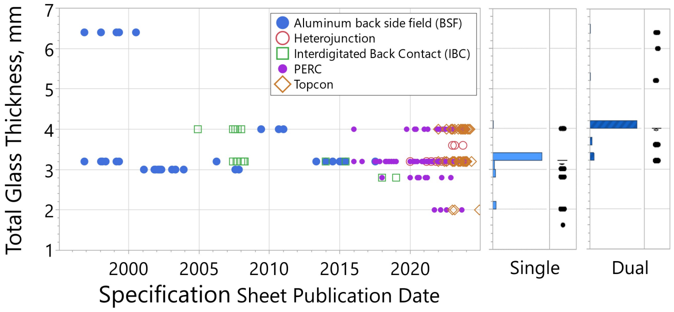

Fig. 2. Total glass thickness collated from dated module specification sheets indicates no obvious trend. Distributions from sheets dated 2019-2024 indicate that single-glass modules are nominally 3.2mm while dual-glass modules consist primarily of dual 2.0mm glass components (4.0mm overall thickness).

Of potential interest to those performing simulation or modeling activities, data from the most recently published specification sheets (2019-2024) was analyzed and the temperature coefficient statistics are provided in Table I.

3) Normalized Cell Parameters: Within the existing dataset, 19.1% of entries do not clearly state the cell architecture, a necessary parameter for subsequent analyses and developing parameter distributions. To address this, we imple-

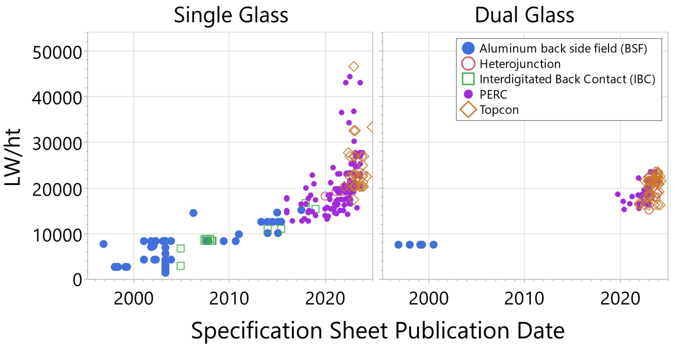

Fig. 3. The LW/ht ratio for single- and dual-glass constructions from dated specification sheets is shown. The trend is driven by increasing 3.2mm single glass module sizes, while dual-glass modules are more clustered.

TABLE I
TEMPERATURE COEFFICIENT STATISTICS FOR SPECIFICATION SHEETS DATED 2019-2024

Cell Arch.	n	α (%/K)	β (%/K)	γ (%/K)
Al-BSF	77	$\overline{X}$ = +0.0481 s = 0.0102	$\overline{X}$ = -0.322 s = 0.0213	$\overline{X}$ = -0.411 s = 0.0215
HJT	180	$\overline{X}$ = +0.0408 s = 0.0027	$\overline{X}$ = -0.239 s = 0.0058	$\overline{X}$ = -0.259 s = 0.0101
IBC	98	$\overline{X}$ = +0.0498 s = 0.0084	$\overline{X}$ = -0.243 s = 0.0143	$\overline{X}$ = -0.286 s = 0.0128
PERC	1372	$\overline{X}$ = +0.0461 s = 0.0072	$\overline{X}$ = -0.274 s = 0.0183	$\overline{X}$ = -0.348 s = 0.0182
TOPCon	1124	$\overline{X}$ = +0.0458 s = 0.0023	$\overline{X}$ = -0.252 s = 0.0072	$\overline{X}$ = -0.299 s = 0.0129

mented a set of rules based on data from specification sheets with stated cell architectures to assign probable architectures to those without. First, we calculated the cell-level open-circuit voltage (V_{OC}/cell, mV) and short-circuit current density (J_{sc}, mA/cm2), which required knowledge of the module cell layout and cell area. The layout is typically discernible from the specification sheet's tabular data, mechanical drawing, or module image. Additionally, the cell count, cell layout, and module physical dimensions provide sufficient information to assign a probable cell size to modules without stated cell dimensions with reasonable accuracy based on algorithm tests conducted against modules with stated cell dimensions.

