

Screening Metal Halide Perovskite Solar Modules for Premature Field Failures

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Developing metal halide perovskite (MHP) photovoltaic (PV) devices into reliable large-area solar modules could accelerate global solar energy deployment. Many MHP devices are susceptible to degradation under light and elevated temperature (LT). Published research on LT testing is limited at the module level, and LT testing has not yet been developed for qualification testing of commercial PV products. This report assesses whether results of LT testing at moderately elevated temperatures correlate with those of field-tested modules from the same batch. Six batches of samples from four manufacturers are assessed. It is shown that modules with a robust package that can maintain over 80% of their peak efficiency during LT testing at 55 °C for 100 h are more likely to retain over 80% of their peak efficiency during outdoor operation for 10 weeks. This finding is a step towards developing a validated test protocol that could be incorporated into a qualification standard for the commercialization of MHP PV technologies.

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I. INTRODUCTION

Metal halide perovskites (MHPs) are a promising class of thin-film photovoltaic (PV) materials. Although photoconversion efficiency was the initial focus of many studies, recently, more attention has been given to MHP thermodynamic stability and overall device reliability [1,2]. There have been multiple improvements in both the material-level cell stack [3–12] and the module-level package [13–17] that have improved material stability and module reliability, but there is still much progress to be made before MHPs can be a leading utility-scale technology [18].

Accelerated stress testing can be used to screen for known field failures and provide confidence that a solar module will not fail prematurely. The most well-known and industry-accepted stress test protocols are outlined in type-approval standards, such as the International Electrotechnical Commission's (IEC's) 61 215 series [19]. These standards do not quantify lifetimes but, when applied to the materials they have been developed for, can increase confidence that a passing module design has a higher chance of operating outside without early failure [20,21]. The IEC 61 215 type-approval standard, however, has not yet been validated for use on MHP modules. Development and validation of standards requires modules to be tested in the field and under various stress conditions to confirm that the relevant degradation modes and mechanisms are observed [22]. Thus, the presented study seeks to develop a validated accelerated stress test, with a focus on degradation modes that occur due to light and elevated temperatures.

Light and elevated temperature (LT) is a combined stressor that can drive significant degradation in MHP devices. Studies have shown that light generates excess charge

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carriers that can lead to chemical reactions in an MHP cell stack, with reactions accelerated at higher temperatures [23–25]. Such reactions can include phase separation of MHP layers, photooxidation of fullerene transport layers, and ion migration that can enable chemical reactions between MHP and metal electrode materials [25,26]. LT stressors in MHPs are distinct from light and elevated temperature induced degradation in silicon solar cells, and they are not meaningfully accounted for in any of the current type-approval or safety standards published by the IEC. Jiang *et al.* have demonstrated a strong correlation between LT testing indoors and field performance for their MHP solar cells [27]. Zhao *et al.* took a similar approach to determine acceleration factors for LT testing on their all-inorganic solar cells [28].

Here, we build on these foundational studies at the cell level towards a module-scale protocol that is broadly applicable across MHP formulations. While LT testing with constant light and temperature is regularly used in research development of MHP cells [29], published results are scarce for larger-area modules, which can degrade differently from cells due to the presence of scribes and other effects [25,26]. In particular, comparative LT and field testing on MHP modules will be needed to determine which conditions (i.e., temperature, duration) allow LT testing to replicate the same degradation modes that occur in field operation. Our previous work described degradation processes and chemical reactions that could occur during LT testing [2].

This work reports on comparative field and LT testing of packaged MHP modules. Field testing is done with modules held under maximum power point tracking (MPPT) with fixed-tilt open-rack mounting in Golden, Colorado, USA (Fig. S1 within the Supplemental Material [36]). The indoor LT test is done with constant light, ambient air, and $55\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$ back module glass temperatures, herein referred to as LT-55. $55\text{ }^{\circ}\text{C}$ is the maximum observed field temperature for the modules reviewed in this report, as deployed in our test field in Golden, Colorado, so effectively we are accelerating with the harshest condition that the fielded modules are subjected to at this location.

The main question for this study is whether LT-55 effectively screens for field failures: Will module batches that retain 80% of their initial peak efficiencies after 100 h of LT-55 testing, defined as a “pass” condition, also pass 10 weeks of field testing?

To contextualize the 10-week milestone, we reviewed data for all of the modules tested in the field to date by the Photovoltaic Accelerator for Commercializing Technologies (PACT) center [30]. We found that a majority of the modules failed before 10 weeks (69%), while many passed the 10-week mark (31%), which suggested that it was a useful benchmark for the majority of module makers.

We find that the 100-h LT-55 test can save time and effort by screening modules that will fail before 10 weeks in the field. This enables a more rapid feedback loop for MHP module development. Furthermore, this examination of the field relevance of LT-55 provides a framework for developing future tests at higher temperatures that could extend beyond 10 weeks of validated field performance. The research community has increasingly recognized the need for more and better durability testing of MHP modules [18,22]. Without valid qualification tests that screen for premature field failure in MHP solar modules, this technology will struggle to become commercially competitive with incumbent PV technologies.

II. METHODS

The LT test chamber simulates a subset of field-relevant stressors—the purpose is not to recreate all field stressors within the LT chamber. Modules in the field can fail from a degradation mode that does not occur in LT testing. One example is degradation from ultraviolet (UV) light, which is at a lower intensity in the LT chamber utilized relative to the AM1.5G solar spectrum. The light spectrum in the LT chamber has a 400-nm cutoff, as detailed in Fig. S2 within the Supplemental Material [36].

Figure 1 outlines the experimental stress testing protocols used in our experiments. Samples in a batch are separated into test conditions, including LT-55, field testing, package testing, and dark storage (for a control).

For batches with a unique package type, a “package test” is used on a subset of the modules to assess whether the module packages can mitigate moisture ingress during applied thermomechanical stresses. The package test, adapted from IEC 63 209 [31], incorporates damp heat (85% relative humidity, $85\text{ }^{\circ}\text{C}$, 48 h) and thermal cycling (-40 to $85\text{ }^{\circ}\text{C}$ for 50 cycles), as depicted in Fig. 1. Further details on the experimental methods are provided in the Supplemental Material [36].

