DuraMAT
Durable Module Materials Consortium

ANNUAL REPORT

FY 2020

A year of capability development and new collaborations

Energy Materials Network
U.S. Department of Energy

NREL

Sandia National Laboratories

BERKELEY LAB

SLAC NATIONAL ACCELERATOR LABORATORY

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About DuraMAT

The Durable Module Materials Consortium (DuraMAT) launched in November 2016 with five years of funding as part of the U.S. Department of Energy's (DOE's) Energy Materials Network. DuraMAT is a multilab consortium, led by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories (Sandia), with SLAC National Accelerator Laboratory (SLAC) and Lawrence Berkeley National Laboratory (LBNL) as core research labs. DuraMAT's overarching goal is to discover, develop, de-risk, and enable the rapid commercialization of improved materials, designs, predictive tests, and models for PV modules that increase performance, extend lifetime, and enable new applications. We work in partnership with our 15-member Industry Advisory Board and the technical management team in DOE's Solar Energy Technologies Office.

DuraMAT Director's Letter

DuraMAT managed to have an exceptionally productive year, despite the many challenges of 2020. We were fortunate to have experiments that could run unattended, modeling and analysis that could be done from home, and labs and communities that enabled us to continue working. The pandemic also let (forced?) our researchers to catch up on publications from the first three years of work. DuraMAT continued our outreach and communications efforts virtually with invited and contributed talks at NIST/UL Workshop on Photovoltaic Materials Durability, PV Reliability Workshop (PVRW), 47th IEEE Photovoltaic Specialists Conference, and many other virtual meetings. At the end of FY20, DuraMAT has 22 published journal articles and over 90 presentations. We are looking forward to interesting new results in FY21, with special efforts on the reliability of glass/glass modules and the impacts of cell cracking on module reliability.

DuraMAT Director's Letter (Cont.)

Our core objectives are focused on establishing and applying critical capabilities to address the big challenges for PV module durability. Improving PV modules' outdoor reliability and our ability to predict reliability requires more durable materials and designs, better tests to screen for weaknesses, robust modeling, more materials and module characterization data, and a way to combine all of this data with historical performance data to extract meaningful results. Here are our key results in FY20 for each core objective.

Please refer to the publication list on page 30 for details on the work mentioned here.

DuraMAT's five core objectives are:

- A Central Data Resource
  - Improved usability and added new capabilities, including an accelerated testing data link, data quality and PVAnalytics data cleaning, text analysis for operations and maintenance data, and a new levelized cost of energy calculator
- Multi-Scale, Multi-Physics Modeling
  - Mechanical, thermal, and electrical models of electrically conductive adhesive joints in shingled modules, validation of mechanical loading conditions in accelerated testing, and cracking mechanisms in backsheets
- Module and Material Forensics
  - Publications on backsheet degradation, progress on degradation modes in glass/glass packages, and outdoor characterization of anti-reflectin coatings (ARCs)
- Disruptive Accelerated Testing
  - High-impact publication of combined-accelerated stress testing results showing field-relevant accelerated aging of backsheets in different climates; initial results of UV degradation studies
- Module and Material Solutions
  - Continued development of crack-tolerant metallization pastes with Osazda and recyclable backsheets with DSM.

DuraMAT held two workshops in FY20. The first was held in conjunction with PVRW in late February, and we were lucky enough to meet in person for the final time this year. The second was held virtually in late September. The September virtual workshop allowed us to spend time with the Industry Advisory Board (IAB), and many of our researchers discussed the core objectives and projects in detail. We identified two technical goals for FY21—quantitatively addressing the reliability of glass/glass modules and the energy impacts of cell cracking—that will leverage our capabilities and current project portfolio to address critical questions for the U.S. PV industry. We formed a working group to focus on each goal and help integrate work on that topic across projects in DuraMAT and communicate with external groups working in similar areas. The working groups plan to present a public webinar on their results and submit a paper in late FY21. The first working group is addressing the reliability and risks of glass/glass module packaging, and the second is quantifying the impacts of cell cracks on module performance and reliability. We will present quantitative results on the reliability of glass/glass modules based on what we learn this year and a plan for future work. We will also present our answer to the question, "when does a crack become damage?" Both topics were specifically requested by the DuraMAT IAB when we asked them to identify the things DuraMAT could do that would define success at the end of our first five years. We are looking forward to the results and invite you to join us for monthly working group meetings and seminars on topics of interest.

Please reach out to us at duramat@nrel.gov or www.duramat.org if you are interested in learning more about our work.

Sincerely,

Teresa Barnes
DuraMAT Director

DuraMAT Working Groups

One of the things DuraMAT strives to do is stay up to date on the most important questions facing our community. This year at the Fall 2020 virtual workshop, two areas became the focus of several breakout discussions, leading us to two important questions:

When does a cell crack become damage?

How does the glass/glass module design affect module durability?

To address these questions, we challenged a small group of early-career researchers to organize working groups around these topics with the ultimate goal of understanding the impact that DuraMAT can have in these areas, both short-term (one year) and long-term (five years). Below, we provide a brief description of these working groups and contact information. We hope you will join us for future discussions!

DuraMAT Cell Cracks Working Group

Cell cracks remain a challenging topic in crystalline silicon (c-SI) PV panels. Cell cracks can occur during manufacturing, transportation, installation, and service through mechanical or thermal loads acting on the module. Lately, severe weather events like hurricanes and hailstorms causing cell cracks in a majority of modules in utility scale power plants have increased the pressure to find solutions for the proper assessment of and dealing with cell cracks. Cracked cells have the potential to impact and degrade the electrical performance of modules. However, a classification as to when cracks are impacting performance and to what extent module performance is impacted remain open questions. Therefore, DuraMAT has established a working group focusing on the topic of cell cracks in c-Si PV. The working group brings together subject matter experts from universities, national laboratories, and industry, and is looking at a wide variety of aspects associated with the topic. Research activities include crack detection methods and characterization of crack progression under service conditions, accelerated test conditions, or severe weather events, as well as investigations into emerging topics such as glass/glass module designs, increasing module size, and new interconnect technologies and their effects on cell cracking.

Contacts:

Martin Springer, NREL, martin.springer@nrel.gov

Jenn Braid, Sandia, jlbraid@sandia.gov

Oliver Zhao, Stanford, ozhao32@stanford.edu

DuraMAT Glass/Glass Modules Working Group

Glass/glass packaging of PV is quickly rising as a popular scheme for module construction, where sheets of glass cover both the front and rear sides of the module. The glass/glass architecture eliminates the polymer backsheet used in standard modules, promising greater durability (e.g., from decreased moisture ingress and greater mechanical strength) while enabling advanced technologies such as bifacial, thin-film, and building-integrated PV. Based on the rising implementation of these technologies, the growing market share of glass/glass construction and strong interest from the PV community and DuraMAT's industry advisors, DuraMAT has established a focus group to evaluate the path forward for glass/glass module construction. The group contains participants with interests ranging from academic curiosity to manufacturing to maintaining long-lifetime field performance, including universities, national labs, and industry. The relatively early stage of modern glass/glass module development and deployment makes DuraMAT particularly well positioned to have high impact on the durability and materials choices for this module scheme.

