Perspective

DuraMAT: Building a Consortium to Accelerate the Photovoltaic Module Reliability Learning Cycle

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Durable and reliable photovoltaic (PV) modules are critical to enabling an efficient transition to sustainable energy generation. The rate at which new module designs and materials are developed and deployed currently outpaces the rate at which we can identify failure mechanisms and understand degradation rates. Increasing the service life of PV modules, and our ability to predict performance over time, requires more durable materials and designs, better durability testing, more extensive material characterization, robust modeling, and methods to cross-examine historical performance data to extract meaningful results. This is a multidisciplinary challenge that requires expertise from a broad range of fields and, therefore, benefits significantly from a collaborative approach. In this Perspective, we outline the approach taken by the Durable Module Materials Consortium (DuraMAT), present a few case studies where our approach was successful, and provide an outlook on where this approach might be applied as the PV technology landscape continues to rapidly evolve.

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I. ACCELERATING THE RELIABILITY LEARNING CYCLE

The photovoltaic (PV) module reliability field emerged from the Jet Propulsion Laboratory's (JPL's) Block Buy program, which ran between 1975 and 1985 [1]. The information garnered from field degradation and failure analysis allowed JPL to design accelerated stress tests to screen failure modes so that design flaws in new modules could be identified before deployment. The JPL's Block Buy program ended in 1985 after its fifth round (or block). In 1993, the continuation of that research eventually incorporated test protocols developed by a parallel effort, the Commission of European Communities' Specification 503 [2], to become the first International Electrotechnical Committee (IEC) standard for PV module qualification, IEC 61215:1993. For decades, the reliability learning cycle [Fig. 1(a)] that was established by the JPL's Block Buy program (and others) continued to be the method with which failure modes and mechanisms were identified. With use of this approach, IEC 61215, now the primary type-approval qualification standard, has evolved and improved through repeated applications of the learning cycle over the past few decades, with the most recent iteration being published in 2021 [3]. This evolution is shown in Fig. 1(b). This process starts with an observation of failures in the field, a collaborative and deliberate failure analysis, and then extensive experimentation at laboratories around the world to develop a repeatable, economical, and effective test to screen the observed failures. The purpose of international standards is to reduce barriers to trade by establishing common (often minimum) expectations for safety and performance, and this process is intentionally slow and deliberative to avoid introducing barriers without safety or performance benefits.

As the PV industry has rapidly grown, the IEC 61215 series has helped to continuously increase reliability in PV modules. Multiple published reports indicate that failure rates dramatically decreased following the adoption of these qualification standards [4–6]. The reliability learning cycle supporting these standards has generally kept up with the pace of PV technology innovation, especially with the widespread use of extended or expanded testing going beyond the requirements of the standards throughout the PV industry. Recently, PV module innovation has

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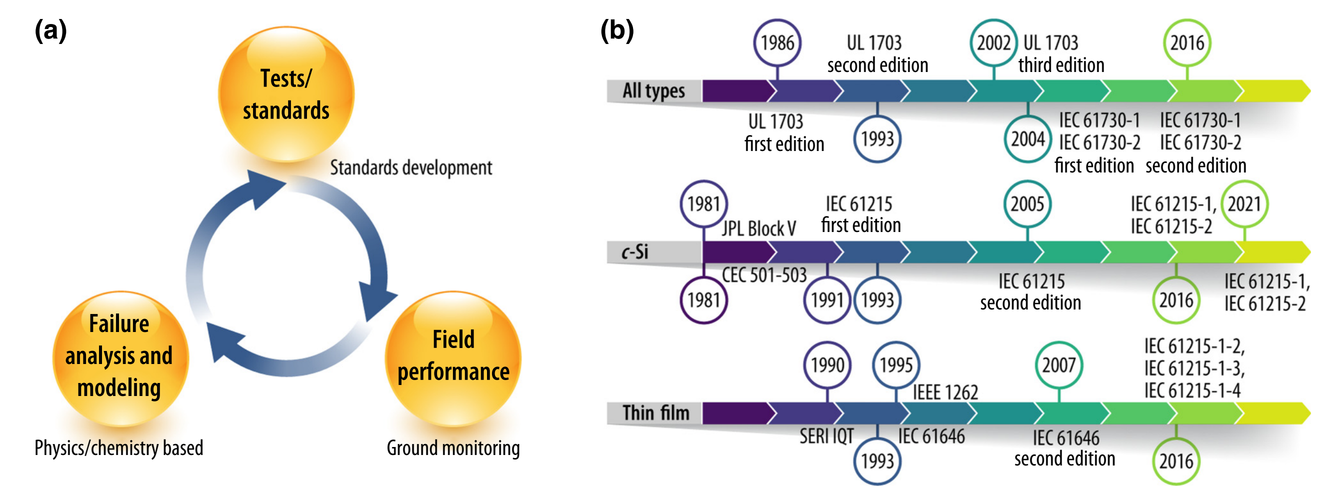

