Final Report: R&D to Ensure a Scientific Basis for Qualification Tests and Standards

Ingrid Repins and Steve Johnston

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Technical Report
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Executive Summary:

Project return on investment in a photovoltaic (PV) system depends increasingly on maintaining high energy yields, and the system lifetime is a major factor in levelized cost of electricity (LCOE). Thus, the rate of PV deployment and the success of these assets depends upon reliable long-term power generation.

The overarching objective of this program is to improve photovoltaic (PV) module reliability via development of tests and standards. Where reliability problems or risk are discovered, we can design tests to ensure that these liabilities don't affect future generations of products. Customers can use these tests to understand which products are susceptible to certain degradation mechanisms, and manufacturers can use the tests to design unwanted characteristics out of their products.

The work under this program identifies PV reliability needs, performs characterization that provides scientific understanding of targeted degradation mechanisms, and translates those data into practical and predictive test protocols and standards. Major accomplishments include:

- A model for polarization-type potential induced degradation (PID-p) was developed and validated against experimental data. NREL is currently leading a new edition of IEC 62804-1 for PID detection. PID-p can cause large losses in current and voltage for some module designs on cloudy days.
- Finite element modeling (FEM) and experiment was used to determine when cells crack in a module. It was shown that cells in landscape orientation are much more likely to crack than those on portrait orientation. Shortly thereafter, the first products with portrait-oriented cells were introduced.
- Studies of how to test for light and elevated temperature degradation (LeTID) culminated with the publication of IEC TS 63342. Software to predict the progression of LeTID was developed, validated, and made publicly available.
- Field validated tests and international standards for durability of PV module coatings abrasion, backsheets, and encapsulants were developed. Examples are IEC 62788-1-1, IEC 62788-2 ED2, IEC TS 62788-7-2, IEC 62788-7-3 ED1, IEC 63209-2.
- NREL led the development a high-temperature testing technical specification, and published guidelines that enable installers to determine whether higher-temperature testing is needed, simply based on location and mounting configuration.
- In a number of our case studies, variations in the bills of materials or workmanship have been associated with variations in reliability. These observations emphasize the importance of quality assurance to reliability.
- A framework for criticality (i.e. Pareto) analysis was developed and published. The framework helps us and other researchers determine what problems should be addressed for reliability research to have the biggest industry impact.
- NREL continues to participate actively in international standards development and stakeholder engagement activities, including organizing an annual PV Reliability Workshop. These activities are important for ensuring we address issues that are relevant and timely, and that we convey our results to those who may benefit.

Hyperlinks in the above text will take you to some of the products related to these main accomplishments. A full list of products with links can be found in Tables 4 through 9.

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Background

Project return on investment in a photovoltaic (PV) system depends increasingly on maintaining high energy yields,[1] and the system lifetime is a major factor in levelized cost of electricity (LCOE).[2] Thus, the rate of PV deployment and the success of these assets depends upon reliable long-term power generation. While most PV systems perform as expected,[3] a small fraction of systems (<10%) of systems underperform. It is important to detect product designs likely to underperform before these products hit the market. Such identification – via standardized testing - reduces investor risk, ensures reliable products to consumers, and avoids market spoiling.

This program advances PV module reliability and extends useful life of commercial products through identification of reliability needs, characterization that provides scientific understanding of targeted degradation mechanisms, and translation of those data into practical and predictive test protocols and standards.

Introduction

The overarching objective of this program is to improve photovoltaic (PV) module reliability via development of tests and standards. Where reliability problems or risk are discovered, we can design tests to ensure that these liabilities don't affect future generations of products. Customers can use these tests to understand which products are susceptible to certain degradation mechanisms, and manufacturers can use the tests to design unwanted characteristics out of their products.

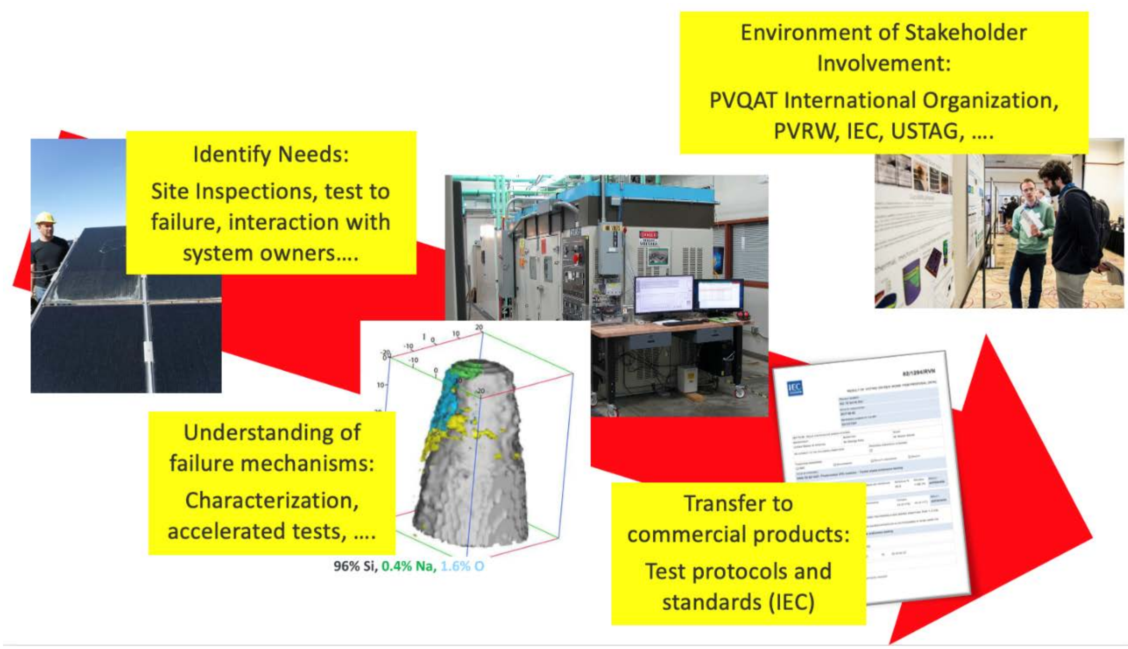

Figure 1: Schematic representation of the flow of research under this program.

The general path of research under this program is shown schematically by the red arrow in Figure 1. The first step is the identification of reliability needs, which NREL performs via site inspections, test to failure (for products with short fielded history), and interaction with system owners and other stakeholders. The next step is understanding how the degradation progresses. This step involves extensive characterization and accelerated testing, so that all the important factors in the degradation are identified, a physical model can be developed, and thus an acceleration factor to relate test and fielded behaviors can be derived. 30% of the resources in this program have been dedicated to characterization, to ensure robust interpretation of physical mechanisms. The final step is to transfer findings to commercial products via test protocols, the most mature of which may be included in international standards. The entire process is performed in an environment of stakeholder involvement (upper right in Figure 1), which includes a yearly PV Reliability Workshop (PVRW), continued leadership in the International PV Quality Assurance Task Force (PVQAT, www.pvqat.org), participation in standards organizations such as the International Electrotechnical Commission (IEC) and the U.S. Technical Advisory Committee (USTAG), and dissemination of results via publications and presentations. While Figure 1 shows each step being performed in succession (as for a single degradation mechanism), several degradation mechanisms are studied under this program. Thus, each type of activity exists concurrently in our research.

Four tasks are carried out to accomplish the goals and process introduced above:

Task 1: Targeted Degradation Modes in Commercial Modules
In task 1, we study and develop predictive tests for several prominent degradation modes in commercial modules. We choose degradation mechanisms for study that may impact a large fraction of future products, cause significant power loss, and are not yet adequately quantified by existing tests, and fit well with capabilities at NREL.

Task 2: Case Studies and Pareto Analysis
In task 2, we use a variety of techniques to identify reliability needs and assess their relative importance and frequency.

First, we study fielded modules. Such studies have been a cornerstone of NREL's reliability program for years. They provide guidance on most frequent module failure types, and allow development of site inspection protocols.[4] More recently, the emphasis of NREL's site inspections has shifted from detecting the most apparent problems to understanding those with the largest impact on energy generation, where the root cause is often elusive. NREL brings a suite of advanced characterization techniques[5] to bear on root cause identification and understanding of how degradation will progress in accelerated test or fielded conditions. As part of such efforts, NREL collects modules from underperforming systems.

We also coordinate with system owner partners to identify underperforming systems. This includes leveraging the Fleets dataset to identify systems in the tail of high degradation. We review owner measurements and may collect additional field data if gaps are identified. Modules are harvested from the field and system spares and brought to NREL for detailed characterization and failure analysis, including luminescence and thermal imaging, IV characterization, exploratory accelerated testing, and coring for electron microscopy.

NREL has also performed Pareto analysis under task 2. The goal of the Pareto (or "criticality") analysis is to ensure that we are working on the most important research problems.

Task 3: Industry Impact and Stakeholder Involvement

A key aspect of NREL's reliability core program is maximizing the benefit to the industry. This maximization is performed via several activities. First, NREL performs direct work on standards, which reduce risk, and thereby cost, to the PV customer and investor. These efforts include both development of individual standards resulting from the technical studies in this program, and support of the IEC TC 82 secretary and USTAG leadership. Second, NREL continues to engage PV stakeholders across the value chain in standards development via the international PVQAT. Since co-founding PVQAT with METI (Japan) in 2010, NREL continues to lead several PVQAT technical task groups, act on the PVQAT steering committee, and host the PVQAT website. Third, NREL promotes stakeholder engagement via the yearly PVRW. Finally, publications and presentations are used to disseminate information, solicit collaboration, and help build the documented scientific basis for reliability test protocols.

Task 4: NREL Module Measurement Throughput

Flash testing is a key ingredient in assessing degradation in both fielded and stress-tested modules. The reliability core program has benefited from the support of NREL's Cell and Module Performance (CMP) group. However, our demands on the CMP group have increased by nearly a factor of two over the FY20 to FY21 period. This increase occurred due to an increased emphasis on field validation, a larger number of samples used in accelerated testing, and the increasingly recognized role of reliability in LCOE. This increase in demand overloaded the CMP group. Task 4 is a year 1-only effort to improve reliability group throughput and accuracy for current-voltage measurements. The improvement enables the reliability group to perform more of its own measurements and leave the CMP group available for other work.

Program Milestones

Program milestones are shown in Table 1. The milestone number is in the format (# year).(#task).(# count per task).

Table 1: Program milestones, in chronological order.