We tested modules from six different batches from four different manufacturers with areas from $2.3\text{--}35\text{ cm}^2$ and initial efficiencies from 11% to 17%, as measured on a solar simulator. For field testing, “failing” is defined as the daily irradiance-weighted average efficiency dropping below 80% of its peak value for 3 consecutive valid days before the 10-week point. For LT tests, “failing” is defined as the 5-min-averaged efficiency dropping below 80% of its peak value before the 100-h point. For the package test, “passing” is defined as a lack of macroscopic color changes to the MHP absorber material. The package test applies a qualitative condition to focus on whether the module package can prevent moisture ingress. Because the package test is focused on assessing the robustness of a specific package type and because module samples are limited, each individual package type is tested at least once but is not always

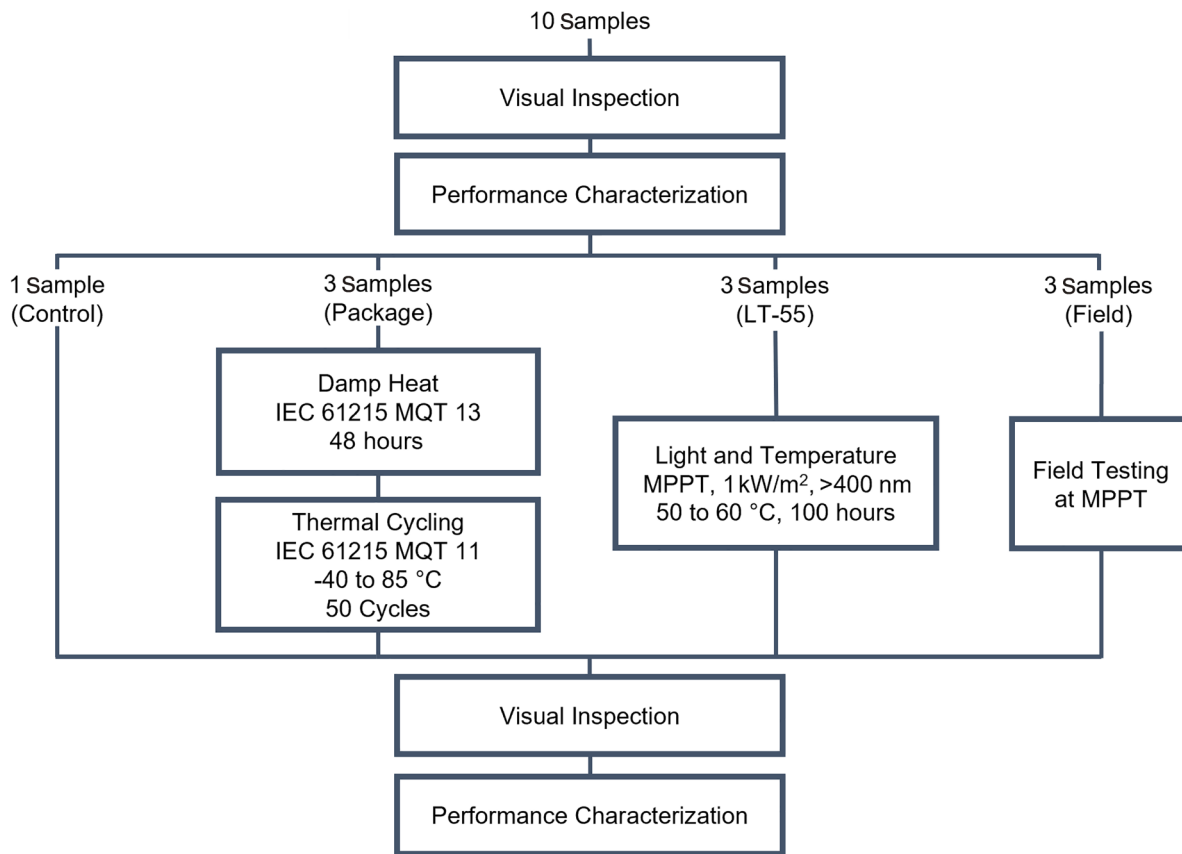


FIG. 1. Experimental design for testing a representative batch of 10 modules. Parallel test conditions allow for the comparison of an unstressed module to modules that went through field, LT-55, or package testing.

repeated for all batches using the same type. Here, package type β uses a UV-curing polyacrylate to attach a rear cover glass to the cell, and package type γ uses a polymer encapsulant and a desiccated polyisobutylene (PIB) edge seal. Both package types are glass/glass modules.

III. RESULTS AND DISCUSSION

Table I summarizes the results of field and LT-55 testing and identifies the package type of each module. Notably, batches that passed both LT-55 and the package test also passed 10 weeks of field testing, and batches that failed either accelerated test also failed field testing sooner than 10 weeks.

It should be noted that batches were deployed at different times as they were received during a 1.5-year period, but modules within a batch were always deployed together. Modules' field temperature and solar insolation measurements are summarized in Tables S1 and S2 within the Supplemental Material [36]. One of the two batches that passed the 10-week field test (D1) received relatively high temperature and solar insolation levels relative to the batches that failed, so weather differences were not

expected to be a dominant factor in which batches failed or passed 10 weeks of fielding.

A. Batches that failed the 10-week field test

Batches A1, A2, B1, and C2 failed the 10-week field test. Figures 2(a)–2(d) show the change in module efficiency during LT-55 and outdoor field testing for batches A1 and A2. The field data show each day's irradiance-weighted average efficiency, i.e., the daily efficiency, which is calculated as the energy produced by the PV device in a day divided by the energy incident on the device on that day. The LT data show the efficiency averaged over a 5-min rolling window. To better understand the behavior of a batch in LT testing, module efficiencies are normalized to their peak efficiency value. The peak efficiency is defined as the maximum 1-h median for LT testing. For field testing, the peak efficiency is defined as the maximum 5-day median calculated over acceptable days. "Acceptable days" are days with plane-of-array solar insolation over 4 kWh/m², no snow on modules or instruments, and no hardware malfunctions. In the field testing plots, data from unacceptable days are blocked out with gray bars. Days with plane-of-array solar insolation

TABLE I. Summary of stress testing results, initial efficiencies, and aperture areas for all modules tested. Batches named with the same letter are from the same provider. Green highlights indicate passing (no moisture ingress in the package test for a package type, and no sustained drop below 80% of peak efficiency for LT-55 and field tests), while red highlights indicate failing.