Contacts:

Dana Sulas Kern, NREL, dana.kern@nrel.gov

Archana Sinha, SLAC, asinha@slac.stanford.edu

DuraMAT Fiscal Year 2020 Financial Report

DuraMAT is a five-year, $30M research program that kicked off early in FY17. Soliciting and awarding high impact work in the national labs and outside entities is a key aspect of DuraMAT's work. In FY19, DuraMAT made its final open call awards to Stanford University and Arizona State University, who started work at the end of FY20. Figure 1 shows the overall breakdown of DuraMAT's spending, which can be divided into five broad categories: core management, DuraMAT lab call projects, industry-led projects, academic-led projects, and spark projects. DuraMAT core management funding is a flat funding amount allocated to each of the four core labs to cover technical leadership, consortium management, and the DuraMAT postdoc at each lab. DuraMAT lab call funding is awarded competitively to the laboratories to develop and demonstrate new capabilities. Academic- and industry-led projects are awarded competitively through our open calls for work led by outside institutions in collaboration with the lab capabilities. Spark projects are small ($50k) six-to-nine-month projects at the labs to test out new ideas or work directly with industry. Figure 1 shows the overall breakdown of DuraMAT's spending, which can be divided into five broad categories: Core Management, DuraMAT Lab Call Projects, industry-led project, academic-led project, and spark projects. DuraMAT Core Management funding is a flat funding amount allocated to each of the four core labs to cover technical leadership, consortium management, and the DuraMAT postdoc at each lab. DuraMAT Lab call funding is awarded competitively to the laboratories to develop and demonstrate new capabilities.

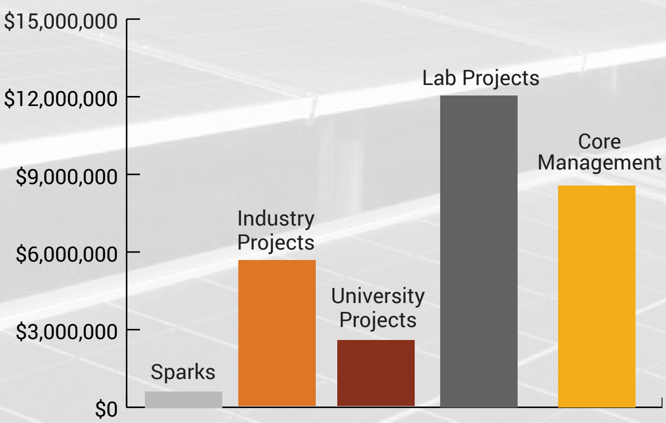
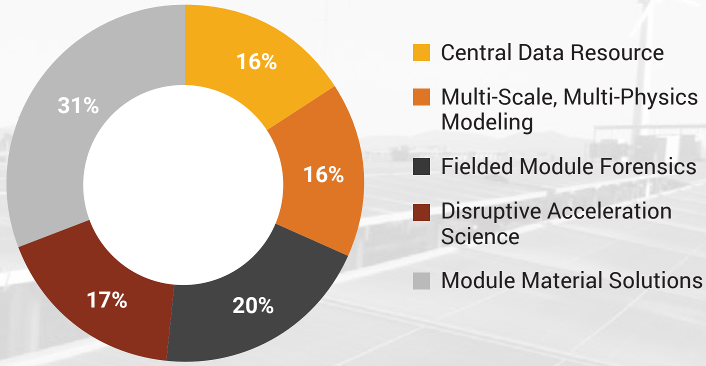
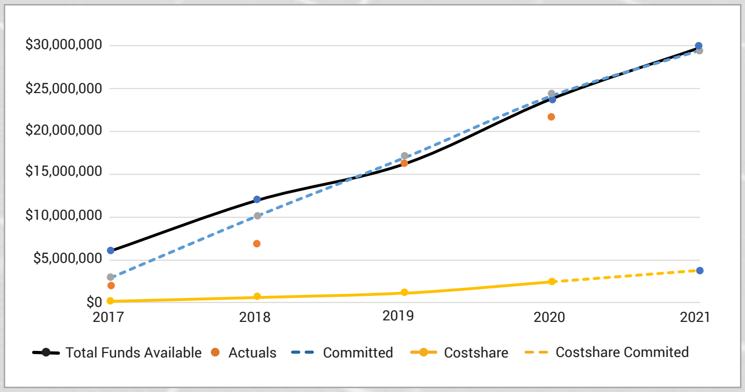


Figure 2 shows the investment DuraMAT has made into each of our five core objectives: central data resource, multi-scale, multi-physics model, fielded module forensics, disruptive acceleration science, and module material solutions. These research priorities have been vetted through our Industry Advisory Board (IAB), which not only provides funding recommendations for our lab and spark calls, but also provides feedback on every DuraMAT project through their critical review at our biannual workshops. IAB's guidance has helped determine our research goals for the upcoming year.



DuraMAT's spending continues to stay on track through the beginning of FY21. Figure 3 shows DuraMAT's total available funding of $30M, committed dollars that have been awarded, actual spending totals, and actual/committed cost share through the end of FY20 (Sept. 30, 2020).

DuraMAT has a 10%, $3.3M cost share requirement. Each of our open call (industry- and academic-led) projects ended up contributing in excess of 20%. This is critical because about 70% of DuraMAT's funding stayed within the national lab network, and national labs are unable to contribute cost share. The remainder of the cost share is from the U.S. Department of Energy Cooperative Research and Development Agreement projects that leverage the DuraMAT capabilities with companies including First Solar, Hyet Solar, and SunPower.



Central Data Resource

Core Objective Lead: Anubhav Jain, ajain@lbl.gov

Collect and disseminate module reliability-related data and apply data science to derive new insights.

Key Results:

- Demonstrate a central data resource, the DuraMAT DataHUB, that securely hosts a mix of private and public data of multiple data types.
- Develop open-source software libraries that apply machine learning to solve module reliability challenges, leveraging the data available in the DataHUB.
- Demonstrate applications of the data and software tools to address short-term commercial challenges that are beyond current industry capabilities and long-term research challenges.
- Conduct technoeconomic analysis of the effects of more predictive accelerated testing, lower degradation, and resilient module designs and materials.