Status	Milestone Type and Number	Milestone or Requirement Description	Completion Date
Complete	Quarterly 1.4.1	For five modules, output power measurements match within 3% measured in the cell and module performance (CMP) flash tester, reliability group Spire 4600, and reliability group Sinton tester at STC.	12/31/2021
Evaluation and Comments: Five modules (n = 1 through 5), met the prescribed conditions on measured power: $0.03 \geq \lvert P_{n,Sinton} - P_{n,CMP}\rvert / P_{n,CMP}$; $0.03 \geq \lvert P_{n,Spire\ 4600} - P_{n,CMP}\rvert / P_{n,CMP}$. This capability supports our infrastructure by enabling the reliability group to perform many of our module measurements, freeing up time for other work in the CMP group.			
Complete	Reporting	Quarterly Review Call	1/26/2022
Complete	Reporting	Quarterly RPPR-2 form	1/15/2022
Complete	Reporting	Peer Review Meeting Participation	2/2/2022
Complete	Quarterly 1.3.1	Stakeholder engagement: NREL will host the PV Module Reliability Workshop, with more than 100 attendees.	3/31/2022
Complete	Quarterly 1.2.1	Present a detailed framework for the Pareto analysis that answers the question of what are the most important PV reliability research problems to work on.	3/31/2022
Evaluation and Comments: A Pareto analysis was requested by SETO, and can both help the industry identify the most important problems and allow prioritization of our own studies. The framework was developed and used in planning research. Four papers and external presentations on this subject were completed.			
Complete	Reporting	Quarterly review call	4/26/2022
Complete	Reporting	Quarterly RPPR-2 form	4/15/2022
Complete	Reporting	RPPR-1 written report	7/15/2022
Complete	Reporting	Quarterly Review call	7/2022
Complete	Reporting	Quarterly RPPR-2 form	7/15/2022
Complete	Annual 1.2.2	• NREL leads or is on the project team for at least one standard published in FY 22, • analysis of at least two degradation mechanisms is reported in terms of prevalence and effects on energy yield or cost, • at least two peer-reviewed papers are published.	9/30/2022
Evaluation and Comments: • 10 standards were published. In Table 6, see S1-S3, and S4-S10. • Seven peer reviewed journal papers were published. In Table 4, see P2, P6, P13, P15, P18, P24, P30. • Quantitative analysis of degradation mechanism prevalence and cost was reported for backsheet cracking and LeTID. The Pareto framework was presented at the PVRW (C59) to solicit stakeholder feedback.			

Complete	Reporting	Quarterly review call	10/25/2022
Complete	Reporting	Quarterly RPPR-2 form	10/15/2022
Complete	Quarterly 2.2.1	Publish a paper in which microscopy is used to determine degradation root cause and show the impact and utility to the project and/or stakeholders.	12/31/2022
Evaluation and Comments: See P6, P11, and P13.			
Complete	Quarterly 2.1.1	Accelerated test data fit a physical model for at least one degradation mechanism, with correlation coefficient $R^2 > 0.7$.	12/31/2022
Evaluation and Comments: A model for polarization-type potential induced degradation (PID-p) was developed. The model describes charge collection and dissipation under various conditions and the resulting impact on performance. The model was presented in P7. The model was compared against experimental data from Yamaguchi,[6] and $R^2 = 0.996$ resulted.			
Complete	Reporting	RPPR-1 written report	1/15/2023
Complete	Reporting	Quarterly Review call	1/30/2023
Complete	Reporting	Quarterly RPPR-2 form	1/15/2023
Complete	Quarterly 2.3.1	NREL hosts the Photovoltaic Reliability Workshop (PVRW)	3/31/2023
Complete	Reporting	Quarterly review call	4/26/2023
Complete	Reporting	Quarterly RPPR-2 form	4/15/2023
Complete	Quarterly 2.2.2	Publish a paper in which imaging is used to evaluate the reliability of a new product.	6/30/2023
Evaluation and Comments: See C33 and C34 about evaluations of new emitter wrap-through modules. C33 was given "Best Poster" award by the IEEE.			
Complete	Quarterly 2.3.2	Conduct month 18 review in conjunction with Duramat IAB board and stakeholder invitees. Solicit their feedback on project goals and tasks.	6/30/2023
Complete	Reporting	RPPR-1 written report	7/15/2023
Complete	Reporting	Quarterly RPPR-2 form	7/15/2023
Complete	Reporting	Quarterly Review call	7/28//2023
Complete	Annual 2.2.3	• NREL is on the project team for at least one standard published in FY23. • Analysis of at least two more degradation mechanisms (e.g. LeTID, PID-p, etc.) is reported in terms of prevalence and effects on energy yield or cost. • At least two peer-reviewed papers are published.	9/30/2023
Evaluation and Comments: • 5 standards were published. In Table 6, see S14, and S16-S18. • Ten peer reviewed journal papers were published. In Table 4, see P3, P4, P11, P14, P16, P22, P23, P26, P28, P29.			

• Quantitative analysis of degradation mechanism prevalence and cost was reported for AR coating degradation and BO LID. Results were presented in quarterly reports and conferences. (See C56 and C62.)			
Complete	Reporting	Quarterly RPPR-2 form	10/15/2023
Complete	Reporting	Quarterly review call	10/16/2023
Complete	Quarterly 3.1.1	Predictive test protocol reproduces fielded behavior.	12/31/2023
Evaluation and Comments: Development of proven, science-based tests leads to more effective international standards, longer product lifetime, lower perceived risk, and lower LCOE. In this fiscal year, a test protocol for PID-p was developed and demonstrated. The test protocol is consistent with fielded behavior and prior modeling. This FY the test protocol is described in a publication (P10) and work started to incorporate it into a standard.			
Complete	Reporting	RPPR-1 written report	1/15/2024
Complete	Reporting	Quarterly RPPR-2 form	1/15/2024
Complete	Reporting	Quarterly Review call	1/29/2024
Complete	Quarterly 3.3.1	Stakeholder engagement: NREL will host the PV Reliability Workshop (PVRW), with more than 100 attendees.	2/29/2024
Complete	Reporting	Participate in peer review meeting	3/26/2024
Complete	Reporting	Quarterly RPPR-2 form	4/15/2024
Complete	Reporting	Quarterly review call	4/15/2024
Complete	Quarterly 3.1.2	Test protocol developed under this program is ready to enter the standards process or be offered as a commercial service at a test lab	6/30/2024
Evaluation and Comments: The test protocol for PID-p developed under this program is at the draft technical specification (DTS) stage. Publication in FY25 is anticipated.			
Complete	Reporting	RPPR-1 written report	7/15/2024
Complete	Reporting	Quarterly RPPR-2 form	7/15/2024
Complete	Reporting	Quarterly Review call	7/15/2024
Complete	Annual 3.2.1	• NREL is on the project team for at least one standard published in FY 24, • a report or presentation on multi-input Pareto analysis is given, and • at least two peer-reviewed papers are published.	9/30/2024
Evaluation and Comments: • 1 standard was published. In Table 6, see S22-S25. • Ten peer reviewed journal papers were published. In Table 4, see P1, P5, P8, P9, P10, P12, P17, P19, P25, P27. • A summary of findings related to Pareto analysis was presented in reviews and also in IEEE Journal of Photovoltaics. (See P25.)			
Complete	Reporting	Quarterly review call	10/28/2024
Complete	Reporting	Quarterly RPPR-2 form	10/15/2024
Complete	Reporting	Project final report	12/10/2024

Project Results and Discussion:

Results on Task 1: Targeted Degradation Modes in Commercial Modules

In task 1, we have studied and developed predictive tests for several important degradation modes in commercial modules.[P14,P15] Investigations of specific degradation modes are described further in the paragraphs below.

Prior to this program, light and elevated temperature induced degradation (LETID) received a great deal of attention,[7] as degradation greater than 10% was observed in some cases.[8–10] Fielded degradation was seen to occur over months in the field, with regeneration happening only over the course of decades.[11,12] Degradation has been associated with excess H in the Si.[13]

During this program period, we wrapped up studies of how to test for LeTID. This activity culminated with the publication of IEC TS 63342, "LeTID tests for c-Si PV Modules".[S8] In order to develop and gain consensus on the test method, NREL led an international round robin experiment.P16 NREL also performed measurements[P13] and calculations[P18] to understand the behavior of LeTID-susceptible modules in tests and outdoors.[P26] Software to predict the progression of LeTID as a function of climate and test conditions was created and made publicly available.[SW2] An example of the output of this software is shown in Figure 2.

An understanding of the impact of LeTID on system performance and an accelerated test to quantify LeTID susceptibility provide motivation and a feedback mechanism to mitigate LeTID in new module designs. Recent reports show a greatly reduced susceptibility to LeTID in modern products. Approximately 90% of products that undergo quality programs at certified test labs have less than 1% LeTID.[14,15]

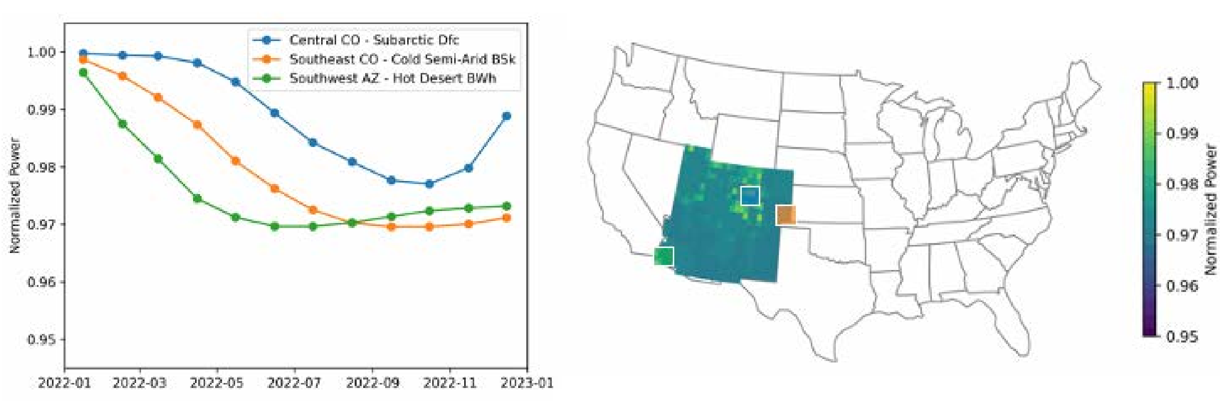

Figure 2: Geospatial modeling (utilizing PVDeg developed under the DuraMat program) showing how LeTID will progress differently even withing different climates within the southwest United States. LeTID algorithms developed as part of the reliability core were integrated into the PVDeg suite from DuraMat.

PID-p can cause large losses in current and voltage for some module designs on cloudy days. Power losses exceeding 30% have been reported.[16] NREL is developing the science necessary to create a meaningful test for polarization-type potential induced degradation (PID-p).[P23] A model for polarization-type potential induced degradation (PID-p) was developed.[P7] The model describes charge collection and dissipation under various conditions and the resulting impact on performance. The model was consistent with experimental data from Yamaguchi,[6] satisfying milestone 2.1.1. A test protocol for PID-p was then developed and demonstrated. The test protocol was found to be consistent with fielded behavior and prior modeling,[P10] satisfying milestone 3.1.1. NREL is currently leading a new edition of IEC 62804-1 for PID detection,[S15] which will now add the PID-p test protocol to the existing PID-s test. This standards activity satisfies milestone 3.1.2.

The occurrence of cracking cells within an intact module package has raised concerns about the associated performance loss.[P5] While it is agreed that cell cracking eventually causes performance loss, there is no general algorithm for predicting performance loss as a function of module design and exposure conditions. This lack of understanding means system owners and insurers do not know if they should replace modules after a damage event, such as a hailstorm, when the glass is intact but cells are cracked. Large unnecessary expenses may occur.