Batch	Package Type	LT-55 Test		Field Test		Initial Ex Situ Efficiency (%)	Area (cm ²)
		Modules Passed	Modules Tested	Modules Passed	Modules Tested		
A1	β	4	4	0	3	10.4 $\pm$ 1.1	31–35
A2	β	1	3	1	3	15.4 $\pm$ 1.5	32–35
B1	γ	0	2	0	3	14.1 $\pm$ 1.5	12
C1	γ	0	2	0	3	11.2 $\pm$ 1.5	8–15
C2	γ	6	6	3	3	13.8 $\pm$ 1.4	13–23
D1	γ	4	4	3	3	15.1 $\pm$ 0.6	2.3

under 4 kWh/m² are indicated by lighter blue bars. No temperature correction is applied to any plots.

To simplify the visualization, a shaded region bounds the maximum and minimum performing module in a batch, with the average normalized efficiency of the batch plotted as the dark curve. A horizontal dashed line of 80% of peak efficiency is shown to identify the time until the efficiency drops to 80% of peak efficiency (T_{80}). The individual unnormalized data for all modules are detailed in Figs. S4 and S5 within the Supplemental Material [36] for LT testing and field testing, respectively. Data for module temperatures (Table S1) and daily solar insolation (Table S2) are also presented in the Supplemental Material [36].

Batch A1 failed the 10-week field test but passed the 100-h LT-55 test. Batch A2 had two out of three modules fail field testing before 10 weeks (module A2-03 failed at 10.5 weeks of field testing) and two out of three modules failed LT-55 testing before 100 h (module A2-05 failed at 150 h of LT testing).

The discrepancy between A1 failing the 10-week field test while passing the 100-h LT-55 test is attributed to this batch not having a robust package; so, the batch failed outdoors due to a degradation mode that was not accelerated in LT testing. The failure mode of an A1 module of package type β is evident in Fig. 2(g). Modules in this batch use a proprietary encapsulation material that has not been vetted for field testing. Although the modules did not change color during dark storage or LT-55 testing, they did turn yellow during field testing and package testing, indicating a failure due to moisture ingress [Figs. 2(e)–2(h)]. The efficiencies of the modules also dropped from about 10% to 0%–5% after just 48 h of damp heat (85% relative humidity at 85 °C). These results underscore the importance of using a well-tested encapsulation scheme for field testing

MHP modules; modules must be able to withstand both moisture and light under varying temperature conditions to withstand field conditions in most environments.

Batch A2 exhibited a similar package failure to batch A1. Batch A2 used a similar packaging scheme as A1, but A2 incorporated a modification to the device layers that resulted in higher initial efficiencies. The faster degradation of A2 in LT-55 testing compared to A1 could be due to the failure of a chamber fan, which resulted in higher module temperatures for A2 (63 °C on average) than for A1 (56 °C on average). Individual module operating temperatures for all batches are detailed in Table S1 within the Supplemental Material [36]. In any case, comparing the field and LT testing in batches A1 and A2 highlights the fact that LT testing likely will not correlate to field testing for MHP modules that do not have a robust moisture-proof package.

Batches B1 and C1 failed both field and LT-55 tests while having a packaging type that passed (type γ). The efficiency of batch B1 dropped to half its peak efficiency within a few hours of fielding and did not recover (Fig. S6 within the Supplemental Material [36]). Batch C1 failed both field and LT-55 tests (Fig. 3). Originally, two more C1 modules were put into LT-55 testing (for a total of four modules), but their efficiencies never went above 5%, as shown in Fig. S4 within the Supplemental Material [36]. Those two samples were thus excluded from Table I and Fig. 3, as they likely incurred degradation before stress testing began.

The degradation of batch C1 modules is attributed to the encapsulant used in the package. The encapsulant is the only known manufacturing difference between C1 modules, which failed the 10-week field test, and C2 modules, which passed the 10-week field test. The C1