Central Data Resource

Core Objective

Key Result:

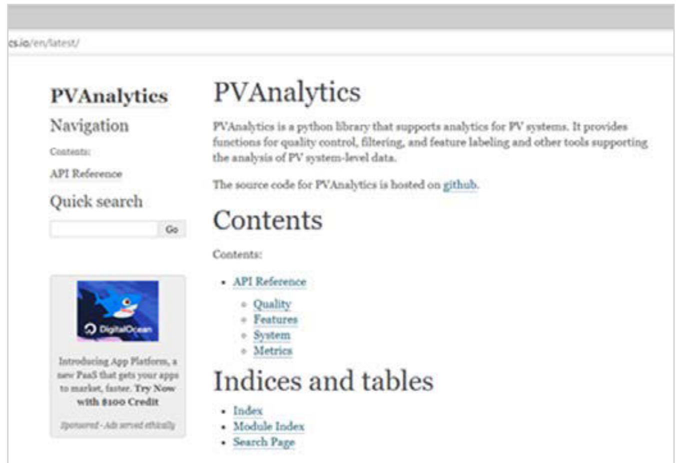
Data Cleaning for Degradation Analyses

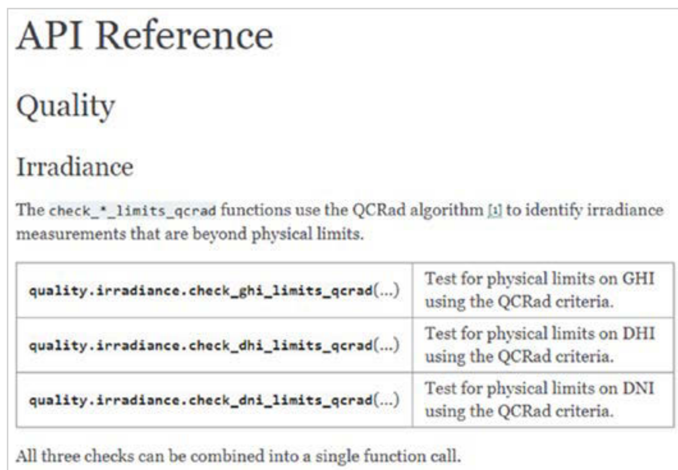
PI: Clifford Hansen, Sandia

Summary of Result: Our project improves tools to prepare data for analysis of PV system degradation. Data preparation involves filtering to remove low-quality data and labeling times when system output is affected by external factors such as inverter outages. Currently, data preparation is labor-intensive and relies heavily on visual interpretation by analysts.

We have launched the first collaborative public software library—PVAnalytics—to organize and distribute reusable code for data preparation: *https://github.com/pvlib/pvanalytics*. This resource provides functions for quality control, filtering, feature labeling, and other tools supporting the analysis of PV system-level data.

We are pioneering methods to automatically translate textual operations and maintenance records to time series of system condition, an exciting application of state-of-the-art text analytics we call "text to timeseries." Our work has potential to automate and democratize the labor-intensive work to prepare data for analysis.





We have created a public software library—PVAnalytics—that provides functions for quality control, filtering, and feature labeling and other tools supporting the analysis of PV system-level data. It can be accessed on GitHub, as shown here.

LEARN MORE

GitHub. 2020. "*pvanalytics." https://github.com/pvlib/pvanalytics*.

Contact Dr. Clifford Hansen (*cwhanse@sandia.gov*) for pvanalytics or Dr. Thushara Gunda (*tgunda@sandia.gov*) for the text-to-timeseries research.

Central Data Resource

Core Objective

Key Result:

Data Hub Achieves Tremendous Growth in Users, Resources, and Capabilities

PI: Robert White, NREL

Summary of Result: Constructing a virtual laboratory-based consortium requires functionality where all the researchers and resources can effectively, efficiently, and securely manage their data and share it with other colleagues and eventually the public. The Data Hub provides the platform for data management and sharing to support the DuraMAT Consortium. Over the past four years, the Data Hub has continued to grow and improve in capability, visibility, and available resources. In the last year especially, there has been a tremendous surge in the number of users, resources archived, and Hub capabilities.

The Hub interface for researchers has been improved by a major upgrade of the main underlying platform, an additional capability to upload many files at once during a single upload, and a new tool that can extract, process, and push data from the accelerated testing instrument directly to the Data Hub.

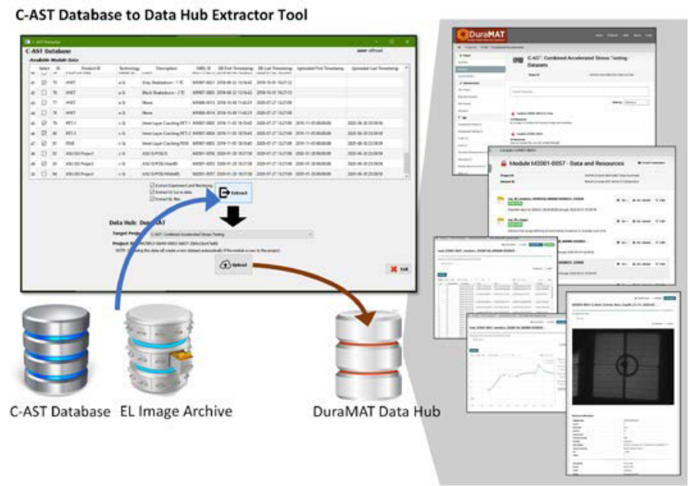


Figure 1: The combined-accelerated stress test (C-AST) extractor tool Extractor tool automatically scans the instrument database and file archives to marshal data files into a payload for uploading into the C-AST project on the Data Hub.

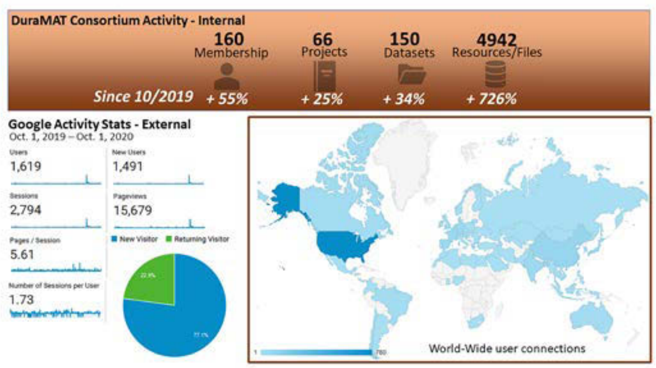


Figure 2: Current usage statistics for internal and external activity on the Data Hub.

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DuraMAT. 2019. "An Introduction to the DuraMAT DataHub Webinar (Text Version)." *https://www.duramat.org/datahub-recording-text.html*.

DuraMAT. 2020. "Data Hub User Manual." *https://datahub.duramat.org/dataset/help-and-tutorial/resource/eac65053-2a30-432f-b7e5-c95d8702ff60*.

White, Robert R. 2020. "A Researcher's Guide to the DuraMAT Data Hub: How to Make It Work for Your Project and Research." DuraMAT. *https://www.duramat.org/assets/pdfs/duramat-webinar-august2020.pdf*.

Central Data Resource

Core Objective

Key Result:

PV-Pro: Extracting Module Parameters from Operating Data

PIs: Todd Karin and Anubhav Jain, LBNL

Summary of Result: The production and operating data of PV commercial systems typically do not provide detailed insight into module performance. For example, while total power output is recorded (which measures total degradation), detailed measurements that provide insights into the cause of degradation are lacking. The PV-Pro project aims to reconstruct module parameters by examining DC voltage, DC current, module temperature, and plane-of-array irradiance measurements. The methodology is based on the recent *Suns-Vmp* method developed in the research literature and is being expanded upon and formalized for this project.

Using both synthetic and field operation data as a basis, the PV-Pro library implements a series of data processing steps that ultimately lead to data with voltage versus current characteristics at maximum power point and under different temperature and irradiance conditions. These data, usually averaged over a few days, are fit to a diode model to extract parameters such as series resistance, shunt resistance, diode factor, and more. With the method in place, more insight into performance degradation can be obtained without needing to conduct field I-V studies or installing *in situ* I-V monitoring equipment. PV-Pro has demonstrated the capability to determine module parameters accurately on synthetic datasets and has also produced results consistent with field I-V measurements on outdoor data.