We set out to develop this general algorithm for the evolution of cracked-cell performance loss. It was found in prior years of this program that the cell fragments within a package make contact with each other in ways that cause electrical resistance to be a function of the module's temperature and bending history. Electrical resistance between pieces gradually degrades. Grid fingers were found to be severed when cell cracking occurs and are not responsible for the gradual degradation of resistance between cell fragments. Thus, mechanism for decreasing electrical contact between cells is not a simple fatigue model for the grid fingers. Rather, it is a complicated wear model between irregularly shaped cell fragments and rough surfaces. While we were able to use finite element modeling to predict some aspects of cell fragment motion,[P29] the complexity of the wear problem precluded deriving a general performance loss prediction.

A more successful approach appears to be finding ways to avoid cell cracking. Finite element modeling (FEM) and experiment was used to determine under what conditions cells will crack. The initial model developed under this program has been validated with full-size modules. FEM indicated that modules with half-cut cells oriented in portrait mode (i.e. the long dimension of the cell aligned with the long dimension of the module) should result in less cell breakage.[P2,P3] Subsequently, a simplified version of the FEM was turned into a user tool "The WhatsCracking" app, developed under the DuraMat program. The app was publicized at a PVRW presentation, and app downloads spiked. A module manufacturer then contacted the lead researcher and mentioned that the company had changed the cell orientation due to these results. The first two products with cells oriented in portrait mode are illustrated in Figure 3. The industry has since made further design changes that minimize cell cracking or associated performance loss, including glass-glass module construction, and more bus bars.

Figure 3: Data sheet covers for the first two products with cells in portrait mode, introduced during this reporting period. The orientation of the cells is highlighted in the upper right magnification.

Most PV modules utilize anti-reflective coatings, yet the durability of these coupons is rarely discussed. Under this program, fielded and laboratory-abraded coating samples were compared[P1] to enable the development of field-relevant abrasion standards.[S3,S24]

Shingled cells have been used a way to decrease dead area between cells or occupied by bus bars, thus increasing module efficiency. Electrically conductive adhesive (ECA) and electrically conductive tape (ECT) may be used between the shingled cells, but have a short history in this application. It is unknown whether some of these materials may experience early failures. Under this program, properties of ECA's and ECT's, as well as techniques to measure them techniques were explored for eventual incorporation into measurement and durability standards.[P9,S22]

The importance of backsheet durability has come to the forefront in recent years, with warranty claims due to cracking in some the polyamide (PA), polyvinylidene fluoride (PVDF), or and polyethylene terephthalate (PET). Earlier work in this program outlined methods for testing backsheets that reproduce the field-observed cracking.[17] With new backsheets being introduced into the market, work under this program continues to understand the origin of backsheet cracking and ways to predict it, for incorporation rigorous and widely-applicable backsheet standards.[P19,P22,P30,S10,S23,S14,S16,S18] Work under this program was instrumental in the development of IEC 62788-2 and IEC TS 62788-2-1 including the incorporation of NREL's "solder bump test" to predict cracking in PV modules.

An international round robin was performed to evaluate how a variety of encapsulants degrade under UV exposure, and how the degradation exposures and measurement can be performed reproducibly.[P24] These learnings feed into standards under development being led by NREL.[S22]

For modules installed in very hot locations, design qualifications at higher test temperatures may be appropriate. NREL led the development a high-temperature testing technical specification[S21] (IEC TS 63126) and published guidelines so that installers can determine, simply based on location and mounting configuration, whether higher-temperature testing is needed.[P17]

Results on Task 2: Case Studies and Pareto Analysis

Under the case studies activity, there are approximately five different degradation modes under investigation. Conducting several examinations in parallel helps expedite work, since work can be performed on one study while another is on hold during length stress exposures or sample shipping.

The groups found examples at multiple sites in multiple products where switching the grid ink composition caused cell series resistance to increase.[P6,P11] An example electroluminescence (EL) image is shown in Figure 4. Samples with the dark “halo” around the bus bars exhibited high series resistance, low performance, and a different grid composition than other cells.

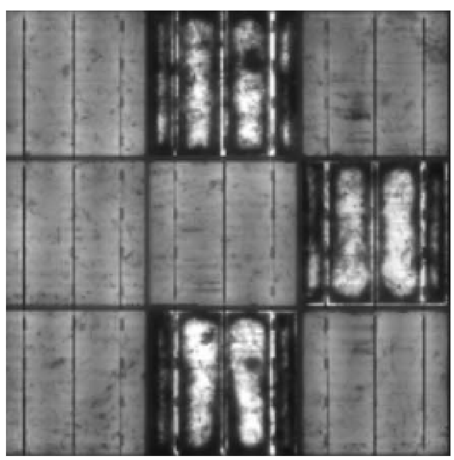

Figure 4: EL image of a fielded module. Degraded cells have a different grid ink composition.

Shaded cells in a module are known to experience reverse bias. Depending on the module design, reverse bias can induce conditions such as elevated temperature, shunt formation, or arcing. The possibility of arcing during shading for some module designs, and how to test for it, was explained.[P27]

In a number of our case studies, variations in the bills of materials over a single product have been associated with variations in reliability.[P4] In addition to the grid ink variations mentioned above, we have seen instances of the same product with backsheets that did or did not crack, and hydrophilic or hydrophobic coatings. NREL has participated in revisions of the IEC re-test guidelines, which help manufacturers and test labs determine what changes to a BOM require repeating which accelerated tests.[S17] We also saw multiple cases of pristine modules that flash tested significantly (e.g. 15% relative) below the nameplate value, and misaligned wires between cells that caused heating. These observations emphasize the importance of quality assurance to reliability.

Broken glass in large modules installed according to manufacturer instructions has been an urgent concern in recent months.[M3] We have identified sites with broken glass, and tools to measure important related quantities in module construction. Such quantities include glass temper, frame clearances, and edge pinch.

A framework for criticality (i.e. Pareto) analysis was developed to determine what problems should be addressed for reliability research to have the biggest industry impact.[P25] The "research opportunity number" is based on a traditional risk priority number,[18] tailored for reliability research. For a given degradation type, factors include the severity (increase in LCOE if the degradation exists), the frequency (fraction of products that could be susceptible, the absence of quantitative tests, and the test duration. Test duration is not included in a traditional risk priority number. It was included in our framework to enable quality assurance testing rather than simply design qualification. In design qualification a small number of modules (e.g. < 20) are tested to ascertain whether the design, used for GW of product, is good. A single test, such as damp heat, may take weeks to complete, and the entire battery of tests may take months. Very short tests, on the other hand, can be used to evaluate whether every product maintains the important characteristics. Such tests could be performed in-line, or by customers, for quality assurance. Our case studies and stakeholder interactions indicated that insufficient quality assurance played a part in multiple cases of underperformance.

Results on Task 3: Industry Impact and Stakeholder Involvement

NREL promotes industry impact and stakeholder involvement in a number of ways. First, NREL performs direct work on standards, which reduce risk, and thereby cost, to the PV customer and investor. These efforts include both development of individual standards resulting from the technical studies in this program, and support of the IEC TC 82 secretary and USTAG leadership. The standards developed under this program are listed in Table 6.

Second NREL maintains an active role in the internation PV Quality Assurance Task Force (PVQAT). PVQAT provides a collaborative setting to develop the science needed for rigorous standards. NREL hosts and updates the PVQAT website (www.PVQAT.org). NREL leads the following active PVQAT task groups: task group 5 on UV weathering; task group 8 on thin films; task group 10 on connectors, cables, and other balance of systems components; and task group 15 on repair, reuse, recertification, and recycling of PV.

Also as a part of task 3, NREL holds an annual Photovoltaic Reliability Workshop (PVRW, https://pvrw.nrel.gov/) to promote stakeholder engagement. The workshop is held at the end of February. It is typically held in Lakewood, Colorado, but in 2022 it was held virtually due to CoVID travel constraints. The PVRW's completion satisfies milestones 1.3.1, 2.3.1, and 3.3.1.

The 2023 PVRW (Figure 5) drew 233 attendees from 14 countries and 98 different organizations. Presentations included 115 posters, and 36 oral presenters. Audience engagement in the presentations was high: There were an average of 20 questions submitted to the on-line Q&A platform per oral presentation. The impact of the workshop was summarized by a presenter who stated, "I buy modules from people in this room. I don't buy modules from people who are not in this room." In 2023, we experimented with open abstract submission, rather than choosing only from program committee recommendations. The process was a success, with 45 early abstracts submitted, a wider representation of industry stakeholders and new voices, and 16 of the early abstracts advanced to the program committee for possible oral presentation. Statistics on attendance and abstracts were similar for the 2024 PVRW. We decided to retain the open abstract submission for following years.

Figure 5: Photos from the 2023 PVRW.

Results on Task 4: NREL Module Measurement Throughput

Task 4 was performed predominantly in the first year of the program, to improve measurements on existing reliability group Spire 4600 (circa 2008) and Sinton Instruments (2020) flash testers. The goal was to improve IV throughput within the reliability group, thus returning CMP workload to a reasonable level.

Milestone 1.4.1, which requires demonstration of accurate measurements on the reliability group simulators, was satisfied on time. The instruments utilized for this task are shown in Figure 6. The data satisfying milestone 1.4.1 are shown in Table 2. Measurements on the "Spire 5600" originate from the CMP group, and the reliability group "Spire 4600" and "Sintonulator" measurements agree with the CMP measurements, within required 3% .

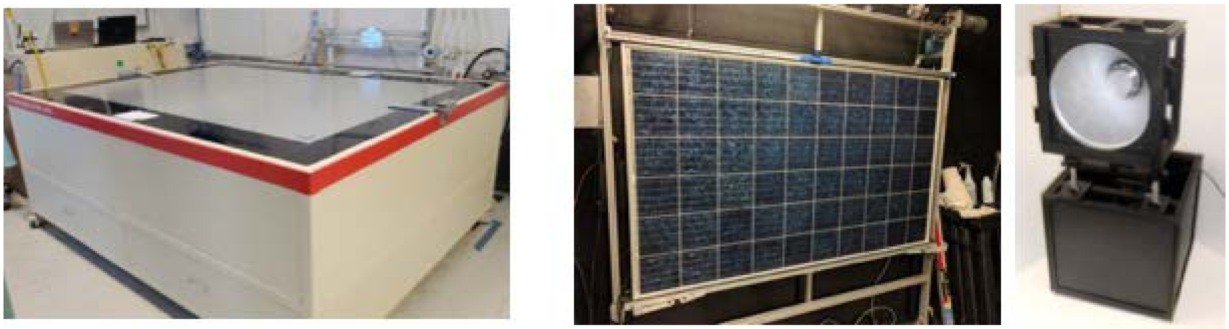

Figure 6: Spire 4600 (left) and “Sintonulator” (right, Sinton Instruments FMT-500) used to meet task 4 milestone.