FIG. 1. (a) PV reliability learning cycle and (b) timeline of PV technology type approval qualification standards.

rapidly accelerated, and the number of different products with different designs and bills of materials has dramatically increased [7]. As a result, the reliability learning cycle struggles to keep up with the number of new failure mechanisms and modes introduced by these changes. There are examples of products that were qualified with use of standards (e.g., IEC 61215-2 and IEC 61730-2) and often extended testing that have failed in the field because the testing requirements are not sophisticated enough to identify the degradation mechanisms being introduced by new bills of materials and materials. Some of these new mechanisms require sequential or combined stressors, which are not typically required in the standards. Examples here include backsheet failures [8–11], light-induced and elevated temperature–induced degradation [12] and potential-induced degradation (PID) [13]. In response to a need for extended testing that goes beyond IEC 61215, a new technical specification, IEC TS 63209 [14], was developed and published in 2021. The goal of IEC TS 63209 was to provide a standardized method for evaluating longer-term reliability for PV modules and materials. The specification comes in two parts, IEC TS 63209-1 and IEC TS 63209-2, which specify reliability testing for full-module products and polymeric components (backsheets and encapsulants), respectively. In addition to identifying and mitigating early failures in new PV modules, there is also a greater need for predicting service life. This requires a better understanding of long-term wear-out mechanisms, which often depend on degradation of latent defects.

New module products can be developed and commercialized very quickly, and reliability testing is still relatively slow. We need to accelerate the identification and understanding of new degradation mechanisms to keep up with the rate of technological innovation and industry growth required for decarbonization. An accelerated learning cycle could reduce the risk of early-life to mid-life failures and enable long-term predictions of service life that do not rely on prior field observations of failure modes. This approach needs to hit several metrics, including more robust durability testing that addresses the multistep nature and synergies of many degradation mechanisms, more extensive material characterization to better understand the degradation pathways and mitigate them, robust modeling to quantify degradation rates with respect to the operating environment and understand the impact of design features on some behaviors (such as thermomechanical), and rapid analysis of streaming performance data to understand performance degradation in large module fleets. These metrics are inherently multidisciplinary and require a broad range of expertise, which can be afforded by a multi-institution research consortium that is not typically available to the usual federally funded programs.

II. THE CONSORTIUM APPROACH

PV module reliability research is a broad, multidisciplinary field requiring expertise in subject matters such as fracture mechanics, polymer chemistry, electrochemistry, computation modeling, and acceleration science. A research consortium can bring together expertise from multiple institutions to address the multi-disciplinary needs for PV module reliability research.

The Durable Module Materials Consortium (DuraMAT) was established in recognition of the need to rapidly advance PV reliability science for a growing and evolving industry [15]. The primary goals of DuraMAT are to advance our ability to predict failures in new PV module designs and materials, to better understand degradation mechanics and wear-out, and ultimately to accelerate our learning of PV module reliability. While DuraMAT has evolved over time, the core capability areas focused on data, modeling, acceleration science, forensics, and materials solutions remain largely unchanged. DuraMAT enables collaboration between experts from a broad range of scientific disciplines, which includes national laboratories including the National Renewable Energy Laboratory, Sandia National Laboratories, Lawrence Berkeley National Laboratory, and SLAC National Accelerator Laboratory, as well as multiple university and industry partners. An industry advisory board made up of industry leaders helps identify critical mid-term to long-term research problems that would benefit from broader expertise, extensive national laboratory resources, and more time commitment than would be available at individual companies or research institutions. This close relationship with industry allows DuraMAT to keep pace with the technology development curve and investigate emerging designs and materials before their widespread deployment. The collaborative nature of DuraMAT allows us to efficiently address needs identified by the industry advisory board. DuraMAT's organizational structure is such that there are more frequent funding cycles and more opportunities for collaboration than with typical federal programs. This allows greater flexibility and enables rapid pivoting to address new challenges as they arise, while still finishing out planned studies. For example, backsheets were a large focus early in the program; however, as module architectures evolve, DuraMAT has pivoted focus to address challenges associated with newer bifacial packages. Focus areas are evaluated annually through cross-project working groups. These working groups allow collaboration across projects to apply results to a variety of emerging questions. The following sections cover specific case studies that highlight the successful application of the DuraMAT consortium model. If readers are interested in more of DuraMAT's work over the years, summaries of all past and current projects can be found in the program's annual reports.