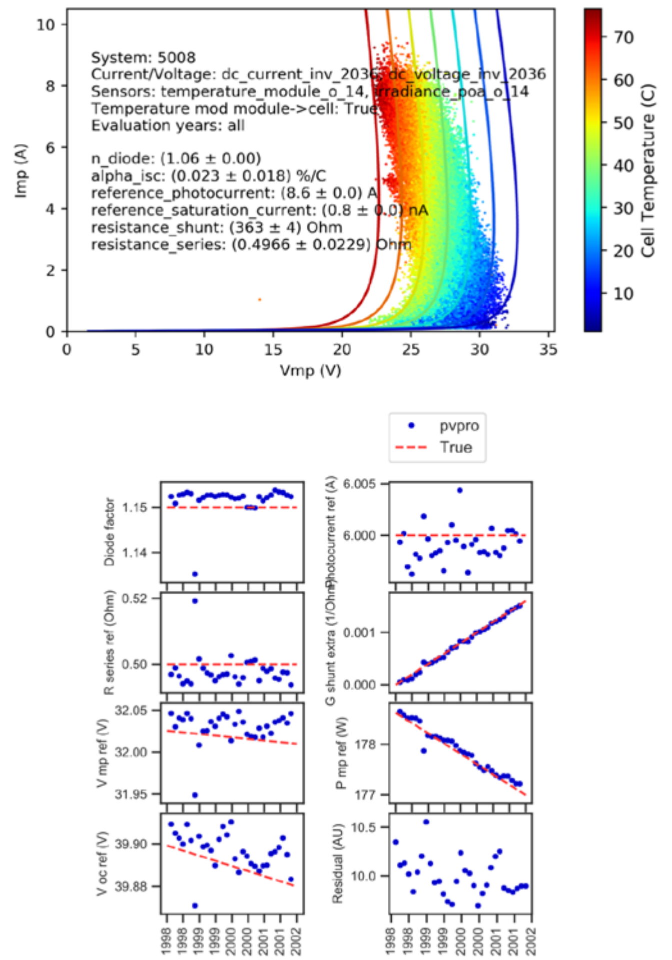

Figure.2 Top: Example of data (scatter points) collected over a few days of maximum power point current and voltage under different conditions. These data are used to fit a single set of diode parameters that explain the variation of the I-V curves with temperature and irradiance (solid lines). Bottom: Example of PV-Pro-determined module parameters (blue) as compared to the true values (red line) that were used to generate a synthetic dataset for testing.

LEARN MORE

Code repository:
GitHub. 2020. "pvpro." *https://github.com/DuraMAT/pvpro*.

Multi-Scale, Multi-Physics Model

Core Objective Lead: Nick Bosco, nick.bosco@nrel.gov

Develop modeling tools to rapidly scale accelerated testing results and quantitatively assess the impacts and degradation modes of new materials and designs.

Key Results:

- Quantify relevant driving forces for mechanically related failures in full-sized modules.
- Define equivalent mini-module form and mechanical loading to replicate the relevant stress induced in full-sized modules through both accelerated testing and field deployment.
- Define an equivalent accelerated test for modules containing electrically conductive adhesive (ECA) interconnects.
- Define an accelerated test for ECA interconnect durability that is equivalent to the well validated testing used for metallic solders.

Multi-Scale, Multi-Physics Model

Core Objective

Key Result:

A Fully Detailed, Multi-physics Minimodule Computational Modeling Platform

PI: James Hartley, Sandia

Summary of Result: Mechanisms for PV damage and degradation depend on the specific materials, construction, and cell interconnection designs used. Our research aims to better understand the relationships between these factors. By constructing highly detailed, 3D minimodule computational models with resolution of components down to individual solder joints, we can simulate the response of the module package in coupled electrical, thermal, and mechanical environments while capturing the effect of geometric interactions and time- and temperature-dependent materials. Degradation predictions such as cell fracture, delamination, or joint fatigue can be made in the context of a real-life laminate with minimal simplifications about how exposure environments propagate to damage sites.

Minimodule models were developed based on the combined-accelerated stress test protocol to enable validation against experimental observations. These minimodule models build on previously developed full-module models by also accepting the full-scale predicted module states as input boundary conditions for localized, component-scale analyses. Sensitivity analyses will rank the relative influence of geometric design parameters and material properties on the thermal-mechanical stresses in the cell and backsheet of minimodules.

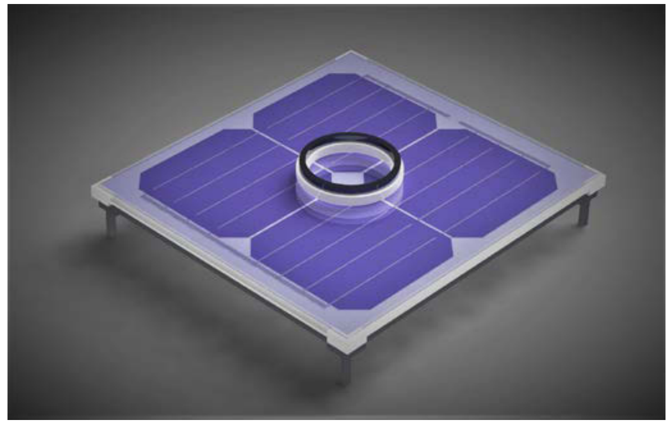

Figure 1. Rendering of modeled minimodule with resolution of interconnects, bussing, and test fixtures. Fully modeling the domain enables environmental inputs to be realistically propagated to areas of interest without simplification.

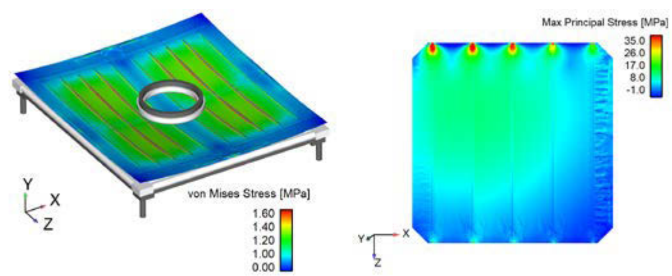

Figure 2. Simulated principal stresses occurring on the backsheet (right) and cell (left) for a tested minimodule. Simulations enable analysis of how geometry and materials influence the localized propensity for failure.

LEARN MORE

Meert, Joseph, et al. 2020. "Computational Modeling of Photovoltaic Mini-Modules Undergoing Accelerated Stress Testing. " IEEE 47th Photovoltaics Specialists Conference (Virtual). June 15–Aug. 21, 2020.

Hartley, James Y., et al. 2020. "Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load. " IEEE Journal of Photovoltaics 10, no. 3 (May): 838–843, May 2020, *https://ieeexplore.ieee.org/document/9016369*.

Multi-Scale Multi-Physics Model

Core Objective

Key Result:

First Measurement of Module Displacement with Digital Image Correlation

PI: Joshua Stein, Sandia

Summary of Result: Although much effort has been made to identify the presence and length of PV cell cracks in laminated modules using electroluminescence (EL) and ultraviolet fluorescence imaging techniques, little is known about the distribution of crack apertures or gaps and how they change with variable temperature and mechanical stress. One major challenge for researchers is accurately measuring crack apertures in full-sized modules with most existing optical methods (e.g., microscopy, optical profilometry, light transflection, etc.).