Table 2: Data satisfying milestone 1.4.1

NREL ID	Description	Pmp (W) SPIRE 5600	**Pmp (W) Sintonulator**	Fraction Difference	% Difference	Calibration module
M2106-0004	1-cell (SBM)	3.233	3.268	0.011	1.068	M2106-0003
M2106-0006	4-cell (SBM)	14.152	14.102	0.004	0.352	M2106-0005
M2106-0014	33-cell (Renogy)	90.12	92.053	0.021	2.145	M2106-0013
M2107-0041	91-cell ("60-cell" SBM)	328.3	327.957	0.001	0.104	M2107-0042
M2107-0046	105-cell ("72-cell" SBM)	377.3	377.416	0.000	0.031	M2107-0045

NREL ID	Description	Pmp (W) SPIRE 5600	**Pmp (W) SPIRE 4600**	Fraction Difference	% Difference	Calibration module
M2106-0002	1-cell (SBM)	3.25	3.281	0.010	0.954	M2106-0001
M2106-0007	4-cell (SBM)	14.147	14.21	0.004	0.445	M2106-0008
M2104-0014	33-cell (Renogy)	90.12	91.58	0.016	1.620	M2104-0013
M2107-0043	91-cell ("60-cell" SBM)	328.3	331	0.008	0.822	M2107-0044
M2107-0048	105-cell ("72-cell" SBM)	378.6	381.6	0.008	0.792	M2107-0047

Two key factors in increasing measurement accuracy were dealing with irradiance nonuniformity and temperature fluctuations. Measurement error due to nonuniform simulator irradiance can be minimized by matching test sample and reference module sizes. Thus, a set of calibrated reference modules were assembled for each simulator. These reference modules span sizes ranging from single-cell mini-modules to 72-cell commercial module sizes. Prior to this program, there was only one reference module for the Spire 4600, and there were no reference modules for the Sintonulator. Implementation of a temperature-correction routine on the Spire 4600, to allow standard temperature coefficients to be utilized to correct for ambient fluctuations, was also important to meeting the accuracy milestone.

The improved capabilities have produced the desired decrease in CMP workload. Table 3 shows the number of measurements made by the CMP group performed in Q3 of FY22 versus a year earlier. There has been a substantial increase in the portion of measurements handled by the reliability group.

Table 3: Number of measurements made by CMP group this quarter versus one year ago.

IV System	Owner	# of IV Curves in Q3 FY21	# of IV Curves in Q3 FY22
SPIRE 5600	CMP	703	251
SOMS	CMP	8	0
LACSS	CMP	142	88
SPIRE 4600	Reliability	1	899
Sintonulator	Reliability	0	200
Total Measurements:		854	1438
CMP Measurements:		**853**	**339**

Conclusions:

- Studies of how to test for light and elevated temperature degradation (LeTID) were completed, culminating with the publication of IEC TS 63342, "LeTID tests for c-Si PV Modules". Software to predict the progression of LeTID was developed, validated, and made publicly available.
- A model for polarization-type potential induced degradation (PID-p) was developed and validated against experimental data. NREL is currently leading a new edition of IEC 62804-1 for PID detection.
- Finite element modeling (FEM) and experiment was used to determine under what conditions cells will crack, and the model was validated with experiments on full-size modules. These results have already shown industry impact through the introduction of products with portrait-oriented half-cut cells.
- Field validated tests and standards for durability of PV module coatings abrasion, backsheets, and encapsulants were developed.
- NREL led the development a high-temperature testing technical specification, and published guidelines that enable installers to determine whether higher-temperature testing is needed, simply based on location and mounting configuration.
- In a number of our case studies, variations in the bills of materials or workmanship have been associated with variations in reliability. These observations emphasize the importance of quality assurance to reliability.
- Broken glass in large modules installed according to manufacturer instructions has been an urgent concern in recent months.
- A framework for criticality (i.e. Pareto) analysis was developed and published. The framework helps researchers determine what problems should be addressed for

reliability research to have the biggest industry impact. We will continue to let these principles guide our choices of the highest-impact activities.

- NREL continues to participate actively in international standards development and stakeholder engagement activities, including organizing an annual PV Reliability Workshop.

All milestones were completed. (See Table 1.)

Budget and Schedule:

Cumulative monthly spending information over the course of the project is shown in Figure 7. The project has proceeded over the planned original period of performance of 36 months. 95.5% of the original $15,000,000 budget has been spent. This budget is comprised entirely of federal share.

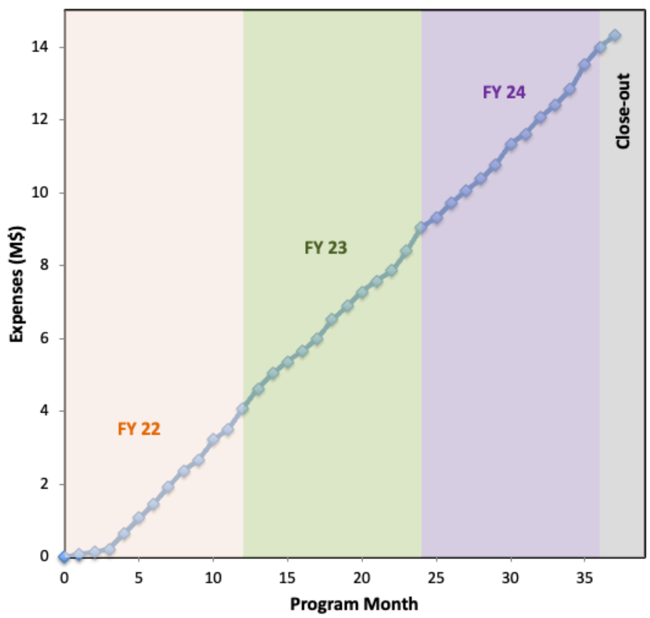

Figure 7: Cumulative monthly spending.

Path Forward:

Our results from this program suggest a path for future research to continue improving PV module reliability.

To identify reliability needs, we should continue our case studies, which have been successful in identifying root causes of failure and the associated reliability needs. As non-module components (e.g. connectors, inverters) figure increasing prominently in system energy loss and maintenance, we should begin to include these components in our analyses.

We should perform experiments to understand the reliability of module types with less deployment history. Commercial products containing newer technology (TopCON, HJT, co-extruded backsheets, etc.) pose a larger risk of failure or degradation due to the short deployment history. Also, new deployment conditions, such as 3,000V systems, may require new test conditions or methods.

Where existing standards are known to be insufficient - for example UV dosage or the mechanical interactions of rack, module, and load – we should provide science-based guidance for testing. We should continue to remain responsive to new and urgent industry needs for tests (e.g. how to predict which modules will experience egregious glass breakage).

As technology evolves, we should use criticality analysis for identifying the most high-impact research opportunities.

We should continue to work with the international community on standards, both in the actual document creation, in collaborative efforts that precede standard creation, and in stakeholder engagement activities such as the yearly PVRW. These activities help ensure we address issues that are relevant and timely, and that we convey our results to those who may benefit.

Publications Resulting from This Work:

This section lists products resulting from work under this program. These products include publications in refereed journals (Table 4), conference papers and presentations (Table 5), standards (Table 6), publicly-available software (Table 7), awards (Table 8), and media mentions(Table 9).

Table 4: Refereed journal articles produced under this program. Articles are listed in alphabetical order by first author. Each entry is followed by a link to the open access version of the article and to the article on the publisher's site. Some articles are collaborations between institutions or programs, as detailed in acknowledgements section of those articles.

Paper	Open Access Link	Journal link
P1. J. Bomber, A. Einhorn, C. Engtrakul, C. Lanaghan, J. Linger, L. Micheli, D.C. Miller, J. Morse, H. Moutinho, M. Muller, J.M. Newkirk, L. Simpson, B. To, S. Toth, T. Curtis, F. Li, G. Tamizhmani, S. Tatapudi, V. Alberts, A. Al Nuaimi, P. Banda, J.J. John, G. Mathiak, A.O.M. Safieh, M. Stefancich, B. Alabdulrazzaq, A. Al-Qattan, S. Bhaduri, A. Kottantharayil, B. Bourne, Z. deFreitas, F. Farina, G. Kimball, A. Hoffman, 'Soiling, Cleaning, and Abrasion: The Results of the 5-Year Photovoltaic Glass Coating Field Study ,' Solar Energy Materials & Solar Cells, 275, 113035; September, 2024.	https://www.osti.gov/biblio/2375836	https://www.sciencedirect.com/science/article/pii/S0927024824003477
P2. N. Bosco, 'Turn Your Half-Cut Cells for a Stronger Module,' IEEE JPV, 12(5), 1149-1153; September, 2022.	https://www.osti.gov/pages/biblio/1884297-turn-your-half-	https://ieeexplore.ieee.org/document/9844898

Paper	Open Access Link	Journal link
	cut-cells-stronger-module	
P3. N. Bosco, 'Rotate half cells for stronger modules,' PV Magazine, 44986; March, 2023.		https://www.pv-magazine.com/magazine-archive/rotate-half-cells-for-stronger-modules/
P4. M.G. Figure 3, Gaulding, E.A., J.S. Mangum, T.J. Silverman, S.W. Johnston, J.A. Rand, M.J. Reed, R. Flottemesch, I. Repins, 'Bill of Materials Variation and Module Degradation in Utility-Scale PV Systems,' IEEE JPV, 12(6), 1349 - 1353; November, 2022.	https://www.osti.gov/biblio/1899997	https://ieeexplore.ieee.org/document/9911195
P5. M.G. Deceglie, T.J. Silverman, E. Young, Wi.B. Hobbs, C. Libby, 'Field and accelerated aging of cracked solar cells,' IEEE Journal of Photovoltaics, 13(6), 836-841; November, 2023.	https://www.osti.gov/biblio/2001011	https://ieeexplore.ieee.org/document/10255107
P6. E.A. Gaulding, J.S. Mangum, S.W. Johnston, C.-S. Jiang, H. Moutinho, M.J. Reed, J.A. Rand, R. Flottemesch, T.J. Silverman, M.G. Deceglie, 'Differences in Printed Contacts Lead to Susceptibility of Silicon Cells to Series Resistance Degradation,' IEEE JPV, 12(3), 690-695; 44682, May, 2022.	https://www.osti.gov/servlets/purl/1866388	https://ieeexplore.ieee.org/document/9731801
P7. B.M. Habersberger, P. Hacke, “Impact of illumination and encapsulant resistivity on polarization-type potential-induced degradation on n-PERT cells,” Progress in Photovoltaics 30(5), 455-463, May 2022.	https://doi.org/10.1002/pip.3505	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3505
P8. P. Hacke, A. Kumar, K. Terwilliger, P. Ndione, S. Spataru, A. Pavgi, K.R. Choudhury, G. TamizhMani,, 'Evaluation of Bifacial Module Technologies with Combined-Accelerated Stress Testing,' Progress in Photovoltaics, 31(12), 1270-1284; December, 2023.	https://www.osti.gov/biblio/1897655	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3636
P9. P. Hacke, D.C. Miller, D. Pierpont, T. Wu,, 'Performance of Electrically Conductive Adhesive of Shingled Si Heterojunction Technology Cells,' Progress in Photovoltaics, Early view; 2024.	https://www.osti.gov/pages/biblio/2228670-performance-durability-electrically-conductive-tape-shingled-si-	https://onlinelibrary.wiley.com/doi/10.1002/pip.3749