III. COMBINED-ACCELERATED STRESS TESTING

As a result of downward cost pressure and supply chain issues, new materials and designs for PV modules are constantly being introduced to the market. One example of this was a novel polyamide-based backsheet referred to as "AAA," named for the three coextruded polyamide layers. AAA was a commercial success with multiple gigawatts of deployed modules, but had a field failure rate greater than 95% within 5–7 years of deployment despite passing all of the IEC type-approval and safety standards, IEC 61215-2:2008 [16] and IEC 61730-2:2016 [17]. Failure of AAA manifested itself as major fracturing that compromised the electrical insulation properties, and while it was not considered a major performance issue, it was a significant safety risk. The mechanism of failure was later determined to be a two-step process, requiring exposure to elevated temperatures, humidity, UV light, and thermal cycling [8,18], a combination of stressors that did not exist in standard test protocols at the time of development. The test protocols outlined in the IEC standards were largely developed to screen known failures from field observations and have a limited capacity to identify new failures due to their single-stress nature and, as such, did not apply the necessary combination of stressors to identify the failure mechanism present in AAA.

One of DuraMAT's first goals was to develop accelerated testing methods that could detect weaknesses in new materials and new designs (which the single-stress tests could not) without waiting for large-scale field failures. Previous efforts to expand on the existing test standards used sequential accelerated stress testing to try to capture the synergistic mechanisms of degradation by ensuring all the relevant stressors were all being applied to the same samples [19,20]. DuraMAT's approach is a combined-accelerated stress test that applies multiple stressors in a single test such that new degradation mechanisms that require interactions between stresses can be detected [21]. The stress cycles were developed to better replicate the stress conditions of the outdoor environment so that testing would be agnostic to any specific degradation modes or mechanisms in PV modules. When coupled with more in-depth material characterization, combined and sequential testing has the capacity to screen out unsuitable materials and designs before deployment. Historically, PV modules were quite limited in terms of their design and variety of bills of materials, which meant that degradation modes were also quite limited and largely captured by the existing module qualification tests at the time. The benefits to applying combined-accelerated stress test methods were not commensurate with the cost of developing and routinely using such techniques. Only when module designs and bills of materials (and degradation mechanisms) became more complex did the value of being able to capture synergies [and therefore using combined-accelerated stress testing (CAST)] increase.

The initial exposure conditions for CAST were based on standardized tests for paints and coatings used in aerospace and automotive applications. These included diurnal irradiance cycling, elevated humidity, and rain spray cycles typical of a subtropical region. They were modified to include the increased temperatures and mechanical loading typically experienced by PV modules under normal operation conditions. Minimodules with different backsheet materials were used to develop the test because there were "known bad" materials (e.g., AAA) that fail in the field and "known good" materials that regularly perform for more than 30 years in the field. Validation experiments on backsheets revealed that CAST needed to include multiple climatic conditions to identify all potential degradation mechanisms. In the backsheet case, near-universal field failures of polyvinylidene fluoride–based backsheets had been observed in high-desert climates. However, the PVDF backsheets fared well in the subtropical conditions first tested in CAST. They failed in subsequent low-humidity "high desert" conditions [21]. Additional cycle conditions were added to cover varying use environments. These included very cold climates, more temperate climates, and dry climates with high irradiance and temperatures. Addition of mechanical loading required collaboration across the DuraMAT network to calibrate the mechanical stresses used in the chamber to real-world conditions and for material forensics to identify degradation mechanisms in materials and modules [18,22].

Once conditions had been established that replicated field behavior for "known bad" and "known good" commercial materials, CAST was used for the development of a novel multilayered coextruded product based on a polyamide-ionomer blend (PMR). This was a precommercial material and CAST was being used to evaluate its durability before any field deployment (Fig. 2). Although the PMR outperformed the "known-bad" AAA backsheets, which have a field failure rate of more than 95% within 5 years [10,23], it ultimately failed by way of major cracking, which could present a significant safety hazard if failure were to occur during service. Further analysis of the failed PMR identified structural changes in the polymer, which led to the cracking failure under mechanical stress. These finding were provided to the manufacturer for material improvement and further testing. Subsequent CAST evaluation of newer materials showed increased durability due to material changes made in response to initial testing. This is an example of rapid reliability testing accelerating product development and degradation science in parallel.

One of the key findings of the CAST studies is that many degradation modes observed in the field are multistep, requiring an initiation condition, followed by stresses that trigger propagation of the degradation or defect to failure. This approach has been used to study multiple backsheet materials, leading to an understanding of the likelihood of field failures [12,14]. It is now being used to study double-glass modules, degradation mechanisms in high-efficiency cells, and balance-of-system components such as connectors.