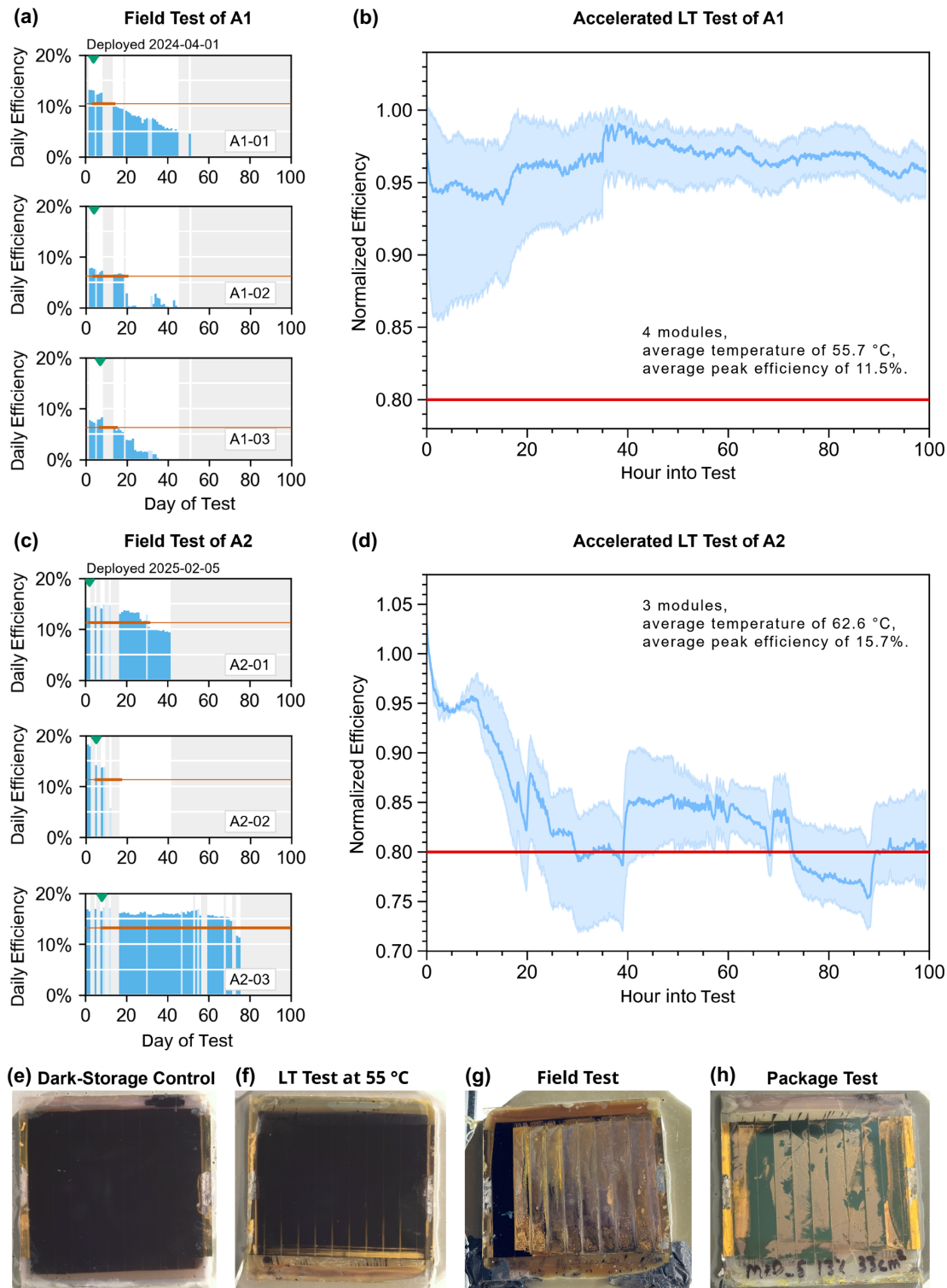


FIG. 2. Stress testing of batches A1 (deployed 2024-04-01) and A2 (2025-02-05). (a),(c) Irradiance-weighted average efficiency versus day for field-tested modules. Horizontal red lines indicate 80% of the peak efficiency, and green arrows point to the 5-day period that contains the peak efficiency. Thicker horizontal lines show the time between the day the efficiency reaches the peak efficiency and the day it drops below 80% of the peak efficiency. (b),(d) Efficiency versus time under 1 sun and 55 °C for LT tested modules, showing the minimum, average, and maximum efficiency normalized by peak efficiency. Photographs of batch A1 modules after (e) dark storage, (f) LT-55, (g) field, and (h) package testing.

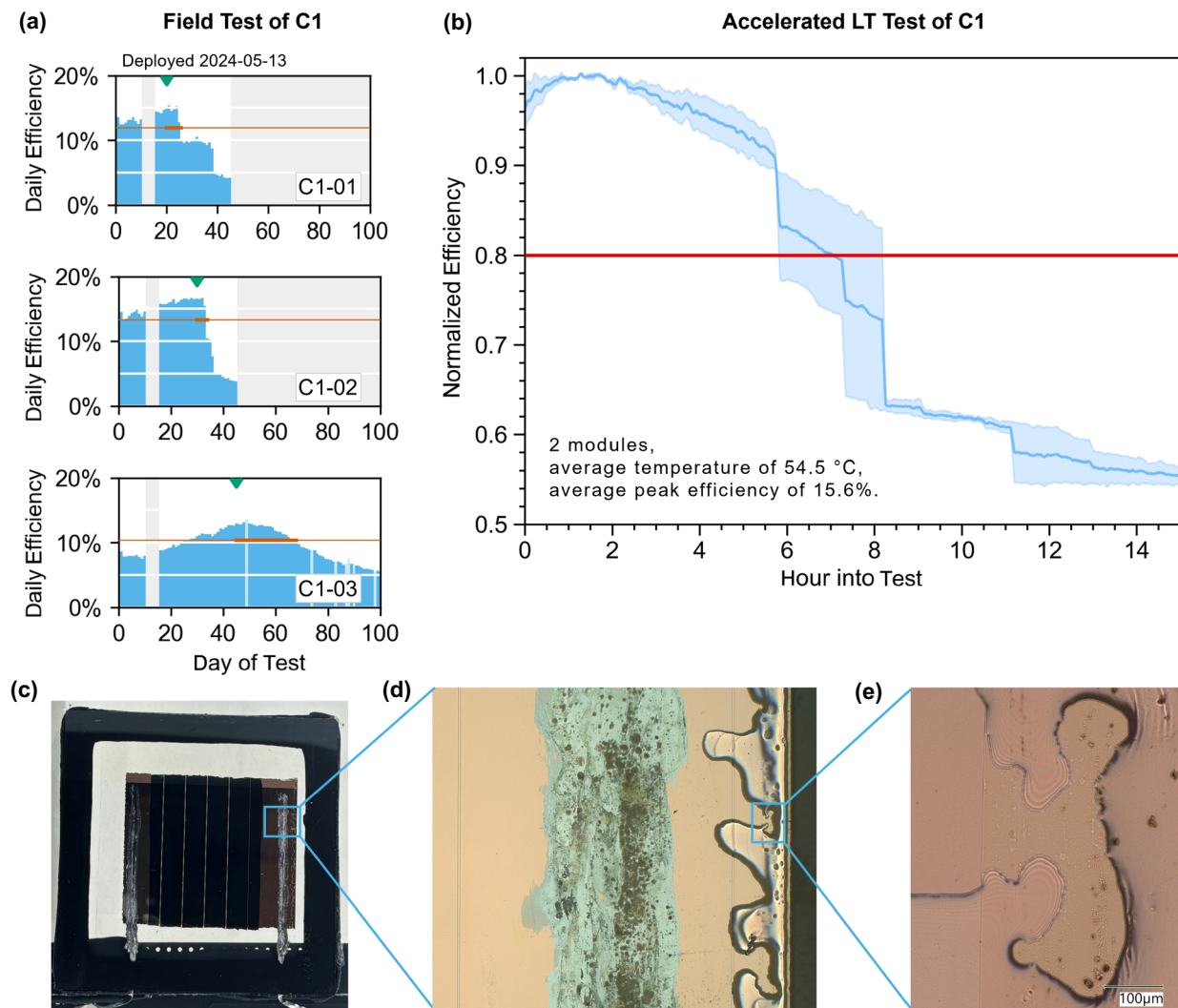


FIG. 3. Stress testing of batch C1 (deployed 2024-05-13). (a) Daily efficiency versus test day for field-tested modules. Horizontal red lines indicate 80% of the peak efficiency, and green arrows point to the 5-day period that contains the peak efficiency. Thicker horizontal lines show the time between the day the efficiency reaches the peak efficiency and the day it drops below 80% of the peak efficiency. (b) Efficiency versus time in LT-55 testing, showing the minimum, average, and maximum efficiency normalized by the peak efficiency. Images of a C1 module taken with (c) a camera and (d),(e) an optical microscope with progressive magnification, showing evidence of encapsulant delamination.