Precise cell area is, however, rarely published. Thus, we had two options: 1) obtain physical exemplars of each module to measure the cell area, accounting for clipped and rounded corners, or 2) assume all cells are rectangular, and calculate cell area based on the module layout, dimensions, and probable cell dimensions. Since obtaining physical exemplars of all modules is impractical, we assume all cells are rectangular. This simplification introduces an error in the calculated J_{sc}, on the order of the reciprocal of the remaining cell area fraction. For instance, if the rectangular simplification overestimates cell area by 5% (0.05), then the simplified J_{sc} must be scaled by a factor of $0.95^{-1} = 1.0526$.

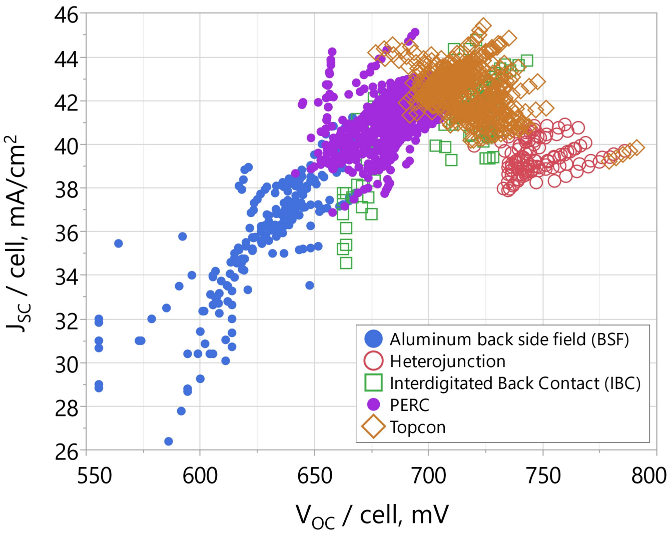

Fig. 4. Normalized cell parameters of open-circuit voltage per cell (V_{OC}, mV) versus short-circuit current density (J_{SC}/cell, mA/cm2) are shown using a rectangular cell simplification, which may underestimate the actual current density. Modern cell architectures exhibit clear clustering.

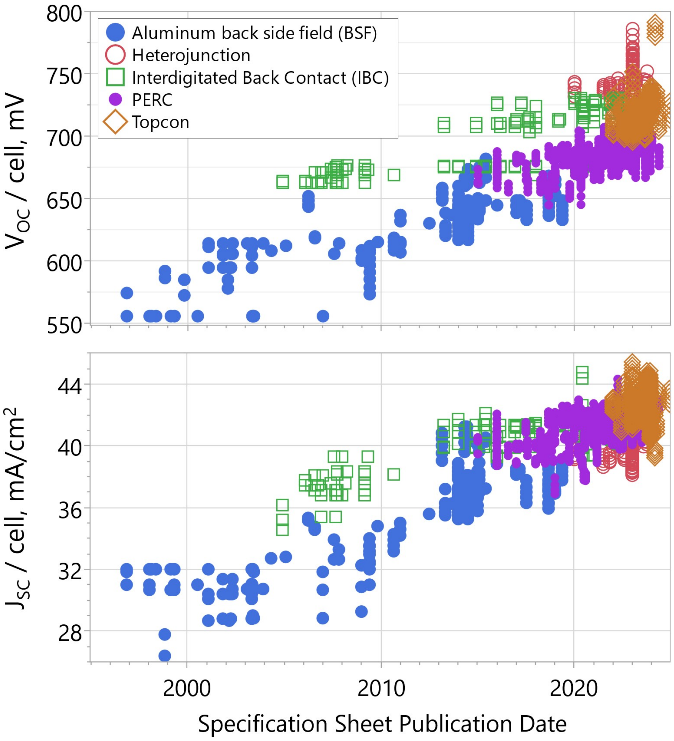

Fig. 5. Normalized cell parameters of (top) open-circuit voltage per cell (V_{OC}, mV) and (bottom) short-circuit current density (J_{SC}/cell, mA/cm2) using a rectangular cell simplification are shown by specification sheet publication date, illustrating technology changes over time by cell architecture.

Resulting normalized cell parameters are shown in Fig. 4 and are considered accurate for V_{OC}/cell, however J_{SC}/cell may be underestimated due to the rectangular cell simplification. Nevertheless, distinct populations defined by cell architectures are evident, similar to published data [7], and even a modest error in J_{SC} would not alter these observations.