Paper	Open Access Link	Journal link
	heterojunction-technology-cells	
P10. P. Hacke, S.V. Spataru B. Habersberger, YF. Chen, 'Field-Representative Evaluation of PID-Polarization in TOPCon PV Modules by Accelerated Stress Testing,' Progress in Photovoltaics, 32(5), 346-355; May, 2024.	https://www.osti.gov/biblio/2282922	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3774
P11. C.-S. Jiang, S. Johnston, E.A. Gaulding, M.G. Deceglie, R. Flottemesch, C. Xiao, H.R. Moutinho, D.B. Sulas-Kern, J. Mangum, T.J. Silverman , M. Al-Jassim, I. Repins, 'Nanometer-Scale Measurement of Grid Finger Electrical Conduction Pathways to Detect Series Resistance Degradation of Utility-Scale Silicon Solar Cells,' IEEE JPV, 12(6), 1289-1295; November, 2022.	https://www.osti.gov/biblio/1899963	https://ieeexplore.ieee.org/document/9901440
P12. S.W. Johnston, D.C. Jordan, D.B. Kern, D.J. Colvin, K.O. Davis, H.R. Moutinho, G.F. Kroeger, 'Degradation-related defect level in weathered silicon heterojunction modules characterized by deep level transient spectroscopy,' Solar Energy Materials & Solar Cells, 262, 112527; October, 2023.	https://www.osti.gov/biblio/2004923	https://www.sciencedirect.com/science/article/pii/S0927024823003483
P13. S. Johnston, C. Xiao, M.G. Deceglie, A. Gaulding, C.-S. Jiang, H. Guthrey, D.B. Kern, G.F. Kroeger, M. Al-Jassim, I.L. Repins, 'LeTID-affected Cells from a Utility-scale Photovoltaic System Characterized by Deep Level Transient Spectroscopy,' IEEE JPV, 12(3), 703-710; May, 2022.	https://www.osti.gov/biblio/1883563	https://ieeexplore.ieee.org/document/9518401
P14. D.C. Jordan, T. Barnes, 'Degradation Science from nanometers to kilometers: Rapid Detection for Reliable PV,' Solar Rapid Research Letters, 7, 2300170; September, 2023.	open access	https://onlinelibrary.wiley.com/doi/full/10.1002/solr.202300170
P15. D. C. Jordan, N. Haegel, T.M. Barnes, 'Photovoltaics module reliability for the terawatt age ,' Progress in Energy, 4(2), 022002; April, 2022.	https://www.osti.gov/servlets/purl/1871659	https://iopscience.iop.org/article/10.1088/2516-1083/ac6111/meta
P16. J. Karas, I.L. Repins, K. Berger, B. Kubicek, F. Jiang, D. Zhang, J.-N. Jaubert, A.B. Cueli, T. Sample, B. Jaeckel, M. Pander, E. Fokuhl, M.B. Koentopp, F. Kersten, J.-H. Choi, B. Bora, C. Banerjee, S. Wendlandt, Tr. Erion-Lorico, K.J. Sauer, J. Tsan, M. Pravettoni, M. Caccivio, G. Bellenda, C. Monokroussos, H. Maaroufi,, 'Results	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3573	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3573

Paper	Open Access Link	Journal link
from an international interlaboratory study on light- and elevated temperature-induced degradation in solar modules,' Progress in Photovoltaics, 30(11), 1253-1362; November, 2022.		
P17. M.D. Kempe, S. Ovaitt, M. Springer, M. Brown, D. Jordan, W.Sekulic, C. O'Brien, J.-N. Jaubert, Y. Yu, J. Oh, G. Tamizhmani, B. Li, 'Close Roof Mounted System Temperature Estimation for Compliance to IEC 63126,' Solar Energy Materials & Solar Cells, 275, 112987; September, 2024.	https://www.osti.gov/biblio/1990035	https://www.sciencedirect.com/science/article/pii/S092702482400299X
P18. A.N. McPherson, J.F. Karas, D.L. Young, I.L. Repins,, 'Excess Carrier Concentration in Silicon Devices and Wafers: How Bulk Properties are Expected to Accelerate Light and Elevated Temperature Degradation,' MRS Advances, 7, 438–443; February, 2022.	https://www.osti.gov/biblio/1845965	https://link.springer.com/article/10.1557/s43580-022-00222-5
P19. S. Mitterhofer, M. Kempe, X. Gu, 'Evaluation of Surface Crack Formation in Photovoltaic Backsheets Using Fragmentation and Finite Element Simulations,' IEEE Journal of PV , 14(2); March, 2024.	https://www.osti.gov/biblio/2316150	https://ieeexplore.ieee.org/document/10417131
P20. S.L. Moffitt, S. Uličná, S.-S. Jhang, P.-C. Pan, M. Owen-Bellini, P. Hacke, M.D. Kempe, J. Tracy, K.R. Choudhury, L.T. Schelhas, X. Gu, "PVDF-based Backsheet Cracking: Mapping In Situ Phase Evolution by X-ray Scattering," Submitted *to Solar Energy Materials and Solar Cells*, July 2024. P21.	In progress	In progress
P22. S.L. Moffitt, P.-C. Pan, L. Perry, X. Gu, M. D. Kempe, J. Tracy, K.R. Choudhury, 'Microstructure Changes during Failure of PVDF-based Photovoltaic Backsheets ,' Progress in Photovoltaic, 31 (1), 26-35; January, 2023.	https://www.osti.gov/biblio/1882200	https://onlinelibrary.wiley.com/doi/full/10.1002/pip.3605
P23. C. Molto, J. Oh, F. I. Mahmood, M. Li, P. Hacke, R. Smith, D. Colvin, M. Matam, C. DiRubio, G. Tamizhmani, H. Seigneur, 'Review of Potential-Induced Degradation in Bifacial PV Modules,' Energy Technology, 11(4), 2200943; April, 2023.	https://www.osti.gov/biblio/1959074	https://onlinelibrary.wiley.com/doi/10.1002/ente.202200943
P24. J. Morse, M. Thuis, D. Holsapple, R. Willis, D.C. Miller, 'Degradation in photovoltaic encapsulant transmittance: Results of the second PVQAT TG5 artificial weathering study,' Progress	https://www.osti.gov/biblio/1863209	https://onlinelibrary.wiley.com/doi/10.1002/pip.3551

Paper	Open Access Link	Journal link
in Photovoltaics, 30(7), 763-783; 44743, April, 2022.		
P25. I.L. Repins, M.G. Deceglie, T.J. Silverman, D.C. Miller, D.C. Jordan, M. Woodhouse, T.M. Barnes, 'Setting Priorities for Photovoltaic Reliability Research Using Criticality Analysis,' IEEE Journal of Photovoltaics, (14)1, 46-52 ; January, 2024.	https://www.osti.gov/biblio/2283654	https://ieeexplore.ieee.org/document/10297560
P26. I.L. Repins, D. Jordan, M. Woodhouse, M. Thersistis, J. Stein, J.F. Karas, A.N. McPherson, C. Deline, 'Long-term impact of light- and elevated temperature-induced degradation on photovoltaic arrays,' MRS Bulletin: Impact, 48; March, 2023.	https://www.osti.gov/biblio/1905794	https://link.springer.com/article/10.1557/s43577-022-00438-8
P27. T.J. Silverman, I.L. Repins,, 'Brief: Diagonal Shadows May Cause Arcs in Thin-Film Modules with P4 Scribes,' IEEE JPV, 13(6), 917-91; November, 2023.	https://research-hub.nrel.gov/en/publications/diagonal-shadows-could-cause-arcs-in-thin-film-modules-with-p4-sc	https://ieeexplore.ieee.org/document/10246249
P28. G.P. Smestad, C. Anderson, M. Cholette, P. Fuke, A.A. Hachicha, A. Kottantharayil, K. Ilse, M. Karim, M. Khan, H. Merkle, D.C. Miller, J.M. Newkirk, G. Picotti, F. Wiesinger, G. Willers, 'Variability and associated uncertainty in image analysis for soiling characterization in solar energy system,' Solar Energy Materials and Solar Cells, 259(15), 112437; August, 2023.	https://www.osti.gov/pages/biblio/1992827-variability-associated-uncertainty-image-analysis-soiling-characterization-solar-energy-systems	https://www.sciencedirect.com/science/article/pii/S0927024823002581
P29. M. Springer, T. Silverman, N. Bosco, J. Joe, I. Repins, 'Residual stresses affect cell fragment movement,' IEEE Journal of Photovoltaics, 13(4), 547-551; July, 2023.	https://www.osti.gov/servlets/purl/1975214	https://ieeexplore.ieee.org/document/10112583
P30. J. Xia, Y. Liu, H. Hua, X. Zhu, H. Lv, N.H. Phillips, K.R. Choudhury, W.J. Gambogi, M. Rodriguez, E.S. Simon, M. Kempe, J. Morse, 'Impact of specimen preparation method on Photovoltaic backsheet degradation during accelerated aging test,' Energy Science & Engineering, 10, 1961–1971.; September, 2022.	https://www.nrel.gov/docs/fy22osti/81290.pdf	https://scijournals.onlinelibrary.wiley.com/doi/full/10.1002/ese3.1153

Table 5: Conference products, such as proceedings papers and presentations, created under this program. Products are listed in alphabetical order by first author. Each entry is followed by the conference name, the product type, and a link to the product if one is available.