modules were encapsulated with poly(ethylene-*co*-vinyl) acetate (EVA) with a desiccated PIB edge seal, which was relatively impermeable to moisture ingress; thus, they passed the package test as defined. However, patterns of delamination are visible in the modules after encapsulation [Figs. 3(c)–3(e)]. The delamination features indicate that mechanical stress is high during encapsulation and likely causes delamination between the cell layers, as interfaces of MHP cells are known to have very low fracture energies [14,32,33]. The varying mechanical properties of encapsulant can result in higher or lower stresses on MHP films [13,16]. A high mechanical stress in C1 modules likely explains the low durability seen in the field [Fig. 3(a)] and in LT-55 [Fig. 3(b)], as well as the large variation in

initial efficiencies (Fig. S3 within the Supplemental Material [36]). While further investigation is required to identify the various degradation mechanisms arising from internal mechanical stresses in batch C1, it can be concluded that the LT-55 test successfully screens for a batch that fails prematurely in field testing.

B. Batches that passed the 10-week field test

Next, we present the results of modules that passed 10 weeks of field testing. Figure 4 shows the efficiency during LT-55 and outdoor testing for two batches [C2, Figs. 4(a) and 4(b); and D1, Figs. 4(c) and 4(d)] that retained over 80% of peak efficiency after 10 weeks of field testing.

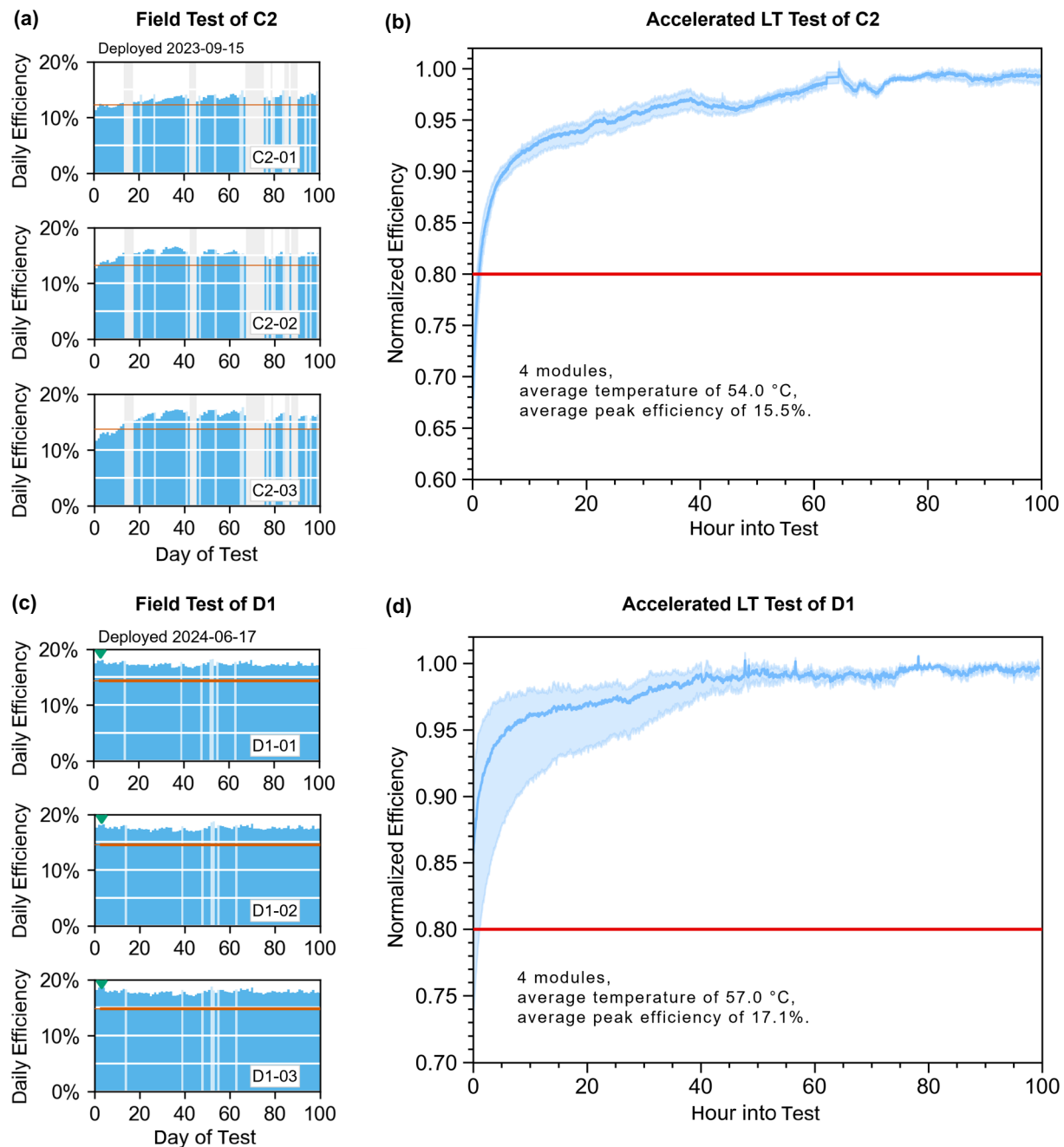


FIG. 4. Stress testing of batches that passed 10 weeks of field testing: batches C2 (deployed 2023-09-15) and D1 (2024-06-17). (a),(c) Daily efficiency versus test day for field-tested modules. Horizontal red lines indicate 80% of the peak efficiency, and green arrows point to the 5-day period that contains the peak efficiency. Thicker horizontal lines show the time between the day the efficiency reaches the peak efficiency and the day it drops below 80% of the peak efficiency. No arrows or thicker lines are shown for C2 because C2 modules reach their peak efficiency after 100 days (Fig. S5 within the Supplemental Material [36]). (b),(d) Efficiency versus time in LT-55 testing, showing the minimum, average, and maximum efficiency normalized by the peak efficiency.