In our work, we are applying a relatively new application of digital image correlation (DIC) to this problem. DIC is able to measure cell crack apertures in laminated, full-sized modules down to a few microns. This method characterizes spatial displacements in 3D by analysis of paired stereoscopic photos of PV modules before, during, and after the stress is applied. The method works best when a random dot pattern is applied to the surface of the cells prior to lamination. The dots can be composed of reflective paint or an infrared-transparent fluorescent ink that allows EL images to locate the position of cracks.

We have recently demonstrated this application to module mechanical load testing, showing the first known example of using DIC to measure full module displacement under loading. We will also attempt to use DIC to measure PV cell crack apertures as a function of mechanical and thermal loading.

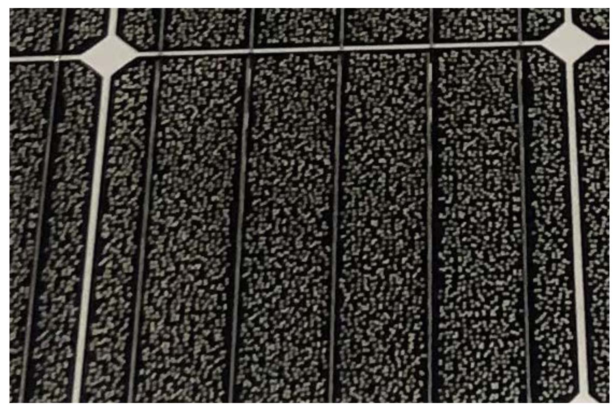

Figure 1: Close-up of dot pattern on full module

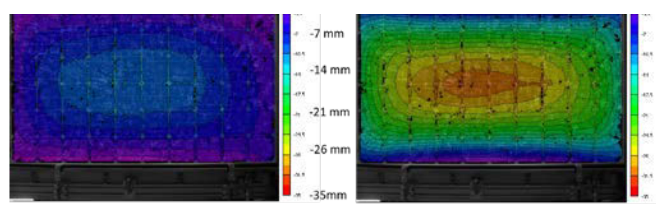

Figure 2: Test applied 0 to -4,000 pascals to back of module in ~-500 Ps increments. Ten images at each pressure were processed using Vic3D software to calculate displacement in Z up to -35 mm.

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Libby, Cara, and Joshua Stein. 2020. "Detailed Investigations into PV Cell Cracks—Why Some Cracks Can Lead to Power Loss." DuraMAT Webinar (November). *https://www.duramat.org/assets/pdfs/duramat-webinar-nov-2020.pdf*.

Multi-Scale Multi-Physics Model

Core Objective

Key Result:

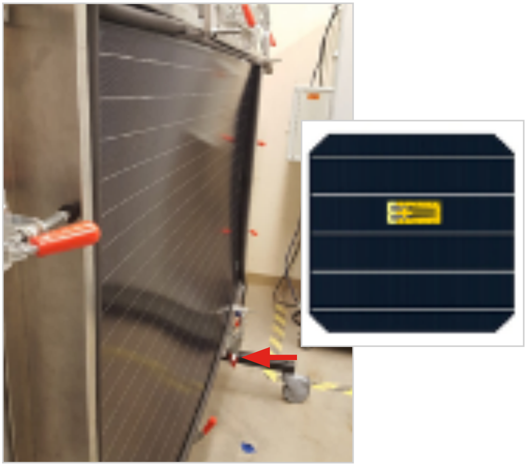
In Situ Measurement of Cell Strain During Module Mechanical Loading

PI: James Hartley, Sandia

Summary of Result: The internal state of modules undergoing mechanical loading is difficult to characterize but has important implications for understanding degradation mechanisms such as cell fracture and crack opening. Our research aims to develop an experimental method for directly measuring cell strains using electromechanical strain gauges laminated inside the module. Measured cell strain information helps to quantify internal module states under environmental loading conditions and provides comparison data for validating cell strains predicted by computational modeling.

In partnership with D2Solar LLC, we have constructed four prototype modules containing strain gauges embedded inside the module laminate. By subjecting these instrumented modules to a controlled mechanical test sequence, we have successfully demonstrated a proof-of-concept correlation between embedded strain gauge outputs, externally measured module shapes, and predicted strains from computational modeling. Following the release of mechanical pressure, we measured time-dependent material relaxation effects.

With more complete baselining and characterization of this methodology, onboard strain gauge outputs could be used to supplement or even replace existing measurement methods for understanding module states in realistic deployment environments.



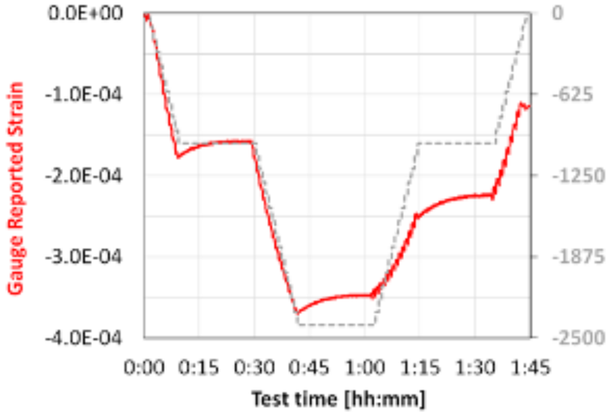


Figure 1: Instrumented module undergoing a mechanical pressure load test sequence (top). Gauge-reported strain correlated closely to applied pressure, and time-dependent effects of material relaxation on cell strain were evident (bottom).

LEARN MORE

Maes, Ashley, James Hartley, Mike Rowell, Charles Robinson, and Tariq Khraishi. 2020. "Instrumented Modules for Mechanical Environment Characterization and Simulation Model Validation." 47th IEEE Photovoltaics Specialists Conference. Virtual. June 15–August 21, 2020.

Multi-Scale Multi-Physics Model

Core Objective

Key Result:

Moisture Can Lower the Fracture Resistance of Epoxy-Based ECAs

PI: Nick Bosco, NREL

Summary of Result: New interconnect schemes that replace metallic solders with electronically conductive adhesives (ECAs) are appearing in recent embodiments of crystalline silicon PV modules. These include shingled cell designs as well as more traditional tabbing ribbon approaches where the ECA is being used as a direct replacement for solders. This transition represents a significant material change, and a proper understanding of the durability and reliability of the new interconnect needs to be established.

Our overall technical goal is to develop the framework for a unified constitutive model for ECA to provide an assessment of the new interconnect's durability and reliability. To achieve this goal, we utilize a three-layered approach: (i) materials characterization, (ii) numerical modeling, and (iii) validation. In our second year, we extended the materials characterization effort to include environmentally influenced fracture mechanics properties and applied our previously developed materials models to complete multiscale numerical simulations of the interconnects through both on-sun and accelerated test conditions. We found that fracture resistance of the candidate ECA decreases with increasing moisture level and that in humid environments, accelerated stress conditions may propagate debonding in low-quality ECA joints.