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C1. N. Bosco	Mounting Matters, experimental validation of the What's Cracking App	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/27/24	https://pvrw.nrel.gov/past-proceedings
C2. M. Caccivio, D. Jordan	40 years of Ticino Solare (TISO), Reliability and durability testing today	World Conference on Photovoltaic Energy Conversion	Oral presentation	9/28/22	
C3. D. Colvin, N. Iqbal, M. Liggett, J.F. Mousumi, B. Babu, C. Neal, S. Seal, D.B. Sulas-Kern, D.C. Jordan, K.O. Davis	Multiscale characterization of degraded silicon heterojunction modules installed in a hot-humid climate	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/22	https://www.nrel.gov/docs/fy22osti/82935.pdf
C4. M.G. Deceglie, E.A. Gaulding, J.S. Mangum, T.J. Silverman, S.W. Johnston, J.A. Rand, M.J. Reed, R.	Bill of Materials Variation and Module Degradation in Utility-Scale PV Systems	IEEE Photovoltaic Specialists Conference	Oral presentation	6/5/22	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Flottemesch, I. Repins					
C5. M.G. Deceglie, E.A. Gaulding, J.S. Mangum, T.J. Silverman, S.W. Johnston, J.A. Rand, M.J. Reed, R. Flottemesch, I.L. Repins	Examples of How Bill of Materials Variation Can Affect Module Degradation in Utility-Scale PV Systems	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C6. M.G. Deceglie, T.J. Silverman, E. Young, W.B. Hobbs, C. Libby	Field and accelerated aging of cracked solar cells	IEEE Photovoltaic Specialists Conference	Oral Presentation	6/11/23	
C7. E.A. Gaulding, S.W. Johnston, J.B. Gallon, J.S. Mangum, J.A. Rand, M.J. Reed, R. Flottemesch, I.L. Repins, T.J. Silverman,	Insight into degradation modes observed in utility scale fielded photovoltaic modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
M.G. Deceglie					
C8. E.A. Gaulding, S.W. Johnston, D.B. Sulas-Kern, M.J. Reed, J.A. Rand, R. Flottemesch, T.J. Silverman, M.G. Deceglie	Investigation of Underperformance in Fielded N-type Monocrystalline Silicon Photovoltaic Modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/22	https://www.nrel.gov/docs/fy22osti/82935.pdf
C9. E.A. Gaulding, S.W. Johnston, D.B. Sulas-Kern, M.J. Reed, J.A. Rand, R. Flottemesch, T.J. Silverman, M.G. Deceglie	Investigation of Underperformance in Fielded N-type Monocrystalline Silicon Photovoltaic Modules	IEEE Photovoltaic Specialists Conference	Oral presentation	6/5/22	
C10. E.A. Gaulding, S.W. Johnston, T.J. Silverman, M.G. Deceglie	UV-induced power losses in fielded utility n-type Si PV modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/27/24	https://pvrw.nrel.gov/past-proceedings
C11. E.A. Gaulding, S.W.	UV Induced Power Losses in Fielded Utility N-	IEEE Photovoltaic	Poster Presentation	6/9/24	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ferenc e Date	Link to Presen-tation or Paper if Available
Johnston, T.J. Silverman, M.G. Deceglie	Type Si PV Modules	Specialists Conference			
C12. E. A. Gaulding, E.C. Palmiotti, J.F. Karas, S.W. Johnston, D.B. Sulas-Kern, J.B. Gallon, J.S. Mangum, I.L. Repins, T.J. Silverman, M.G. Deceglie,	UV + Damp Heat Induced Power Losses in Fielded Utility N-Type Si PV Modules	EU PVSEC	Poster Presentation	9/25/24	
C13. E. A. Gaulding, E. Palmiotti, T. Silverman, M. Deceglie, I. Repins, M. Springer,	Spontaneous Glass Breakage: Field Studies and Analysis	EU PVSEC	Plenary oral presentation	9/25/24	
C14. H. Guthrey, S. Johnston	Tutorial PM3: Multiscale Characterization of PV Degradation and Performance Limitations	IEEE Photovoltaic Specialists Conference	Tutorial Session	6/11/23	
C15. P. Hacke	CAST Acceleration Factors and the Vision and Requirements	NIST/UL Solutions Workshop on Photovoltaic	Oral presentation	12/5/23	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ferenc e Date	Link to Presen-tation or Paper if Available
	for Standardization	Materials Durability			
C16. P. Hacke	How important are aging tests for new PV-modules, new BOMs?	Backsheet reliability affecting module and system performance, remote workshop organized by HI ERN (Helmholtz-Institut Erlangen-Nürnberg für Erneuerbare Energien)	Oral presentation	12/13/22	
C17. P. Hacke, A. Kumar, A. Pavgi, S.V. Spataru, K. Roy-Choudhury, G. TamizhMani	Evaluation of Bifacial Modules and PV Technologies with Combined-Accelerated Stress Testing	8th World Conference on Photovoltaic Energy Conversion	Plenary Oral Presentation	9/26/22	https://www.osti.gov/biblio/1906322
C18. P. Hacke, A. Kumar, K. Terwilliger, P. Ndione, S. Spataru, A. Pavgi, K.R. Choudhury, G. TamizhMani	Examining Light-Induced Degradation with Combined-Accelerated Stress Testing	Silicon Workshop	Poster Presentation	6/11/23	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C19. P. Hacke, S.V. Spataru B. Habersberger, F.I. Mahmood	Field-Representative Evaluation of PID-Polarization in TOPCon PV Modules by Accelerated Stress Testing	EU PVSEC	Oral Presentation	9/23/23	
C20. S. Harvey	In situ Experiments and Probing Measurement Artifacts of Photovoltaic Materials	*24th International SIMS Meeting*	Oral Presentation	9/10/24	
C21. C.-S. Jiang, E.A. Gaulding, S. Johnston, M.G. Deceglie, J. Mangum, and G. Paul	Direct imaging on electrical conduction degradation of front metal/Si contact in utility scale c-Si modules by nanoelectrical probe	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/27/24	https://pvrw.nrel.gov/past-proceedings
C22. C.-S. Jiang, E.A. Gaulding, S. Johnston, M.G. Deceglie, J.S. Mangum, G. Paul	Investigation of electrical conduction degradation in front contact of Si cells by nanoelectrical probe	IEEE Photovoltaic Specialists Conference	Oral presentation	6/9/24	
C23. C.-S. Jiang, S. Johnston, E.A. Gauding, M.G. Deceglie, R.	Series Resistance Degradation of Silicon Solar Cells Investigated by nm-Scale	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/22	https://www.nrel.gov/docs/fy22osti/82935.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Flottemesch, C. Xiao, H.R. Moutinho, D.B. Sulas-Kern, J. Mangum, M.M. Al-Jassim, I.L. Repins	Resistance Imaging				
C24. C.-S. Jiang, S. Johnston, E.A. Gauding, M.G. Deceglie, R. Flottemesch, C. Xiao, H.R. Moutinho, D.B. Sulas-Kern, J. Mangum, T. Silverman, M.M. Al-Jassim, I.L. Repins	Local nm-Scale Imaging of Electrical Contact for Series Resistance Degradation of Silicon Solar Cells	IEEE Photovoltaic Specialists Conference	Oral Presentation	6/5/22	https://www.nrel.gov/docs/fy22osti/83145.pdf
C25. S. Johnston, R. Farshchi, T. Nagle, D. Lu, G. Xiong	Defect Levels in Arsenic-doped CdSeTe Characterized by Deep Level Transient Spectroscopy	IEEE Photovoltaic Specialists Conference	Extended Oral Presentation	6/9/24	
C26. S. Johnston, W. Hobbs	Long-term Monitoring of New Cell Cracks using Ultraviolet Fluorescence Imaging	NREL Photovoltaic Reliability Workshop,	Poster Presentation	2/23/22	https://www.nrel.gov/docs/fy22osti/82935.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ferenc e Date	Link to Presen-tation or Paper if Available
C27. S. Johnston, D.C. Jordan, D.B. Kern, D.J. Colvin, K.O. Davis, H.R. Moutinho, G.F. Kroeger	Degradation-related Defect Level in Weathered Silicon Heterojunction Modules Characterized by Deep Level Transient Spectroscopy	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C28. S.W. Johnston, D.C. Jordan, D.B. Kern, D.J. Colvin, K.O. Davis, H.R. Moutinho, G.F. Kroeger	Degradation-related Defect Level in Weathered Silicon Heterojunction Modules Characterized by Deep Level Transient Spectroscopy	IEEE Photovoltaic Specialists Conference	Oral Presentation	6/11/23	
C29. S. Johnston, D.C. Jordan, D.B. Kern, M.G. Deceglie, E.A. Gaulding, D.J. Colvin, K.O. Davis, H.R. Moutinho, G.F. Kroeger, I.L. Repins	Defect Levels in Weathered and Degraded Modules Measured by Deep Level Transient Spectroscopy	Silicon Workshop	Poster Presentation	7/30/23	
C30. S. Johnston, D.B. Kern	Capacitance Transients, Photoconductive Decay, and	IEEE Photovoltaic Specialists Conference	Conference Proceedings Paper	6/11/23	https://www.osti.gov/biblio/1995010

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
	Impedance Spectroscopy on 19% to 22% Efficient Silicon Solar Cells				
C31. S. Johnston, D.B. Kern	Capacitance Transients, Photoconductive Decay, and Impedance Spectroscopy on 19% to 22% Efficient Silicon Solar Cells	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/11/23	https://www.osti.gov/biblio/2309699
C32. S. Johnston, D.B. Kern, K. Terwilliger, I.L. Repins	Luminescence and Thermal Imaging Applied to Half-cut-cell and Emitter-wrap-through-cell Modules	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/11/23	
C33. S. Johnston, D.B. Kern, K. Terwilliger, I.L. Repins	Luminescence and Thermal Imaging Applied to Half-cut-cell and Emitter-wrap-through-cell Modules	IEEE Photovoltaic Specialists Conference	Conference Proceedings Paper	6/11/23	https://www.osti.gov/biblio/2309700
C34. S. Johnston, K. Terwilliger, R. Wai, D.B. Kern, D. Jordan	Photovoltaic Module Performance for Six Years after Hail Damage	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/9/24	
C35. D. Jordan	PV Reliability Science	Reliability Science for Photovoltaic and Electrochemical Energy	Oral Presentation	3/20/24	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
		Conversion Workshop			
C36. J. Karas, I. Repins	An Open-Source Python Library for Modeling LETID and LID in Silicon Solar Cells and Wafers	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C37. J. Karas, I. Repins	LETID in legacy and modern PV modules: accelerated testing and field deployment	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/5/22	https://www.osti.gov/biblio/1883389
C38. J. Karas, I. Repins, K.A. Berger, B. Kubicek, F. Jiang, D. Zhang, J.-N. Jaubert, A.B. Cueli, T. Sample, B. Jaeckel, M. Pander, E. Fokuhl, M.B. Koentopp, F. Kersten, J.-H. Choi, B. Bora, C. Banerjee, S. Wendlandt, T Erion-Lorico, K.J. Sauer, J. Tsan, M. Pravettoni,	Results from an international interlaboratory study on light- and elevated temperature-induced degradation (LETID) in solar modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/2022	https://www.nrel.gov/docs/fy22osti/82935.pdf