The C2 modules had nominally the same device stack as C1 and used the same packaging type, γ (polymer encapsulant with a PIB edge seal), except the C2 modules were encapsulated with a polyolefin elastomer-based polymer, whereas the C1 modules were encapsulated with an EVA-based polymer. While C1 failed both field and LT-55 tests

(Fig. 3), batch C2 passed both tests (Fig. 4). Moreover, the C2 modules experienced an increase in efficiency during the 70-day field test [Fig. 4(a)] and the 100-h accelerated test [Fig. 4(b)].

The increasing efficiency of the C2 modules during the field and LT-55 tests came primarily from an increasing

fill factor and secondarily from an increasing open-circuit voltage, which was attributed to charge accumulation and passivation effects during light soaking [34]. The three fielded modules in C2 did, however, drop below 80% of their peak efficiency by 318–382 days of fielding (Fig. S5 within the Supplemental Material [36]). More information on the eventual degradation of C2 can be found in Uličná *et al.* [2]. In summary, C2 provides evidence that an MHP module batch that retains more than 80% of its peak efficiency over 100 h under LT-55 is likely to last over 10 weeks outside—but more stringent stress tests are needed for longer-term field evaluation.

Batch D1 also passed both the 10-week field and the 100-h LT-55 tests [Figs. 4(c) and 4(d)]. The fielded modules from D1 achieved a T_{80} of 366–412 days (Fig. S5 within the Supplemental Material [36]). Batch D1 uses the moisture-resistant γ package type (polymer encapsulant and PIB edge seal) but uses a different encapsulant material than the other batches. Another batch from the same manufacturer of D1 with the same packaging as D1 passed the package test with no moisture ingress or visible delamination. Taken together, the results of C1, C2, and D1 emphasize the importance of selecting the correct encapsulant [13].

In summary, two batches passed all stress tests, while four batches failed the field test and partly failed the accelerated test sequence. It should be noted that batches were deployed at different times of the year (Fig. S5 within the Supplemental Material [36]), but batch D1 passed despite being deployed during the hottest period of summer (Table S1 within the Supplemental Material [36]).

C. Considering early field data to predict failure

A useful accelerated test must give information sooner than field testing alone. To confirm that the LT-55 test could screen for field failures more rapidly than early field data, we checked how quickly early field data could predict the outcome of 10 weeks of field testing. The evaluation was based on whether modules dropped below a certain efficiency by a certain day. To make predictions, we chose a number of days of field testing X and a threshold for the normalized efficiency Y ; if the efficiency, η , on day X normalized to the peak efficiency, $\eta(X)/\eta_{\text{peak}}$, drops below threshold Y , then the module is predicted to drop below 80% peak efficiency by 10 weeks. In other words, $(\eta(X)/\eta_{\text{peak}}) \geq Y$ predicts passing and $(\eta(X)/\eta_{\text{peak}}) < Y$ predicts failing before 10 weeks.

The color map in Fig. 5 details the accuracy of these predictions compared to the actual day-70 field results as a function of possible days X and thresholds Y . This is done for the 18 fielded modules in Table I. Data are only calculated for acceptable days (days with plane-of-array solar insolation over 4 kWh/m², no snow on modules or instruments, and no hardware malfunctions). For times when a

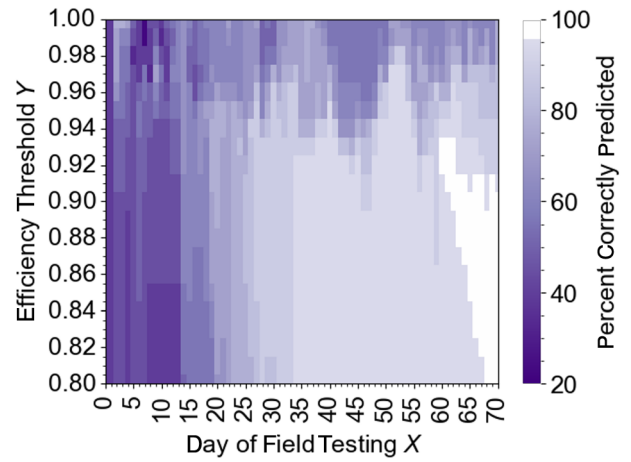


FIG. 5. Accuracy of using early field data to predict whether a module will retain 80% of its peak efficiency through day 70 of field testing. Predictions are based on whether the efficiency on a given day has dropped below a threshold (given as a fraction of the peak efficiency). 100% accurate predictions (in white) are generally only seen after day 60.

module is fielded on an unacceptable day, the prediction is calculated with data from the last acceptable day.

It takes 60 days of field testing to predict the day-70 result for all modules, as indicated by white in Fig. 5 for a range of Y values at day 60 and beyond. Before day 34, the early field data generally leads to multiple inaccurate predictions for these modules. In contrast, the LT-55 test takes only a few days to predict whether a failure will occur before 70 days in the field. For instance, the modules in batch C1 took 27–67 days to reach T_{80} in field testing, but they took less than half a day to reach T_{80} in LT-55 testing.

IV. CONCLUSIONS

The purpose of this work was to develop an accelerated light and elevated temperature stress test that could be completed within 1 week and would inform whether an MHP module would be likely to retain over 80% of peak efficiency during 10 weeks of field operation. While the common LT tests that are currently used for MHPs (such as those outlined by International Summit on Organic Photovoltaic Stability [29]) are useful for comparing changes in device formulations and processes, what they mean for actual field performance is not yet understood.

Six different batches of modules were subjected to parallel LT-55 and field testing to verify the field relevance of the LT-55 test. Of the four batches that had modules that failed within 10 weeks of field deployment, they all either had modules that failed a 100-h light and elevated temperature test at 55 °C (batches B1 and C1) or they were shown not to have a moisture-proof package (batches A1 and A2). Of the two batches that had all modules pass the 10-week field test (batches C2 and D1), all of their modules passed

the 100-h LT-55 test and had a moisture-proof package. In conclusion, we determined that modules that could mitigate moisture ingress during sequential damp-heat and thermal-cycling tests, and could retain over 80% of their peak efficiency after 100 h of LT testing at 1 sun and 55 °C, would be much more likely to retain over 80% of their peak efficiency after 10 weeks of field exposure. This work is an important step towards developing a validated test protocol that can be incorporated into a qualification test standard, which does not yet exist for MHP PV products.