Over time, normalized cell parameters within a given ar-

TABLE II
NORMALIZED CELL PARAMETER STATISTICS FOR SPECIFICATION SHEETS DATED 2019-2024 USING A RECTANGULAR CELL SIMPLIFICATION

Cell Architecture	n	V_{OC} (mV)	J_{SC} (mA/cm^2)
Al-BSF	73	$\overline{X}$ = 625.0 s = 18.9	$\overline{X}$ = 36.20 s = 1.84
HJT	172	$\overline{X}$ = 749.1 s = 12.7	$\overline{X}$ = 39.48 s = 0.71
IBC	89	$\overline{X}$ = 723.0 s = 9.8	$\overline{X}$ = 41.80 s = 1.06
PERC	1285	$\overline{X}$ = 685.9 s = 9.3	$\overline{X}$ = 41.50 s = 0.91
TOPCon	1124	$\overline{X}$ = 713.9 s = 14.1	$\overline{X}$ = 42.55 s = 0.98

TABLE III
MODULE SPECIFICATION SHEET REVISION INSTANCES

Versions Identified	Manufacturer & Model Count (Entries)	Percentage of Entries
7	5 (35)	0.28%
6	3 (18)	0.11%
5	2 (10)	0.07%
4	21 (84)	0.74%
3	80 (240)	2.80%
2	309 (618)	10.8%
1	2433 (2433)	85.2%
Total	2856 (3438)	100.0%

chitecture improve due to continuous improvement activities by manufacturers and enhancements in raw material purity or quality. Fig. 5 shows both V_{OC}/cell (top) and J_{SC}/cell (bottom) over time for dated specification sheets, indicating clear improvements in both voltage and current density for Al-BSF and IBC architectures, with likely improvements in PERC. HJT and TOPCon are too closely bound in time to discern trends, but additional entries into the database may clarify these in subsequent studies. Statistics by cell architecture for specification sheets dated 2019-2024 are provided in Table II, using the rectangular cell simplification.

B. Parameter Evolution

Within the existing dataset, 14.8% of modules had at least one revision; see Table III for a breakdown of revisions contained within the database as of this article. This does not imply that the remaining 85.2% of specification sheets were never revised, only that the database does not yet contain a revision for those makes and models.

TABLE IV
MODULE SPECIFICATION SHEET PARAMETERS REVISED ON MODULES WITH $\geq$3 REVISIONS

Parameter	Percentage
Backsheet type, description, or thickness	44.1%
Weight	36.0%
Front glass thickness or type	34.2%
STC *I-V* parameters (V_{OC}, I_{SC}, V_{MPP}, I_{MPP})	26.1%
Temperature coefficients (α, β, γ)	18.9%
Faciality (monofacial, bifacial)	18.0%
Length	14.4%
Height	14.4%
Series fuse rating	14.4%
Snow and/or wind load	11.7%
Width	9.0%
System voltage (IEC or UL)	5.4%
NOCT / NMOT	4.5%

Models with $\geq$3 revisions were analyzed for changes among the revisions for each module make and model. The results of this analysis are detailed in Table IV. A significant proportion of these revisions pertained to the description of the backsheet (44.1%), including changes in material, thickness (if glass), and color. Revisions also affected the front glass thickness or type (34.2%), potentially impacting a module's ability to withstand environmental factors or achieve aesthetic goals. Physical characteristics, such as weight (36.0%), length (14.4%), height (14.4%), snow/wind load (11.4%), and width (9.0%) may influence system design and installation, such as the selection of racking, ballast, or module placement. Temperature coefficients (18.9%) and normal operating temperature (4.5%) will affect the operating conditions of an array, such as exceeding (low or high) the allowed operating window of inverters under high and low temperature conditions. Revisions to electrical parameters, including key current-voltage (I-V) parameters (26.1%) such as V_{OC}, I_{SC}, V_{MPP}, and I_{MPP}, impact modeling of photovoltaic arrays composed of the revised modules, potentially affecting the anticipated performance and economics of a system. Furthermore, revisions to series fuse ratings (14.4%) and system voltage ratings (5.4%) have critical implications for system electrical safety.

Considering modules with six revisions, three module models from two manufacturers were identified. The revisions involve mechanical, electrical, contractual (warranty), and thermal parameters. It is important to note that these specification sheets are all dated, representing a best-case scenario where system design or analysis activities can place the comparison specification sheet into context.