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ferenc e Date	Link to Presen-tation or Paper if Available
M. Caccivio, G. Bellenda, C. Monokrouss os, H. Maaroufi					
C39. J. Karas, M. Springer, M. Kempe, S. Ovaitt, I. Repins	Energy Yield Loss Due to LETID	SiliconPV 2024	Oral Presentation	4/15/24	
C40. M. Kempe	Tutorial AM4: Experimental considerations for estimating degradation in PV modules	IEEE Photovoltaic Specialists Conference	Tutorial Session	6/11/23	
C41. M.D. Kempe, S. Ovaitt, M. Springer, M. Brown, D. Jordan, W. Sekulic, C. O'Brien, J.-N. Jaubert, Y. Yu, J. Oh, G. Tamizhmani , B. Li	Close Roof Mounted System Temperature Estimation for Compliance to IEC TS 63126	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/11/23	https://www.osti.gov/biblio/1990035
C42. M.D. Kempe, S. Ovaitt, M. Springer, M. Brown, D.	Factors affecting the temperature of roof mounted PV systems and	NIST/UL Solutions Workshop on Photovoltaic	Oral presentation	12/5/23	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Jordan, W. Sekulic, C. O'Brien, J.-N. Jaubert, Y. Yu, J. Oh, G. Tamizhmani, B. Li	compliance to IEC TS63126	Materials Durability			
C43. D.B. Kern, S. Johnston, H. Moutinho, J. Meydbray, C.-S. Jiang, D. Jordan	Solder Pad Degradation in Field-Weathered Silicon Photovoltaic Modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C44. D.B. Sulas-Kern, H. Moutinho, T. Erion-Lorico, S. Johnston	Near-Busbar Degradation of Screen-Printed Metallization in Silicon Photovoltaic Modules	IEEE Photovoltaic Specialists Conference	Oral presentation	6/5/22	
C45. D.B. Sulas-Kern, H. Moutinho, T. Erion-Lorico, S. Johnston	Near-Busbar Degradation of Screen-Printed Metallization in Silicon Photovoltaic Modules	IEEE Photovoltaic Specialists Conference	Conference Proceedings Paper	6/5/22	https://www.osti.gov/biblio/1913965
C46. T. Krajewski, S. Dunfield, I. Repins, P. Bhatt	Emerging Technology	NREL Photovoltaic Reliability Workshop	Panel Discussion	2/27/24	
C47. E. Lee, A. Ward, I. Repins	Meeting Market Needs: How to prove out thin-film PV long-term reliability to stakeholders	Webinar hosted by ADL Ventures.	Discussion Panel	3/4/22	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C48. F. Li, D.C. Miller, G. TamizhMani	Artificial Replication of Field Soiling Losses on PV Modules	IEEE Photovoltaic Specialists Conference	Oral Presentation	6/9/24	
C49. S. Mitterhofer, M. Kempe, X. Gu	A finite Element Model to Simulate Photovoltaic Backsheet Cracking After Aging	EU PVSEC	Oral Presentation	9/23/23	
C50. S.L. Moffitt, P.-C. Pan, M.D. Kempe, J. Tracy, K.R. Choudhury, Y. Mao, P.D. Butler, B.H. Hamadani, X. Gu	Investigating solar panel defect mechanisms in polymer packaging materials	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/2022	https://www.nrel.gov/docs/fy22osti/82935.pdf
C51. J. Newkirk, J. Bomber, J. Morse, D.C. Miller	The IEC 62788-7-3 abrasion methods standard and supporting experiments at NREL on PV surfaces and coatings	Indo UK PV Soiling Workshop	Oral Presentation	2022/1/25	https://www.nrel.gov/docs/fy22osti/82517.pdf
C52. J. Newkirk, J. Bomber, J. Morse, D.C. Miller	The IEC 62788-7-3 abrasion methods standard and supporting experiments at NREL on PV surfaces and coatings	PV Robot Cleaning Workshop	Oral Presentation	2022/3/28	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
C53. G. Oreski, C. Barretta, P. Gebhardt, D.C. Miller, S. Uličná, M. Kempe, L.S. Bruckman, L. Gnocchi, H. Li, Brian Habersberger, K. Proost, M. Kühne	Polyethylene copolymers as solar cell encapsulants: A critical overview	EU PVSEC	Poster presentation	9/23/23	
C54. G. Oreski, C. Barretta, P. Gebhardt, K.A. Weiß, D.C. Miller, S. Uličná, M. Kempe, L.S. Bruckman, L. Gnocchi, H.Li, B. Habersberger, K. Proost, M. Kühne	Polyethylene copolymers as solar cell encapsulants: A critical overview	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/27/24	https://pvrw.nrel.gov/past-proceedings
C55. I.L. Repins	Solar Panel and Systems Reliability Research at NREL Learnings that May be Useful to You	State Farm Lecture Series	Invited Oral Presentation	8/17/23	
C56. I.L. Repins, M.G.	Setting Priorities for Photovoltaic Reliability	IEEE Photovoltaic	Oral Presentation	6/11/23	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
Deceglie, T.J. Silverman, D.C. Miller, D.C. Jordan, M. Woodhouse, T.M. Barnes	Research Using Criticality Analysis	Specialists Conference			
C57. I.L Repins, S. Johnston, H. Guthrey	We Developed Tests and Standards to Prevent Observed PV Degradation from Happening in Future Products	DOE SETO Peer Review Meeting	Poster Presentation	3/27/24	
C58. I. Repins, N. Kopidakis, E. Warren, D. Jordan, L. Schelhas	Challenges for Tandem Reliability: Science to Standards	4th Multi Terawatt Workshop	Invited Oral Presentation	6/6/24	
C59. I.L. Repins, T.J. Silverman, M.G. Deceglie, D.C. Miller, D.C. Jorda	Pareto Analysis Framework for Prioritizing PV Reliability Research Activities	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/22	https://www.nrel.gov/docs/fy22osti/82935.pdf
C60. I.L. Repins, M. Springer, M. Kempe, T.J. Silverman, J. Karas, N. Bosco, P. Hacke, M. Deceglie, E. Young, S.W. Johnston,	Providing Data-Driven Guidance on Long-Term Returns: Successes and Challenges in Accelerated Tests on PV Modules	UK EPSRC SuperSolar Annual Conference	Invited Presentation	9/20/22	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
E.A. Gaulding, D.C. Jordan,					
C61. I. Repins, S. Uličná	PV Module Standards, Accelerated Testing, and Packaging	PERCISTAND Encapsulation Workshop, hosted by EMPA, Switzerland	Invited Oral Presentation	3/13/23	
C62. I. Repins, M. Woodhouse, D.C. Miller, J. Karas, M. Kempe	Costs of Several Photovoltaic Module Degradation Modes	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C63. E.J. Schneller, D.C. Miller, O. Shinde, S. Tatapudi, K. Terwilliger, J. Newkirk, J.H. Wohlgemuth, G. Tamizhmani, N. Dhere	Encapsulation Performance After Five Years in the Field: A Comparison of Hot/Humid and Hot/Dry Climates	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C64. W. Sekulic, B. McDanold, J. Parker, T. Snow, J. Elsworth, E. Hotchkiss, D. Jordan,	Wind Damage to a Rooftop Array at NREL	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/27/24	https://pvrw.nrel.gov/past-proceedings

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ference Date	Link to Presen-tation or Paper if Available
A. Walker, I. Repins					
C65. T.J. Silverman, N. Luna, B. McDanold, J. Parker, W.B. Hobbs	Field Photoluminescence Imaging with Simple Hardware	IEEE Photovoltaic Specialists Conference	Oral Presentation	6/9/24	
C66. L.J. Simpson, M. Brandtl, R. Huntamer	Photovoltaic Module R&D Considerations for Soiling Mitigation	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/5/22	https://www.osti.gov/biblio/1873392
C67. A. Soman, G. Obikoya, S. Johnston, S. Harvey, U. Das, S. Hegedus	Stability of Silicon Heterojunction solar cells having hydrogen plasma treated intrinsic layer	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/5/22	https://www.osti.gov/biblio/1913964
C68. M. Springer, L. Spinella, T.J. Silverman, M. Young, I. Repins	Ribbons affect movement of cracked solar cells	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/23/2022	https://www.nrel.gov/docs/fy23osti/85415.pdf
C69. M. Springer, L. Spinella, T.J. Silverman, M. Young, I. Repins	Quantifying cell fragment movement of fractures c-Si mini-modules	NREL Photovoltaic Reliability Workshop	Poster Presentation	2/28/23	https://www.nrel.gov/docs/fy24osti/87918.pdf
C70. R. Wai, J. Mangum, S. Johnston, D. Kern, K.	Detection of Thermal Cycle and Humidity Freeze Induced Damage on a Half-cut-cell	IEEE Photovoltaic Specialists Conference	Poster Presentation	6/9/24	

Speaker and Author Names	Presentation or Paper Title	Conference Name	Con-ference Product Type	Con-ferenc e Date	Link to Presen-tation or Paper if Available
Terwilliger, I. Repins	Module using Luminescence and Thermal Imaging				

Table 6: Standards documents developed under this program are shown in the following table. Entries are listed in chronological order according to the last date the standard advanced to the next development stage at the standards organization (i.e. at the IEC).

Standard	Status	Date	NREL Role
S1. IEC 62093 ED2 "Balance-of-system components for photovoltaic systems - Design qualification natural environments"	Published	January-22	Project team
S2. IEC 62788-5-1/AMD1 ED1 "Amendment 1 - Measurement procedures for materials used in photovoltaic modules - Part 5-1: Edge seals - Suggested test methods for use with edge seal materials"	Published	January-22	Project lead (Kempe)
S3. IEC 62788-7-3 ED1 "Measurement procedures for materials used in photovoltaic modules - Part 7-3: Environmental exposures - Accelerated abrasion tests of PV module external surfaces"	Published	February-22	Project lead (Miller)
S4. IEC 61215-1-2/AMD1 ED2 Amendment 1 "Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-2: Special requirements for testing of thin-film Cadmium Telluride (CdTe) based photovoltaic (PV) modules"	Published	March-22	Project team
S5. IEC 61215-1-3/AMD1 ED2 Amendment 1 "Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-3: Special requirements for testing of thin-film amorphous silicon based photovoltaic (PV) modules"	Published	March-22	Project team

Standard	Status	Date	NREL Role
S6. IEC 61215-1-4/AMD1 ED2 Amendment 1 “Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-4: Special requirements for testing of thin-film Cu(In,Ga)(S,Se)2 based photovoltaic (PV) modules”	Published	March-22	Project team
S7. IEC 62804-2 "Photovoltaic (PV) Modules – Test Methods for the Detection of Potential-Induced Degradation"	Published	March-22	Project lead (Hacke)
S8. IEC TS 63342 ED1 "Light and elevated temperature induced degradation (LeTID) test for c-Si Photovoltaic (PV) modules: Detection"	Published	July-22	Project team
S9. IEC TS 62788-6-3 ED1 "Measurement procedures for materials used in photovoltaic modules - Part 6-3: Adhesion testing of interfaces within PV modules"	Published	August-22	Project team
S10. IEC 63209-2 "Extended-stress testing of photovoltaic modules for risk analysis – Part 2: Durability characterization of polymeric component materials and packaging sets"	Published	August-22	Project team
S11. IEC 61215-1-1 ED3 Amendment 1 "Terrestrial photovoltaic (PV) modules - Design qualification and type approval - Part 1-1: Special requirements for testing of crystalline silicon photovoltaic (PV) modules”	CD	February-23	Project team
S12. IEC TS 63556 (82/2212) "Coupled-Stress Acceleration Test Sequence for Photovoltaic Modules and Materials"	NWIP	March-23	Project team
S13. IEC TS 62788-7-2 ED2 “Amendment 1 - Measurement procedures for materials used in photovoltaic modules - Part 7-2: Environmental exposures - Accelerated weathering tests of polymeric materials”	CD	July-23	Project lead (Miller)
S14. IEC 62788-2-1 ED1 “Polymeric materials for photovoltaic (PV) modules	Published	August-23	Project team

Standard	Status	Date	NREL Role
– Part 2-1: Safety requirements for polymeric frontsheet and backsheet”			
S15. IEC TS 62804-1 ED2 Photovoltaic (PV) modules - Test methods for the detection of potential-induced degradation - Part 1: Crystalline silicon, approved by the IEC for DTS, August 2023, Peter Hacke from NREL is the project leader.	DTS	August-23	Project lead (Hacke)
S16. IEC 61730-1 ED3 Amendment 1 "Photovoltaic (PV) module safety qualification - Part 1: Requirements for construction"	Published	September-23	Project team
S17. IEC TS 62915 ED2 "Photovoltaic (PV) modules - Type approval, design and safety qualification – Retesting"	Published	September-23	Project team
S18. 61730-2 ED3 “Photovoltaic (PV) module safety qualification - Part 2: Requirements for testing”	Published	September-23	Project team
S19. IEC TR 63525 ED1 "Reuse of PV modules and circular economy"	CD	October-23	Project team
S20. IEC TS 6XXXX "Universal Connector Standard"	NWIP	October-23	Project lead (Kempe)
S21. IEC TS 63126 ED2 "Guidelines for qualifying PV modules, components and materials for operation at high temperatures"	FDIS	December-23	Project lead (Kempe)
S22. IEC TS 62788-8-1 ED1 "Measurement procedures for electrically conductive adhesive (ECA) used in crystalline silicon photovoltaic modules - Part 8-1: Measurement of material properties"	Published	June-24	Project team
S23. IEC 62788-2 ED2 “Measurement Procedures for Materials Used in Photovoltaic Modules – Part: Polymeric materials – Frontsheets and Backsheets”	Published	July-24	Project team
S24. IEC 62788-7-3/AMD1 ED1 "Amendment 1 - Measurement procedures for materials used in photovoltaic modules - Part 7-3: Accelerated stress tests - Methods of	Published	July-24	Project lead (Miller)

Standard	Status	Date	NREL Role
abrasion of PV module external surfaces"			
S25. IEC 62788-1-1 "Measurement procedures for materials used in photovoltaic modules – Part 1-1: Polymeric materials used for encapsulants"	Published	September-24	Project lead (Miller)

Table 7: Publicly available software developed under this program.