It should be noted that the test protocol introduced here (Fig. 1) is not a certification standard. The accelerated tests considered here (100 h of LT-55, 48 h of damp heat, and 50 thermal cycles) are considered to screen for only 10 weeks of fielding. While 10 weeks is decidedly a useful benchmark for the current readiness level of this technology, it will be necessary to develop tests that could provide confidence in module operation of >1 and >5 years. While not yet determined, it could be expected that fielded MHP modules at larger sizes in some locations could have operating temperatures of 75 °C or more. Such higher temperatures must be accounted for in LT testing in any qualification tests. Another variable to consider in future testing is whether the continuous light used in the presented LT test creates distinct degradation modes compared to the light cycling that occurs outdoors, or if it only changes the degradation rate [35]. Understanding is needed on whether UV should be included in combination with LT testing, or if there are separate degradation mechanisms that should be examined separately or sequentially. Ultimately, we anticipate that qualification tests that can provide confidence for longer lifetimes will, at a minimum, require increased temperatures and longer durations, and may also require additional stress conditions to be applied in sequence or combination to tease out unique synergies.

The tests in Fig. 1 do not reproduce all degradation modes that could occur outside. UV light as well as hail damage, wind load, and other external mechanical forces were not considered. Commercial PV modules are expected to need to pass the IEC qualification tests, which include such stressors as well as others. Finally, new degradation modes and temperature onsets can change with perovskite composition, transport layer materials, and scribe designs, so the relevance of accelerated testing protocols to field testing should continue to be assessed as MHP module technology changes.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain commercially sensitive information. The data are available from the authors upon reasonable request.

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- [1] S. Khatoon, S. Kumar Yadav, V. Chakravorty, J. Singh, R. Bahadur Singh, M. S. Hasnain, and S. M. M. Hasnain, Perovskite solar cell's efficiency, stability and scalability: A review, *Mater. Sci. Energy Technol.* **6**, 437 (2023).
 - [2] S. Uličná, Jackson W. Schall, Steven C. Hayden, Nicholas P. Irvin, Timothy J. Silverman, Chengbin Fei, Xiaoqiang Shi, Rachael L. Arnold, Byron McDanold, Joshua Parker, *et al.*, Field-relevant degradation mechanisms in metal halide perovskite modules, *Adv. Energy Mater.* **15**, 2404518 (2025).
 - [3] H. Tang, Z. Shen, Y. Shen, G. Yan, Y. Wang, Q. Han, and L. Han, Reinforcing self-assembly of hole transport molecules for stable inverted perovskite solar cells, *Science* **383**, 1236 (2024).
 - [4] A. E. Louks, R. Tirawat, M. Yang, S. N. Habisreutinger, S. P. Harvey, K. Schutt, K. Zhu, J. J. Berry, and A. F. Palmstrom, Improving stability of triple-cation perovskite solar cells under high-temperature operation, *Sol. RRL* **7**, 2300248 (2023).
 - [5] Z. Dai, S. K. Yadavalli, M. Chen, A. Abbaspourtami-jani, Y. Qi, and N. P. Padture, Interfacial toughening with self-assembled monolayers enhances perovskite solar cell reliability, *Science* **372**, 618 (2021).
 - [6] C. Jiang, J. Zhou, H. Li, L. Tan, M. Li, W. Tress, L. Ding, M. Grätzel, and C. Yi, Double layer composite electrode strategy for efficient perovskite solar cells with excellent reverse-bias stability, *Nano-Micro Lett.* **15**, 12 (2022).
 - [7] A. Liu, X. Li, W. Zhang, H. Yang, X. Guo, C. Lu, H. Yuan, W. Ou-Yang, and J. Fang, Ag electrode anticorrosion