IV. RISK REDUCTION FOR DOUBLE-GLASS MODULE PACKAGING

The advancement of bifacial cell technology has resulted in greater adoption of modules with glass or transparent polymer backsheets to enable light capture from the back side of the module. Double-glass packages now make up almost 40% of the market, compared with less than 5% of the market in 2014, with projections of a 51% world market share by 2030 [15]. The shift to double-glass packages has also resulted in some rethinking of other materials in the module, particularly the encapsulant. Poly(ethylene-*co*-vinyl acetate) (PEVA) has been the encapsulant of choice for decades, but the replacement of a breathable polymer backsheet with glass raises concerns about trapped degradation by-products, such as acetic acid, which is known to enhance some corrosion mechanisms [24]. Encapsulant materials such as polyolefin elastomers (POEs) and mixed encapsulants have become more common, especially as system-level (or string) voltages are increased up to 1500 V. The higher voltages further raise concerns about PID pathways at the interfaces.

The DuraMAT industrial advisory board requested a screening experiment to quickly evaluate the potential risks of new double-glass module architectures and materials using bifacial passivated emitter and rear cells (Fig. 3). The cells were packaged in several different configurations, including double glass, glass with a transparent polymer backsheet, and two different commercial encapsulant types, PEVA and POE, and were exposed to dark damp heat with the cell biased at ± 1000 V or with no bias. In general, minimodules with POE degraded less than the PEVA-containing minimodules, the efficiency of which decreased by 15%–35% [25]. The highest degradation rates were observed under PID test conditions.

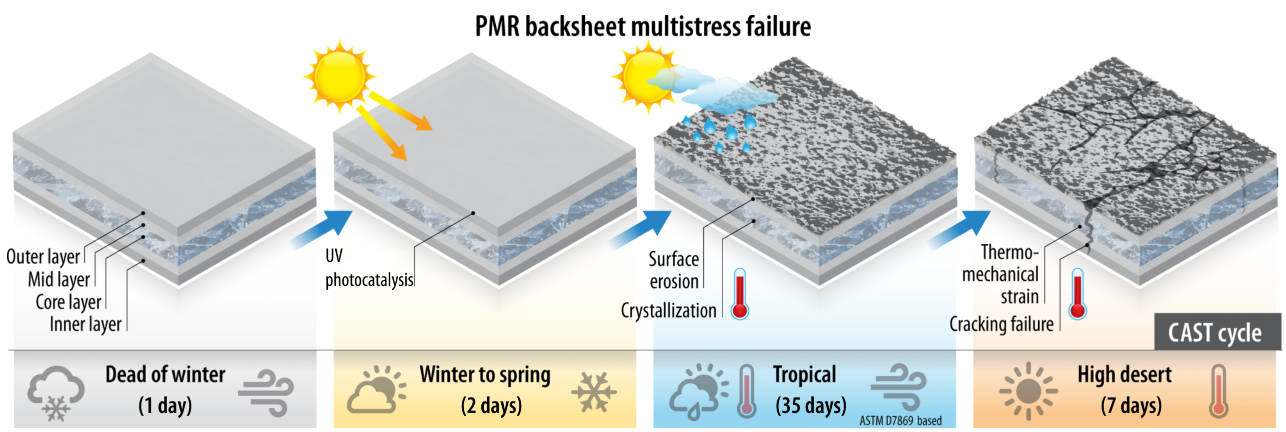

FIG. 2. The multistep combined-accelerated stress testing approach and its effect on the PMR backsheet.

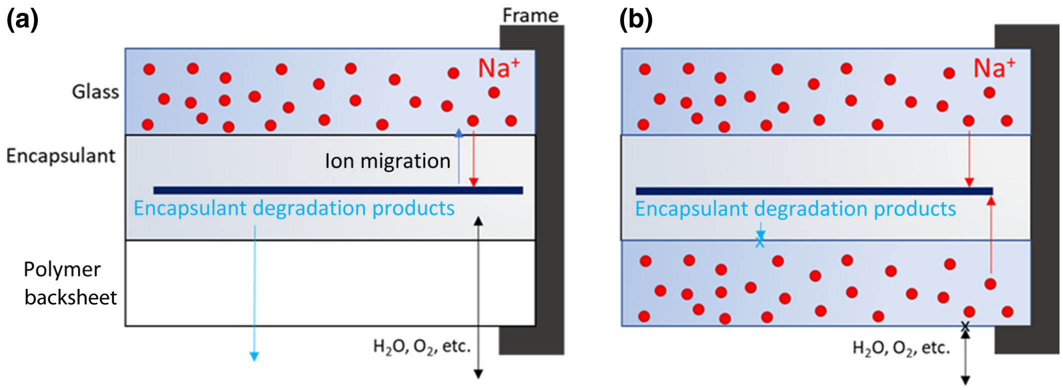

FIG. 3. Cross-section diagram for (a) traditional glass-backsheet PV modules where the breathable backsheet enables outgassing of degradation by-products and high permeation of water and oxygen, and (b) a double-glass module that traps degradation by-products and limits moisture ingress. PID is a more prevalent concern in double-glass modules as there are now additional sources of mobile ions (particularly from the glass).