For the ASE Americas ASE-50-AL module, the backsheet description changed multiple times across the six identified revisions. The change in system voltage appears to be related to ongoing improvements in module testing and certification during the early years of the commercial module market.

Similarly, the SunPower modules show changes likely due to re-testing and refinement of the module design. The most significant changes were in the temperature coefficients of power (γ) and current (α), as well as the front and rear maximum load pressures. Temperature coefficient values are plotted in Fig. 6. Between the first and last identified data sheet revisions for both models, the maximum front side (snow) load

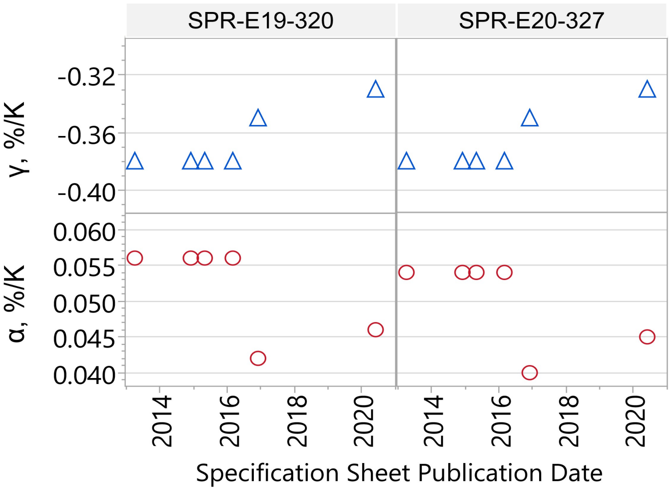

Fig. 6. Two SunPower modules with at least six identified data sheet revisions show the most significant changes in certain temperature coefficients.

increased by 185%, from 5400 to 10000 Pa, and the maximum rear side (wind) load increased by 308%, from 2400 to 7400 Pa. The temperature coefficient of power decreased for both models from -0.38 to -0.33 %/K, a 13.1% decrease from the initial value; notably, these changes were always in the same direction. In contrast, the temperature coefficient of current for the SPR-E20-327 model decreased from 0.054 to 0.040 %/K (-26%) before increasing to 0.045 %/K, a final decrease of 16.7% from the initial value. Similar behavior is observed in the SPR-E19-320 model, albeit with slightly different values. This example underscores the importance of identifying which version of a specification sheet was applicable at the time of a module's manufacture and stating the revision publication date when analyzing fielded modules or performing system modeling.

Although the provided example pertains only to the related modules, the prevalence of various changes described in Table IV underscores the importance of including specification sheet revision dates when referencing modules in academic and related work. It also highlights the need for consumers of modules, regardless of organization or purpose, to insist upon revision dates for all photovoltaic module specification sheets.

C. Uniqueness

A review of the module specification sheets in the database reveals that a small subset of identical modules is marketed by multiple manufacturers. These modules are defined as identical because each specification sheet differs only in the module identifier and the manufacturer name, address, and contact information. All other information, including the graphical layout, non-technical text, technical parameters (electrical, mechanical, thermal), and module dimensional drawings, remains unchanged. The inclusion of these identical modules affects parameter distributions. However, the authors assert that their inclusion is appropriate, as they represent commercially available modules. As the database expands, the impact of these products on the overall analysis will diminish accordingly.

IV. CONCLUSION

In our study, we present an initial dataset and observations from a database specifically created to collate and analyze distinct revisions of photovoltaic module specification sheets. This database facilitates the analysis of the evolution of various parameters over time in commercially available modules and examines how these changes may impact system modeling, performance analysis, and experimental work that evaluates module or system behavior against manufacturer-published data. We provided a selection of examples to demonstrate the value of this dataset in revealing industry trends related to less documented parameters and in tracking the progression of parameter values across module specification sheet revisions.

Our data shows that a significant portion (14.8%) of the analyzed specification sheets have at least one known revision from the earliest publication. Revisions often affect technical parameters such as STC I-V curve metrics, temperature coefficients, and physical dimensions, all of which may impact photovoltaic array modeling and power production predictions. Additionally, revisions to the bill of materials may affect reliability or, at the very least, reliability analysis when comparing field behavior to published data. Revision dates are crucial for contextualizing technical data within a module's evolution, and we encourage academic and research analyses to include the revision date (or other unique revision identifier) of a referenced specification sheet, not just the accessed date.

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