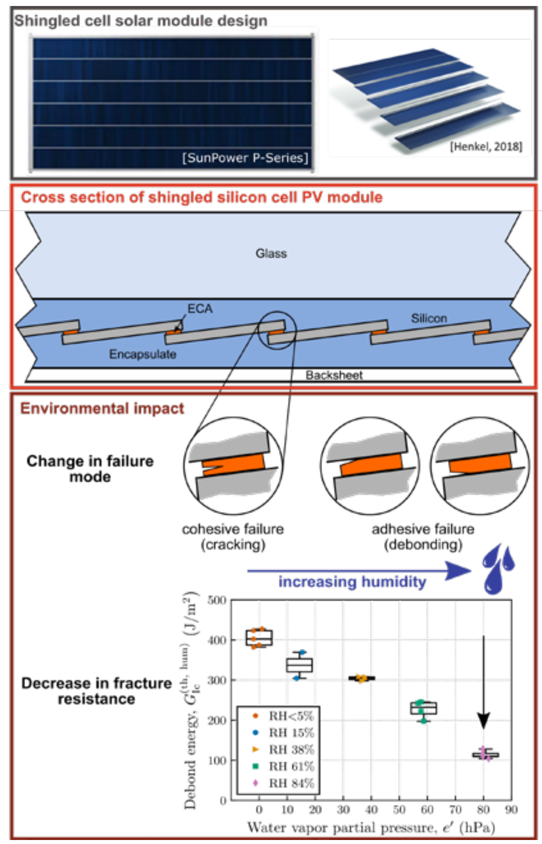


Illustration of the shingled cell technology using ECA as interconnect. Humid environments can weaken the ECA joint by lowering the fracture resistance and changing the failure mode.

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Bosco, Nicholas, and Martin Springer. 2020. "Investigation of Failure Modes, Mechanisms and Driving Forces for Electrically Conductive Adhesives as Interconnects in PV Modules." Paper presented at the 37th European Photovoltaic Solar Energy Conference and Exhibition Proceedings (virtual). *https://www.eupvsec-proceedings.com/proceedings?paper=48987*.

Springer, Martin, and Nicholas Bosco. 2020. "Environmental Influence on Cracking and Debonding of Electrically Conductive Adhesives." Engineering Fracture Mechanics 107398. *https://doi.org/10.1016/j.engfracmech.2020.107398*

Disruptive Acceleration Science

Core Objective Lead: David Miller, David.miller@nrel.gov

Data-driven accelerated testing of PV material, component, module, and system specimens that enables degradation rate models and screening of design or material weaknesses without *a priori* knowledge of failure modes

Key Results:

- Demonstration of an accelerated testing method capable of identifying materials and design field failures that are not identified by standardized industry tests:
    - The application-based, wC-AST method was demonstrated to identify multiple failure modes (e.g. backsheet cracking, interconnect corrosion, LeTID) observed in PV installations.
- Post-examination of specimens (DECS, optical mapping, voltage ionization, and UV-LID projects) has confirmed degradation mode(s) resulting from accelerated testing and revealed mechanism-specific insights to improve the understanding and the corresponding degradation rate model(s).
- Identification and quantification of the effects of UV exposure and its contributions to known degradation modes.

Disruptive Acceleration Science

Core Objective

Key Result:

Application of Acceleration Science and Validation for Combined-Accelerated Stress Test (C-AST) Development

PI: Peter Hacke, NREL

Summary of Result: Numerous new field failures are found in modules that pass qualification testing. As a result, mode-specific tests are created only after the failure has been found in the field and industry has solutions available. Stakeholders considering using new PV technologies realize risk that increases the levelized cost of energy. To lower this risk, we have developed a combined-accelerated stress test (C-AST) to detect both known and new, unknown degradation modes Figure 1.

A multi-environment stress test with winter, spring, tropical, and high-desert protocols was devised to expose the modules to all climatic extremes. Acceleration factors were calculated for the tropical cycle based on mechanism-specific rate equations and activation energies. For the outer polymer layer, acceleration factor was calculated for UV degradation to be $f(T, G) = 17.3$; for inner layer PET hydrolysis, $f(T, RH) = 426$; and for electrochemical corrosion, $f(I) = 14.1$. Here, T is the module temperature, G is the full spectrum irradiance on the plane of array of the module, RH is the relative humidity on the module surface, and I is the leakage current through the module packaging (see ref. Hacke, P. et.al. below for details)

Recent studies in C-AST include differentiation of backsheets for outer and inner layer cracking; studies of durability of flexible front sheets on both silicon and thin film modules; cell breakage; and comparisons between glass/glass modules and glass backsheet modules. An extended duration test of a shingled cell module was also performed over 214 days, for which the power and electroluminescence characterizing its durability are shown in Figure 2.

Figure. 1: The C-AST chamber (left) and modules under test inside (right)

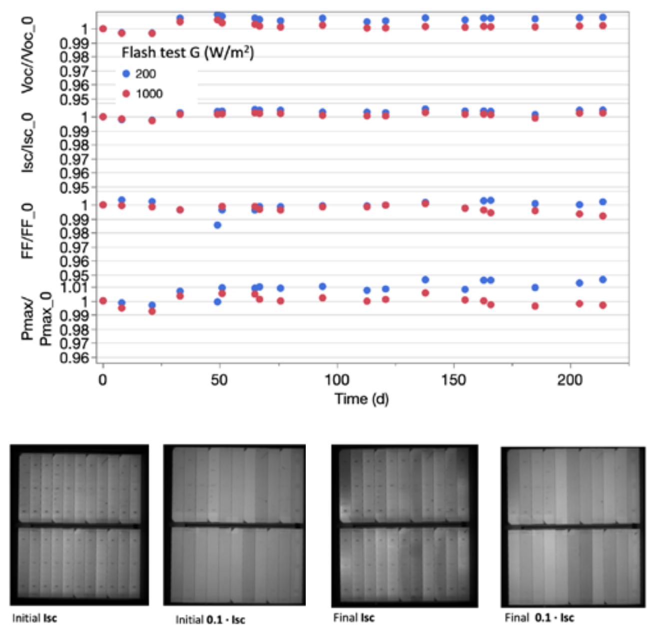


Figure. 2: Shingled module STC power sustained after 214 days of stress testing (top) and initial and final electroluminescence at two current levels (bottom)

LEARN MORE

Hacke, Peter, et al. 2020. "Establishing Module Durability with Combined-Accelerated Stress Testing." Presented at the 10th International Conference of Crystalline Silicon Photovoltaics 2020 (online). *https://cms2020.siliconpv.com/video/list*.

Owen-Bellini, Michael, et. al. 2020. "Advancing Reliability Assessments of Photovoltaic Modules and Materials Using Combined-Accelerated Stress Testing, Progress in Photovoltaics: Research and Applications, 2020; 1– 19. *https://onlinelibrary.wiley.com/doi/10.1002/pip.3342*.