DuraMAT attributed degradation in the PEVA-containing modules to known PID mechanisms. This study identified several risks that, while not unique to bifacial modules, could be enhanced in bifacial module architectures. Some PID mechanisms are typically attributed to sodium ions from the glass moving toward the cell under bias and then causing issues such as shunting or reducing the effectiveness of rear-side passivation known as PID of the polarization type [25,26]. Some of the enhanced PID degradation observed in double-glass modules can be attributed to the presence of a second sodium ion source on the rear side of the module (which does not exist in a glass-polymer backsheet configuration) so more mobile sodium ions are moving toward the cell and causing issues. Sometimes, a loss of surface passivation [indicated by a reduction in open-circuit voltage (V_{oc})] [27] is observed. These mechanisms can often be mitigated by use of a higher resistivity and less reactive encapsulants, such as POE.

Similar module package configurations examined with CAST demonstrated that PID of the polarization type was also prevalent in double-glass packages [28]. The CAST results provide more confidence that PID of the polarization type is a mechanism that could manifest itself in the field because CAST applies stress conditions occurring in the natural environment. CAST also demonstrated increased metallization breakages in double-glass packages as compared with glass-backsheet packages, which suggests elevated stress states in double-glass packages. An x-ray topography method to quantify stress states within module packages was developed in another DuraMAT program at Arizona State University [29]. The findings suggest that double-glass packages indeed exhibit elevated cell stress states and this is consistent with the results produced by CAST.

Direct guidance from industry partners and the breadth of expertise in DuraMAT, including material characterization, accelerated stress testing, and advanced metrology, enabled rapid research into a rapidly emerging trend in the PV industry. As a result, the research community was able to quickly gain an understanding of the potential issues in new module design and material trends. Efforts to further understand and mitigate the potential risks of double-glass packages are ongoing and continue to evolve as new materials and modules are being commercialized, such as coextruded encapsulants that contain both PEVA and POE and modules that use PEVA on the front and POE on the back to mitigate PID.

V. CELL FRACTURE AND DAMAGE ACCUMULATION

Increasing the wafer size and the number of cells per module has resulted in a significantly increased module form factor over the last few years. In addition, to reduce costs associated with module weight, front glass has become thinner, from 3.2 mm to as low as 2 mm [15]. More PV systems are also being installed in extreme-weather-prone areas. All of these factors lead to an increased risk of cell fracture.

Cell fracture is another degradation mechanism that follows a multistep initiation and propagation pathway to eventual failure. The challenge is knowing how long it will take for an initial defect to propagate to failure. Some are almost immediate, and others may take decades. Initial cracks in PV cells do not typically lead to significant performance loss in a module unless they are so severe that they cause disconnections of whole areas of the cell. Modern metallization patterning and an increasing number of bus ribbons help mitigate large-area disconnections. However, long-term exposure to external stressors such as wind and snow can lead to continued damage accumulation, but the rate of propagation and probability of failure are difficult to predict.

One reason for the lack of understanding is the difficulty of testing. Wind is a major source of the mechanical loading a field module will experience, and the amplitude and frequency of loading is extremely variable. During its lifetime, a PV module can experience millions of small-amplitude wind loads. Until now, it has been difficult to evaluate the effect of these loads due to the time limitations of accelerated dynamic mechanical loading methods, which could apply loads that are representative of outdoor conditions. Silverman *et al*. [30] developed a new technique using subwoofer speakers in an enclosed box to apply small-amplitude mechanical loads to full-sized PV modules at up to 20 Hz. This meant that 1×10^6 pressure cycles could be applied in approximately 1 day instead of 100 days. Thus, this technique enables the study of cell crack damage accumulation and metallization wear-out at different amplitudes over the lifetime of a mounted PV module. These studies will begin to elucidate the long-term effects of cell crack damage accumulation and metallization wear-out.

A demonstration study was performed on a 72-cell multicrystalline silicon module with deliberately introduced cell cracks (Fig. 4). Dynamic mechanical acceleration (DMX) was used to apply 1×10^6 cycles each of progressively increasing load at 10, 30, 100, and 300 Pa. It was demonstrated that at 10 Pa, very little damage accumulation occurred through 1×10^6 cycles. Increase of the pressure to 30 Pa caused new, reversible disconnections that continued to worsen through the 1×10^6 cycles. At 100 and 300 Pa, additional cracks were initiated and damage accumulated through the respective 1×10^6 cycles. This case study revealed that gridline wear can occur at amplitudes and frequencies that are expected through wind loading. Additionally, the new cracking and damage accumulation that occurs when loading pressure is progressively increased highlights the complexity of cell fracture mechanics. This complexity might not be fully captured by the standard dynamic mechanical loading tests that apply a singular loading condition.