Software Record Number	Description	DOI	Link
Publicly-available software for current-voltage analysis: "SWR-22-79 IV_analysis."	SW1. Software performs the official ASTM E1036 extraction of parameters from IV curves.		https://github.com/NREL/iv_params , also incorporated into pvlib v0.9.4
NREL Software Record, SWR-23-40 submitted for publicly-available software "pyletid",	SW2. Allows the user to calculate the progression of Light and Elevetated Temperature Degradation for different module types and deployment climates.	DOI: 10.5281/zenodo.808857	https://github.com/NREL/PVDegradationTools/blob/main/pvdeg/letid.py

Table 8: Awards related to this program. Some awards relate directly to program content, such as a best poster award. Other awards recognize personal achievement of an individual working on this program.

Award Name	Type	Recipient	Awarding Organization	Date
Outstanding Poster Award	Program content	Martin Springer, Laura Spinella, Timothy J. Silverman, Matthew Young, Ingrid Repins, "Quantifying cell fragment movement of fractures c-Si mini-modules."	Photo-voltaic Reliability Workshop	February, 2022
Hoyt Clarke Hottel Award	Personal	Steve Johnston, "for significant technical contributions to the PV R&D community, and especially the development of innovative PV measurement techniques."	American Solar Energy Society	May, 2022
Best Poster Award	Program content	Anishkuman Soman, Gbenga Obikoya, Steve Johnston, Steven Harvey, Ujjwal Das, Steven Hegedus, "Stability of Silicon Heterojunction solar cells having	IEEE Photo-voltaic Specialists	June, 2022

Award Name	Type	Recipient	Awarding Organization	Date
		hydrogen plasma treated intrinsic layer.”	Con-ference	
Outstanding Poster Award	Program content	E. Ashley Gaulding, Steve W. Johnston, Dana B. Sulas-Kern, Mason J. Reed, James A. Rand, Robert Flottemesch, Timothy J Silverman, Michael G. Deceglie, “Investigation of Underperformance in Fielded N-type Monocrystalline Silicon Photovoltaic Modules.”	Photo-voltaic Reliability Workshop	February, 2023
Best Poster Award	Program content	Steve Johnston, Dana B. Kern, Kent Terwilliger, and Ingrid L. Repins, “Luminescence and Thermal Imaging Applied to Half-cut-cell and Emitter-wrap-through-cell Modules."	IEEE Photo-voltaic Specialists Con-ference	June, 2023
1906 Award	Personal	Mike Kempe, “honoring IEC experts around the world whose work is fundamental to the IEC"	Inter-national Electro-technical Com-mission	August, 2023
Outstanding Poster Award	Program content	Nick Bosco, “Mounting Matters, experimental validation of the What's Cracking App.”	Photo-voltaic Reliability Workshop	February, 2024
Distinguished Member of Research Staff	Personal	Tim Silverman, "recognizing research staff for overall expertise and highly impactful contributions to the mission of the laboratory."	NREL	March, 2024
Best Poster Award	Program content	Rebecca Wai, et al, “Detection of Thermal Cycle and Humidity Freeze Induced Damage on a Half-cut-cell Module using Luminescence and Thermal Imaging."	IEEE Photo-voltaic Specialists Con-ference	June, 2024

Table 9: Media mentions resulting from this program.

Date	Outlet	Description	Link
June 14, 2022	PVTech	M1. Article highlights Dave Miller's work from this program regarding a standard for measuring abrasion susceptibility of modules.	https://www.pv-tech.org/pv-cleaning-robots-new-test-methods-for-a-new-technology/
August 17, 2022	USA Today	M2. Mike Kempe was interviewed in the public outreach article "Here are the basics on how solar panels work."	https://www.usatoday.com/story/tech/reviewed/2022/08/17/here-basics-how-solar-panels-work/10340623002/
January 6, 2024	PV Mag-azine	M3. PV Magazine interviewed Ingrid Repins about NREL's work on glass breakage. See M. Hutchins, "Temper Tantrum", PV Magazine, 12-2023	https://www.pv-magazine.com/2024/01/06/weekend-read-temper-tantrum/

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References:

References developed under this program are listed in Table 4 - Table 9. Those are cited in this report according to their numbering in the tables. References external to this program are listed below.

(1) Kneifel, J. D.; Webb, D.; O' Rear, E. *Energy and Economic Implications of Solar Photovoltaic Performance Degradation*; NIST SP 1203; 2016. http://dx.doi.org/10.6028/NIST.SP.1203.
(2) Jones-Albertus, R.; Feldman, D.; Fu, R.; Horowitz, K.; Woodhouse, M. Technology Advances Needed for Photovoltaics to Achieve Widespread Grid Price Parity. *Prog. Photovolt. Res. Appl.* **2016**, *24* (9), 1272–1283. https://doi.org/10.1002/pip.2755.
(3) Jordan, D. C.; Marion, B.; Deline, C.; Barnes, T.; Bolinger, M. PV Field Reliability Status—Analysis of 100 000 Solar Systems. *Prog. Photovolt. Res. Appl.* **2020**, *28* (8), 739–754. https://doi.org/10.1002/pip.3262.
(4) Packard, C. E.; Wohlgemuth, J. H.; Kurtz, S. *Development of a Visual Inspection Data Collection for Evaluation of Fielded PV Modules,"*; NREL/TP-5200-56154; 2012. https://www.nrel.gov/docs/fy12osti/56154.pdf.
(5) Johnston, S. W.; Moutinho, H. R.; Jiang, C.-S.; Guthrey, H.; Norman, A.; Harvey, S. P.; Hacke, P.; Xiao, C.; Moseley, J.; Sulas, D.; Liu, J.; Albin, D.; Nardone, M.; Al-Jassim, M. *From Modules to Atoms: Techniques and Characterization for Identifying and Understanding Device-Level Photovoltaic Degradation Mechanisms*; NREL/TP-5K00-72541; 2019. https://www.nrel.gov/docs/fy20osti/72541.pdf.
(6) Yamaguchi, S.; Nakamura, K.; Masuda, A.; Ohdaira, K. Rapid Progression and Subsequent Saturation of Polarization-Type Potential-Induced Degradation of n-Type Front-Emitter Crystalline-Silicon Photovoltaic Modules. *Jpn. J. Appl. Phys.* **2018**, *57* (12). https://doi.org/10.7567/JJAP.57.122301.
(7) Kopecek, R. Is LETID Degradation in PERC Cells Another Crisis Even Worse Than PID? *PVTech Magazine*. November 19, 2018. https://www.pv-tech.org/is-letid-degradation-in-perc-cells-another-degradation-crisis-even-worse-th/ (accessed 2024-11-19).
(8) K. Krauß; A. A. Brand; F. Fertig; S. Rein; J. Nekarda. Fast Regeneration Processes to Avoid Light-Induced Degradation in Multicrystalline Silicon Solar Cells. *IEEE J. Photovolt.* **2016**, *6* (6), 1427–1431. https://doi.org/10.1109/JPHOTOV.2016.2598273.
(9) F. Kersten; P. Engelhart; H. -C. Ploigt; A. Stekolnikov; T. Lindner; F. Stenzel; M. Bartzsch; A. Szpeth; K. Petter; J. Heitmann; J. W. Müller. A New Mc-Si Degradation Effect Called LeTID. In *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*; 2015; pp 1–5. https://doi.org/10.1109/PVSC.2015.7355684.
(10) Chan, C. E.; Payne, D. N. R.; Hallam, B. J.; Abbott, M. D.; Fung, T. H.; Wenham, A. M.; Tjahjono, B. S.; Wenham, S. R. Rapid Stabilization of High-Performance Multicrystalline P-Type Silicon PERC Cells. *IEEE J. Photovolt.* **2016**, *6* (6), 1473–1479. https://doi.org/10.1109/JPHOTOV.2016.2606704.
(11) Köentopp, M. Long-Term Stability and Field Degradation Data for PERC-Type Modules; 2021; Vol. https://www.nrel.gov/docs/fy21osti/80055.pdf.

(12) Kersten, F.; Fertig, F.; Petter, K.; Klöter, B.; Herzog, E.; Strobel, M. B.; Heitmann, J.; Müller, J. W. System Performance Loss Due to LeTID; 2017; Vol. 124, pp 540–546. https://doi.org/10.1016/j.egypro.2017.09.260.

(13) Chen, D.; Hamer, P. G.; Kim, M.; Fung, T. H.; Bourret-Sicotte, G.; Liu, S.; Chan, C. E.; Ciesla, A.; Chen, R.; Abbott, M. D.; Hallam, B. J.; Wenham, S. R. Hydrogen Induced Degradation: A Possible Mechanism for Light- and Elevated Temperature-Induced Degradation in n-Type Silicon. *Sol. Energy Mater. Sol. Cells* **2018**, *185*, 174–182. https://doi.org/10.1016/j.solmat.2018.05.034.

(14) Kiwa PVEL. *2024 PV Module Reliability Scorecard*. https://scorecard.pvel.com/ (accessed 2024-11-19).

(15) RETC. *2024 PV Module Index Report*. https://retc-ca.com/pvmi (accessed 2024-11-19).

(16) Swanson, R.; Cudzinovic, M.; DeCeuster, D. The Surface Polarization Effect in High-Efficiency Silicon Solar Cells. *PVSEC* **2005**, *15*.

(17) Kempe, M. D.; Lockman, T.; Morse, J. Development of Testing Methods to Predict Cracking in Photovoltaic Backsheets; 2019; pp 2411–2416. https://doi.org/10.1109/PVSC40753.2019.8980818.

(18) Ierace, S. The Basics of FMEA, by Robin E. McDermott, Raymond J. Mikulak and Michael R. Beauregard. *Prod. Plan. Control* **2010**, *21* (1), 99–99. https://doi.org/10.1080/09537280903372119.