Disruptive Acceleration Science

Core Objective

Key Result:

Applying the DECS Method to Precommercial Backsheets for More Robust Product Development

PI: Michael Owen-Bellini, NREL

Summary of Result: New PV backsheets have been marred by early failures in the field, due, in part, to insufficient testing and failure analysis during the development phase. Our approach uses thorough post-stress testing materials characterization, which includes a suite of chemical, structural, and mechanical characterization, which we call the DuraMAT's "DECS method." This approach allows a deeper understanding of the backsheet materials and how they deteriorate, informing how they might be improved for longer lifetimes. This allows a deeper understanding of the backsheet materials and how they deteriorate, informing how they might be improved for longer lifetimes.

Previously, our work focused on examining commercial backsheets that already experienced field failures. Recently, we have examined a precommercial polyamide (PA)-based-based fluoropolymer-free co-extruded backsheet that failed in a combined-accelerated stress test (C-AST). By applying the DECS method, we can determine the mechanisms for failure and understand how to mitigate them. Scanning electron microscopy revealed increased surface roughness due to erosion (Figure 1). Differential scanning calorimetry (DSC) revealed that an increase in crystallinity of the polyethylene core layer upon aging was likely responsible for the embrittlement and ultimate failure (Figure 2).

With this work, we demonstrate best practices for testing and characterizing materials during the product development stage, such that early field failures can be avoided. PA-based backsheets have a bad reputation due to the unmitigated failure of the infamous "AAA." We show here that PA is not an inherently bad material and can be made to develop robust backsheets with appropriate design during development.

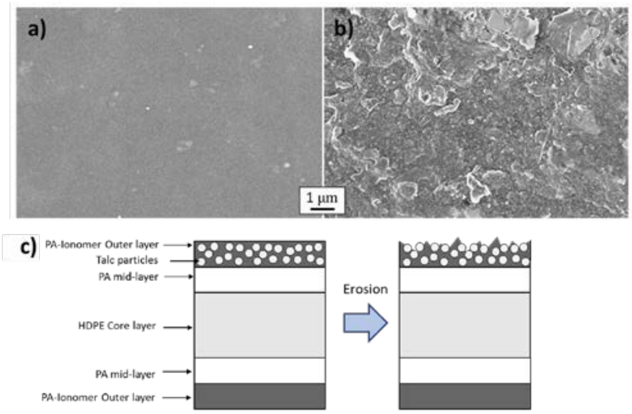


Figure 1. Scanning electron microscope images for (a) unaged and (b) aged backsheet sample outer surface. Increased roughness and erosion are visible at the surface. Fourier-transform infrared spectroscopy spectroscopy and X-ray photoelectron spectroscopy (not shown) were able to detect an increase in talc in the aged samples. Talc is used as a dimensional stabilizer in this backsheet and becomes more exposed with erosion of the outer layer.

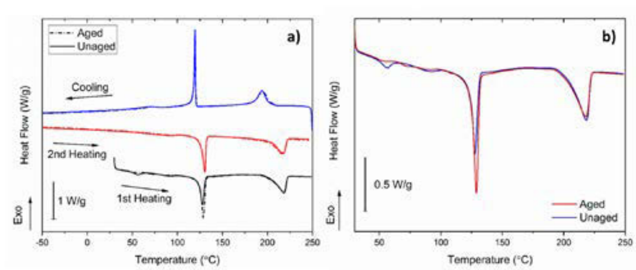


Figure 2. DSC (a) full and (b) cooling curves for aged and unaged backsheet material. Large peak corresponds with the polyethylene core layer, which increases in crystallinity with age. This increase is likely responsible for reduction in tearing energy (not shown) and failure of the backsheet.

LEARN MORE

Owen-Bellini, Michael. 2020. "An Overview of Backsheet Materials for Photovoltaic Modules" DuraMAT Webinar. *https://www.duramat.org/assets/pdfs/duramat_webinar_may2020.pdf*.

M. Owen-Bellini, Michael, et al. 2020. "Towards Validation of Combined-Accelerated Stress Testing Through Failure Analysis of Polyamide-Based Photovoltaic Backsheets." Scientific Reports. *https://doi.org/10.1038/s41598-021-81381-7*.

Key Result:

Specimen Size Effect Identified, with Compromising Loss of UV Absorber in Quantitative Optical Mapping

PI: David C. Miller, NREL

Summary of Result: Spatial quantification can reveal insights about degraded PV materials and modules not realized from bulk- or single-point measurements. We have created a custom optical mapping instrument that can be used to quantify the transmittance and reflectance of a variety of material, coupon, and multiple-input multiple-output specimens. From fiber optics, the instrument uses a 2.5-mm diameter spot size (rather than the test region greater than 1 cm, as in commercial instruments) to allow high resolution mapping, shown in Figure 1. In the Figure 2 example, a specimen size effect was confirmed for glass/encapsulant/glass coupons after ultraviolet (UV) weathering (IEC TS 62788-7-2 method A3).

The standard 5-cm square coupons had uniform discoloration (yellowness index [YI]) and a steady UV cut-off wavelength (λcUV). The larger 7.5-cm coupons had a spatial-dependent YI with λcUV decreased at the center, identifying a critical loss of the protective UV absorber. We have also developed helpful insights, such as sample heterogeneity, from examining samples after falling sand, linear brush abrasion, damp heat (85C/85% relative humidity), and field soiling experiments. After optimizing the instrument to focus on transmittance (direct or with an integrating sphere) measurements in year 1 of the project, we hope to emphasize reflectance measurements (hemispherical or scattered light) in year 2.

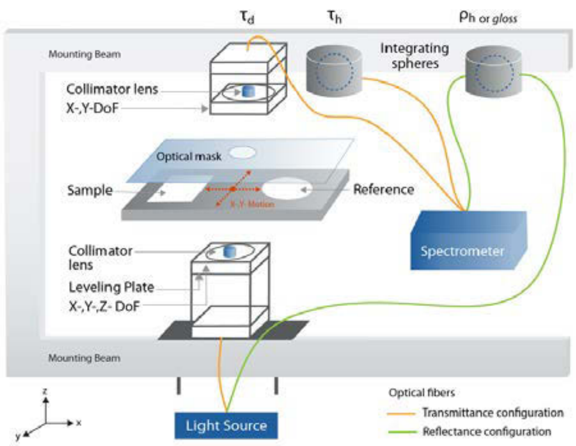


Figure 1: Isometric schematic representing the physical implementation and operational configurations: direct transmittance, τ_d; hemispherical transmittance, τ_h; hemispherical reflectance, ρ_h; and haze (scattered reflectance, ρ_s) for the custom optical mapping instrument.

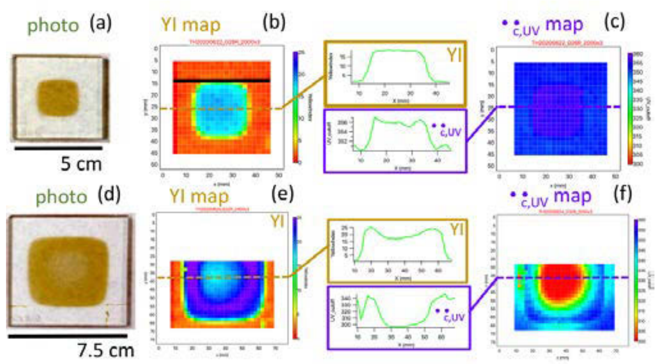


Figure 2: Comparison of 5-cm and 7.5-cm coupons after UV weathering including visual appearance (a) and (d); discoloration (YI) (b) and (e); and the UV cut-off wavelength (c) and (f).