DuraMAT used computational fluid dynamics simulations, leveraging laboratory expertise in wind energy, to characterize and understand the physics of wind loading on modules and trackers. Trackers are relatively new racking structures for PV modules that track the sun along one axis during the day, leading to much higher energy yield. However, they were found to be prone to dynamic mechanical instabilities previously seen in structures such as bridges—torsional galloping. Torsional galloping is a phenomenon whereby PV modules mounted on single-axis trackers become unstable during dynamic fluttering from wind loads and begin twisting and rotating uncontrollably [31]. Simulation techniques born from this work are being used to determine the amplitudes and frequencies of wind loading on mounted PV panels, which can then inform the appropriate accelerated stress tests to use with DMX. Finite-element simulations have also been used to characterize the effect of frame constraints on internal damage of PV modules [32]. Cell fragment displacement, which is the driving force behind gridline metallization wear, is not dependent on the constraints placed on the module frame. Because the current version of DMX requires that modules be fully constrained around the perimeter of the module frame, it was important to understand the effect that this has on gridline wear-out compared with how modules are mounted in a field array.

The method for dynamic mechanical load testing in DuraMAT greatly reduces the time needed to fully assess and appreciate the mechanical robustness of newer PV module designs. DMX is an effective method of condensing multiple years of field wind loading experience

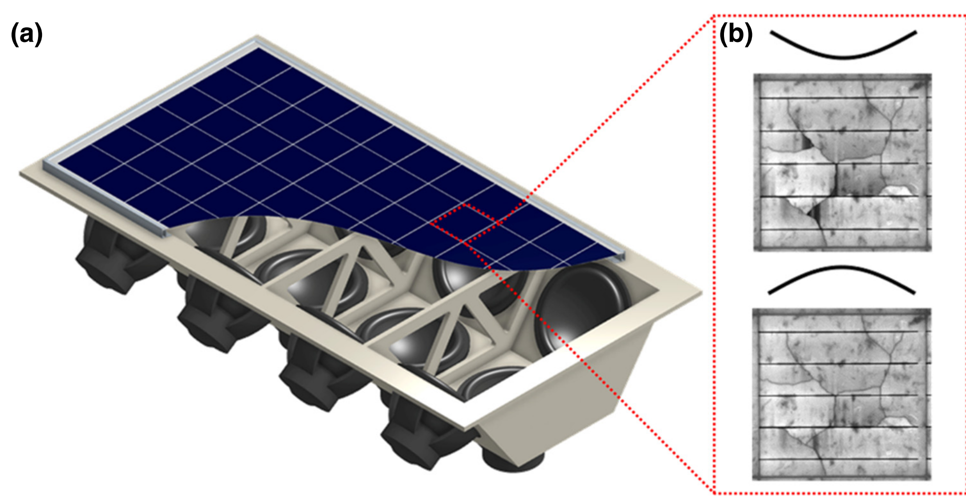

FIG. 4. (a) DMX apparatus, which uses 12 loudspeakers to apply time-varying pressure to a PV module, and (b) its effect on cell cracks (the black lines indicate the deflection state of the module).

(assuming there are no extreme weather events) into days of indoor testing, while also accounting for the complexities of the outdoor environment through dynamic control of the loading conditions being applied. This enables a much more rapid evaluation of the accumulation of damage in cracked solar cells and a better understanding of the potential wear-out of gridlines in specific module architectures.

VI. EFFECTS ON HIGH-EFFICIENCY CELLS

New, higher-efficiency silicon cell types, such as heterojunction, interdigitated back-contact, and tunnel oxide passivated contact, are becoming more common in the global market due to their potential for increased energy yield. However, these cell architectures may present new reliability challenges. For example, these cells often have an enhanced blue response, which has motivated manufacturers to remove UV-blocking additives in packaging to increase the initial power measurements. However, this may lead to long-term power loss due to UV-driven degradation. Early field data from some of these cell types have shown increased degradation in packages without UV blockers, pointing to UV-induced degradation mechanisms [33]. However, the exact nature of the UV degradation, and which UV wavelengths are responsible, is not yet clear. A DuraMAT project was started to investigate the UV sensitivity of different cell types and identify the packaging needs to mitigate degradation. It was found that modern cell architectures are more vulnerable to UV-induced degradation than older cell architectures; however, the exact chemical mechanisms behind this degradation differed by cell type and manufacturer [34–36].

For this study, five different cell technologies were studied, including interdigitated back-contact, n-type passivated emitter rear totally diffused, p-type passivated emitter and rear cells, aluminum back surface field, and heterojunction cells. For each technology, a handful of different cell manufacturers were also investigated. Figure 5 summarizes the relative module power loss after 2,000 h of UV exposure. The chamber temperature during the test was kept low to avoid thermal degradation mechanisms. UV exposure led to a significant power decrease (−3.6% on average; −11.8% maximum) compared with the conventional aluminum back surface field cells (less than −1% on average). Additionally, the rear side of bifacial cells appeared to be more susceptible to UV damage than the front. These results are an important observation, as the increased degradation related to UV exposure in modern cell types may offset the gains predicted from increased UV (or blue) transmission to the cells. Long-term energy yield may be higher with a UV-blocking encapsulant, despite the lower initial flash efficiency.