- in inverted perovskite solar cells, *Adv. Funct. Mater.* **34**, 2307310 (2024).
- [8] Chengbin Fei, *et al.*, Strong-bonding hole-transport layers reduce ultraviolet degradation of perovskite solar cells, *Science* **384**, 1126 (2024).
- [9] Yuanhang Yang, Siyang Cheng, Xueliang Zhu, Sheng Li, Zhuo Zheng, Kai Zhao, Liwei Ji, Ruiming Li, Yong Liu, Chang Liu, Qianqian Lin, Ning Yan, and Zhiping Wang, Inverted perovskite solar cells with over 2000 h operational stability at 85 °C using fixed charge passivation, *Nat. Energy* **9**, 37 (2024).
- [10] J. Dagar, G. Paramasivam, C. Klimm, M. Fenske, C. Schultz, R. Schlattmann, B. Stegemann, and E. Unger, Stability assessment of *p-i-n* perovskite photovoltaic mini-modules utilizing different top metal electrodes, *Micromachines* **12**, 4 (2021).
- [11] N. Rolston, K. A. Bush, A. D. Printz, A. Gold-Parker, Y. Ding, M. F. Toney, M. D. McGehee, and R. H. Dauskardt, Engineering stress in perovskite solar cells to improve stability, *Adv. Energy Mater.* **8**, 1802139 (2018).
- [12] Jing Zhou, Zonghao Liu, Peng Yu, Guoqing Tong, Ruijun Chen, Luis K. Ono, Rui Chen, Haixin Wang, Fumeng Ren, Sanwan Liu, *et al.*, Modulation of perovskite degradation with multiple-barrier for light-heat stable perovskite solar cells, *Nat. Commun.* **14**, 1 (2023).
- [13] H. Jiao, M. Hegde, N. Li, M. Owen-Bellini, L. Schelhas, T. J. Dingemans, and J. Huang, Metal halide perovskite solar module encapsulation using polyolefin elastomers: The role of morphology in preventing delamination, *PRX Energy* **3**, 023013 (2024).
- [14] R. Cheacharoen, N. Rolston, D. Harwood, K. A. Bush, R. H. Dauskardt, and M. D. McGehee, Design and understanding of encapsulated perovskite solar cells to withstand temperature cycling, *Energy Environ. Sci.* **11**, 144 (2018).
- [15] Yanyan Gao, Chong Liu, Mingzhu He, Cuiling Zhang, Liang Liu, Qinrong Luo, Yanghong Wu, Haoyang Zhang, Xuqi Zhong, Rilang Guo, Yi Xie, *et al.*, Efficient and stable perovskite solar modules enabled by inhibited escape of volatile species, *Adv. Mater.* **36**, e2309310 (2024).
- [16] F. Toniolo, Helen Bristow, Maxime Babics, Livia M. D. Loiola, Jiang Liu, Ahmed Ali Said, Lujia Xu, Erkan Aydin, Thomas G. Allen, Moreno Meneghetti, *et al.*, Efficient and reliable encapsulation for perovskite/silicon tandem solar modules, *Nanoscale* **15**, 16984 (2023).
- [17] Lei Shi, Trevor L. Young, Jincheol Kim, Yun Sheng, Lei Wang, Yifeng Chen, Zhiqiang Feng, Mark J. Keevers, Xiaojing Hao, Pierre J. Verlinden, Martin A. Green, and Anita W. Y. Ho-Baillie, Accelerated lifetime testing of organic–inorganic perovskite solar cells encapsulated by polyisobutylene, *ACS Appl. Mater. Interfaces* **9**, 25073 (2017).
- [18] T. J. Silverman, M. G. Deceglie, I. Repins, M. Owen-Bellini, J. J. Berry, J. S. Stein, and L. T. Schelhas, Durability research is pivotal for perovskite photovoltaics, *Nat. Energy* **10**, 934 (2025).
- [19] IEC 61215-1:2021 | International Electrotechnical Commission (IEC). <https://webstore.iec.ch/en/publication/61345>
- [20] J. Wohlgemuth, IEC 61215: What It Is and Isn't. PV Module Reliability Workshop, (2012), <https://digital.library.unt.edu/ark:/67531/metadc839790/>.
- [21] J. H. Wohlgemuth, *Photovoltaic Module Reliability*, 1st ed. (Wiley, Hoboken, NJ, USA, 2020).
- [22] P. V. Kamat, “Highly efficient and stable” perovskite solar cells: Hype versus reality, *ACS Energy Lett.* **10**, 896 (2025).
- [23] B. Chen, J. Song, X. Dai, Y. Liu, P. N. Rudd, X. Hong, and J. Huang, Synergistic effect of elevated device temperature and excess charge carriers on the rapid light-induced degradation of perovskite solar cells, *Adv. Mater.* **31**, 1902413 (2019).
- [24] Y. Lin, Bo Chen, Yanjun Fang, Jingjing Zhao, Chunxiong Bao, Zhenhua Yu, Yehao Deng, Peter N. Rudd, Yanfa Yan, Yongbo Yuan, *et al.*, Excess charge-carrier induced instability of hybrid perovskites, *Nat. Commun.* **9**, 4981 (2018).
- [25] S. P. Dunfield, L. Bliss, F. Zhang, J. M. Luther, K. Zhu, M. F. A. M. van Hest, M. O. Reese, and J. J. Berry, From defects to degradation: A mechanistic understanding of degradation in perovskite solar cell devices and modules, *Adv. Energy Mater.* **10**, 1904054 (2020).
- [26] S. Baumann, Giles E. Eperon, Alessandro Virtuani, Quentin Jeangros, Dana B. Kern, Dounya Barrit, Jackson Schall, Wanyi Nie, Gernot Oreski, Mark Khenkin, *et al.*, Stability and reliability of perovskite containing solar cells and modules: Degradation mechanisms and mitigation strategies, *Energy Environ. Sci.* **17**, 7566 (2024).
- [27] Q. Jiang, R. Tirawat, R. A. Kerner, E. A. Gaulding, Y. Xian, X. Wang, J. M. Newkirk, Y. Yan, J. J. Berry, and K. Zhu, Towards linking lab and field lifetimes of perovskite solar cells, *Nature* **623**, 313 (2023).
- [28] X. Zhao, T. Liu, Q. C. Burlingame, T. Liu, R. Holley, G. Cheng, N. Yao, F. Gao, and Y.-L. Loo, Accelerated aging of all-inorganic, interface-stabilized perovskite solar cells, *Science* **377**, 307 (2022).
- [29] M. V. Khenkin, *et al.*, Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures, *Nat. Energy* **5**, 35 (2020).
- [30] Results and Data, <https://pvpact.sandia.gov/results-and-data/>
- [31] IEC TS 63209-1:2021, International Electrotechnical Commission (IEC) <https://webstore.iec.ch/en/publication/63120>
- [32] M. Casareto and N. Rolston, Designing metal halide perovskite solar modules for thermomechanical reliability, *Commun. Mater.* **5**, 1 (2024).
- [33] M. De Bastiani, *et al.*, Mechanical reliability of fullerene/tin oxide interfaces in monolithic perovskite/silicon tandem cells, *ACS Energy Lett.* **7**, 827 (2022).
- [34] L. Lin, L. Yang, G. Du, X. Li, Y. Li, J. Deng, K. Wei, and J. Zhang, Light soaking effects in perovskite solar cells: Mechanism, impacts, and elimination, *ACS Appl. Energy Mater.* **6**, 10303 (2023).
- [35] Mark Khenkin, Hans Köbler, Marko Remec, Rajarshi Roy, Ulas Erdil, Jinzhao Li, Nga Phung, Ghefar Adwan, Gopinath Paramasivam, Quiterie Emery, *et al.*, Light cycling as a key to understanding the outdoor behaviour of perovskite solar cells, *Energy Environ. Sci.* **17**, 602 (2024).

- [36] See the Supplemental Material at <http://link.aps.org/supplemental/10.1103/g39z-lscx> for a photograph of the outdoor test rack, the light spectrum of the LT test chamber, initial electrical measurements of tested modules, full individual efficiency curves of LT and field tests, and the test results for batch B1. It includes Refs. [37–39].
- [37] N. P. Irvin, D. Martínez Escobar, A. Wheeler, T. Leijtens, H. Lee, A. Santala, R. R. King, C. B. Honsberg, and S. R. Kurtz, in *2022 IEEE 49th Photovoltaics Specialists Conference (PVSC)* (2022), pp. 1059–1059.
- [38] N. P. Irvin, D. M. Escobar, A. Wheeler, R. R. King, C. B. Honsberg, and S. R. Kurtz, Thermal impact of rear insulation, light trapping, and parasitic absorption in solar modules, *IEEE J. Photovoltaics* **12**, 1043 (2022).
- [39] M. Mittag, A. Pfreundt, and J. Shahid, in *30th PV Solar Energy Conference* (Jeju, South Korea, 2020).