This work required expertise in cell technologies, accelerated testing, and advanced characterization approaches. The National Renewable Energy Laboratory's vast knowledge of cell technologies and accelerated testing approaches was critical in the design of experiments. Many other light effects can be present in cells, and choosing of the right preconditioning and exposure types was necessary to interpret the results. SLAC National Accelerator Laboratory's expertise in chemical and structural characterization provided the basis for the deeper dive into the degradation mechanisms. The most critical component was likely the interaction with industry. Sourcing of cells to test was enabled by a direct line to DuraMAT's industry advisory board. The impact of this type of work relies on the ability to source state-of-the-art cells and materials. While it is sometimes possible to purchase materials for these types of study, interaction with industry stakeholders provides a material supply chain and insight into the most relevant materials. Additional studies not discussed here

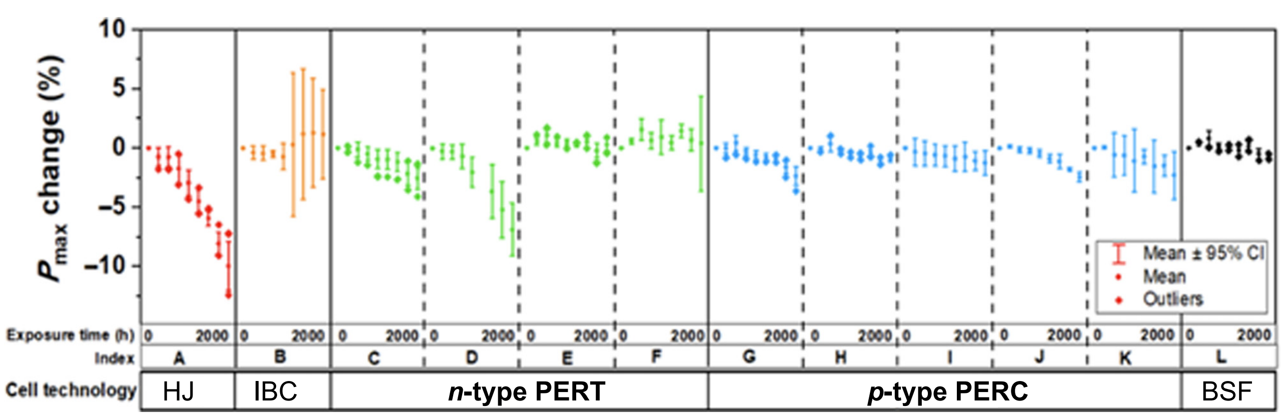

FIG. 5. Change in power output (P_{max}) after 2,000 h of UV exposure of 12 different cells and replicates along with the 95% confidence interval (CI) in the measurement at each read point demonstrating the UV susceptibility of high-efficiency silicon cells [36]. A negative value indicates degradation. BSF, back surface field; HJ, heterojunction; IBC, interdigitated back-contact; PERC, passivated emitter and rear cell; PERT, passivated emitter rear totally diffused.

have also explored possible solutions to mitigating UV-induced degradation through encapsulant-based packaging solutions.

VII. ADVANCING DATA, SOFTWARE, AND MACHINE LEARNING IN SOLAR RESEARCH

As deployed solar installations increase in number, a variety of new and large data sets (predeployment testing data, production and operating electrical data, and field characterization and imaging) can potentially be leveraged to better understand and quantify degradation. However, processing large data volumes and isolating the desired information among other confounding signals, such as soiling, sensor data shifts, and irradiance changes, can be challenging. Even relatively simple (yet important) estimates of degradation rates of a production system can differ significantly depending on the analyst [37] due to the complexity of data filtering, making it difficult to know the true performance of a system. Furthermore, certain data types, such as electroluminescence images or text maintenance logs, are typically analyzed and processed manually, leading to an inability to process large field data sets and accurately determine statistical trends.

One way that DuraMAT is advancing the field is by standardizing data analytics routines into software packages and workflows. Such standardization has been shown to greatly reduce the variance in predicted degradation rates between different analysts who are provided with the same data set [38]. Crucial to this is the development of standard preprocessing routines, such as those implemented in DuraMAT's PVAnalytics library for actions such as clear sky detection or inverter clipping detection. By leveraging the expertise of several analysts across national laboratories, the consortium model can quickly reach consensus on standard data analysis techniques and integrate them into reusable software for the community. These models and tools can be applied in tandem with efforts from other research teams such as pvlib [39], RdTools [40], and various other degradation analysis tools [41] or applied to large data sets compiled by programs such as the PV Fleet Initative [42].

Furthermore, DuraMAT is advancing the role of machine learning to process large production data sets. For example, natural language processing techniques developed by DuraMAT can be used to parse text-based operation and maintenance logs, leading to better understanding of the causes of system downtime and its effect on power production [43]. Furthermore, DuraMAT has developed computer vision software that can rapidly and accurately analyze cracks and other defect types in electroluminescence images. In collaboration with PV Evolution Labs, an industry advisory board member of the consortium, this software was deployed to analyze tens of thousands of modules (millions of cells) to determine the effects of fire damage at a site [44]. Similar efforts are now ongoing worldwide, such as a recent effort in the UK to analyze thermal and electroluminescent images from 3.3×10^6 modules [45] and an effort in Hungary to use automated data analysis to process electroluminescence images of 12 500 modules [46]. Ongoing work aims to develop methods that can examine trends in production data to not only determine degradation rates but also suggest underlying causes of that degradation; this work uses the data-filtering algorithms previously developed by the consortium. In our experience, the development of successful data analysis routines relies on dependable base libraries and good test data sets, and the availability of and expertise regarding both is facilitated through the consortium model.

Although data analytics and machine learning have the potential to make even greater impacts in the future, the data needed to develop, train, and test such capabilities are often lacking or unavailable to researchers. To this end, DuraMAT has developed the DuraMAT Data Hub [47], which aims to capture data from all research projects and make them available for reanalysis. We note that the success of such a data hub in many ways depends on the consortium model. DuraMAT can provide dedicated funding for the development and maintenance of the central hub, which is typically unavailable to individually awarded projects. Furthermore, DuraMAT has now made data contributions a necessary milestone in funded awards, thereby ensuring the availability of data going forward and contributing to the future development of improved data analysis methods.

VIII. OUTLOOK

Although degradation should be considered unavoidable, it can be managed to an extent and folded into appropriate models with the use of a degradation "budget." Decarbonization targets and economics demand an acceleration of deployment and innovation, which have both accelerated dramatically in the last decade. Long-term performance prediction requires appropriate degradation budgeting, but the rate of innovation makes this difficult with the traditionally slow reliability learning cycle. Through an integrated consortium model, DuraMAT has enabled an acceleration of the traditional reliability learning cycle to keep pace with innovation, mitigate early failures, and quantify degradation rates and probabilities in more materials and designs.

IX. MULTISTEP DEGRADATION MECHANISMS

Most degradation processes are multistep, requiring an initiation step, some probability and rate of propagation, and then eventual failure. These processes need to be described by a combination of rate equations and probabilistic statistics. They also require rethinking of some testing protocols. The existing standards test sequences typically provoke known failures in poor materials and designs. New testing may have to carefully consider different initial conditions, propagation conditions, failure criteria, and mitigation options. Cell cracking is a great example—many modules have cracked cells but still produce full power. Those cracks can grow over time, but the probability of power loss depends on the intensity and frequency of the propagation stresses.

X. INNOVATIVE HIGH-ENERGY-YIELD MODULES

New and emerging technologies are critical for increasing PV deployment to meet decarbonization targets. Changes in module design parameters, such as double glass, larger form factors, novel interconnects, and new cell technologies, are the future of the PV industry. Consequently, they will also likely introduce new reliability and durability challenges, which will need to be understood and addressed as quickly as they enter the market. Meeting these challenges at sufficient speed will require a multidisciplinary, collaborative approach. Additionally, the potential unknown degradation mechanisms, especially in new cells and materials, necessitate agnostic accelerated testing procedures, such as CAST combined with predictive modeling, to extrapolate long-term performance from testing and limited field data.

XI. EXTENDED MODULE LIFE

PV system owners, government agencies, and the solar industry are moving toward longer module and system lifetimes. This improves project economics and increases sustainability [48,49]. In addition, increasing energy yields through reduced degradation rates and failures can reduce the environmental impact of PV modules with an increased return on embodied energy and carbon [50]. Estimating service life of PV modules is very complex and at best would have large margins of error. Instead, DuraMAT has a new goal of addressing wear-out failures in PV modules that affect modules at the end of life. When one is considering the traditional failure rate curve model, these wear-out mechanisms are those that affect the failure rate at the right side of the curve. Developing a degradation budget over the full lifetime of the module requires identifying and quantifying degradation rates at the beginning, middle, and end of the module lifetime, and understanding which mechanisms could lead to an abrupt, premature failure requiring immediate replacement. Combining differing chemical, mechanical, thermal, and electrical degradation mechanisms and understanding their behavior in different climates is a challenge that requires an integrated consortium of diverse specialists to build a whole picture that is more informative than the sum of its parts.

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