LEARN MORE

PVQAT. 2020. “UV, Temperature, and Humidity: Task Group 5. *https://www.pvqat.org/project-status/task-group-5.html*.

PVQAT TG5. Sept. 15, 2020. “Recent Results of the PVQAT TG5 Study 2.” *https://www.pvqat.org/project-status/task-group-5.html*

Disruptive Acceleration Science

Core Objective

Key Result:

Understanding UV Wavelength-Dependent Degradation of High-Efficiency PV Modules

PI: Peter Hacke, NREL

Summary of Result: This work aims to quantify the susceptibility of emerging high-efficiency PV cell types under the stress of ultraviolet (UV) light or elevated positive electric potential (Figure 1). This project provides an understanding of the degradation mechanisms to best advise module-level solutions to minimize degradation rates through a 50-year field life.

To determine which cell technologies are most susceptible to UV light-induced degradation, we performed a UV screening test on 10 types of various cells, including bifacial and legacy. The I-V results for the unpacked cells after 3,000 hours show that new cell designs (SHJ, IBC, PERT, and PERC), suffered from a higher P_{max} degradation than the conventional Al-BSF cells.

In the second UV screening experiment, we studied the UV wavelength-dependent degradation of three of the most affected cell types (previously identified) using five different sharp cut-on, long-pass UV filters. For all cell types, the power loss increases with decreasing UV filter cut-on wavelength (Figure 2). Higher P_{max} degradation was observed in SHJ cells with a greater reduction in I_{sc} and V_{oc}. The degradation in the PERT cells is more significant at λ_{333}, while the IBC cells showed minimal degradation at all wavelengths. This suggests that the cell types are dominated by different degradation mechanisms, which will be extensively characterized by external quantum efficiency/reflectance, SIMS, and X-ray photoelectron spectoscopy.

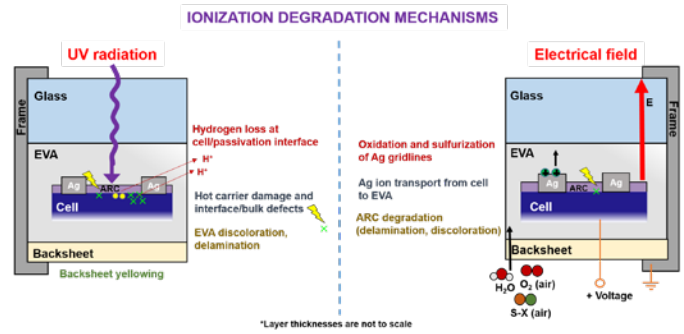


Figure 1: Schematic of the mechanisms contributing to UV-LID (left) and high-voltage positive bias degradation (right) in a silicon PV module

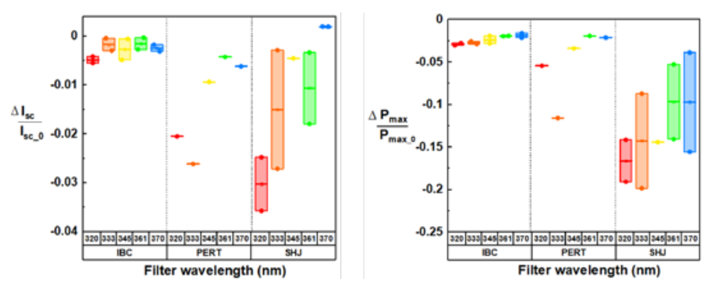


Figure 2: Degradation of I-V parameters for unpackaged solar cells (IBC, PERT, and SHJ) after 2,000 hours of UV exposure using five different sharp cut-on filters: 320 nm, 333 nm, 345 nm, 361 nm, and 370 nm

LEARN MORE

DuraMAT. 2020. "PV Module-Level Solutions for Degradation by Ionization Damage." *https://www.duramat.org/ionization.html*.

Hacke, Peter, David C. Miller, Katherine Hurst, Stephanie Moffitt, Archana Sinha, and Laura Schelhas. 2020. "Module-Level Solutions for Degradation by Ionization Damage." Photovoltaic Reliability Workshop – Lakewood, CO, February 25–27, 2020. *https://pvrw.nrel.gov/sites/default/files/PVRW_2020_program-final_draft.pdf*.

Fielded Module Forensics

Core Objective Lead: Laura Schelhas, laura.Schelhas@nrel.gov

Apply module and material characterization techniques to understand degradation modes, mechanisms, weaknesses, and the impact of design changes to ultimately identify opportunities for improved reliability.

Key Results:

- Pioneer new nondestructive/field compatible methods to evaluate the impact of cell cracks on module performance.
- Directly image cell stress using X-ray topography to quantify the impact of module loading on cell reliability.
- Quantify the potential increase in reliability for glass/glass module construction.
- Validate accelerated test protocols against field failures using a combination of structural, chemical, and mechanical characterization.
- Use lab analysis and characterization to provide feedback for PV materials and components including backsheet, cell, encapsulant, glass, gridlines, interconnects, solder bonds, etc.

Fielded Module Forensics

Core Objective

Key Result:

Antireflection Coatings for Photovoltaic Module Glass: How Long Do They Last in the Field?

PI: Todd Karin and Anubhav Jain, LBNL

Summary of Result: Antireflective coatings (ARCs) on the air-glass interface are used on almost all currently produced PV modules. However, ARC longevity can vary from less than 1 year to over 15 years, depending on coating quality and deployment conditions. A technique that can quantify ARC degradation nondestructively on commercial modules would be useful for both in-field diagnostics and accelerated aging tests.

We are developing a technique to measure ARC characteristics, including estimating thickness and porosity, using reflectance spectroscopy. The measurement is fast and nondestructive and can be carried out on-site using a modified commercially available integrating sphere. The equipment is used to measure the reflection spectrum of a spot on the module; the measured spectrum can be fitted to a theoretical simulation to estimate film thickness and porosity. Improvements to the method are being developed that would replace the integrating sphere with an off-the-shelf RGB camera, further simplifying the procedure. In this scenario, the presence and characteristics of ARCs could be determined by analyzing color shifts in an image of the module.

This project will develop a new method of measuring field degradation of antireflective coatings, which will help better explain the nature of observed power loss in modules as well as eventually lead to better designed coating materials.

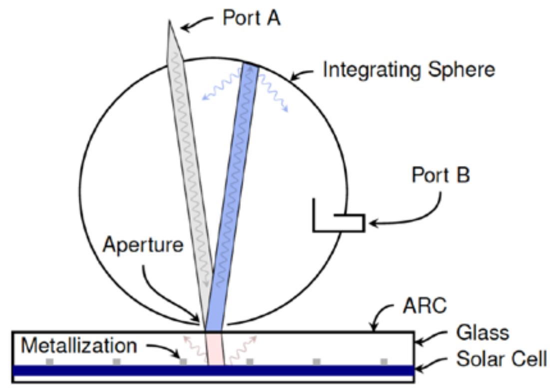


Figure 1: Schematic of integrating sphere probe for measuring ARC spectral reflectance

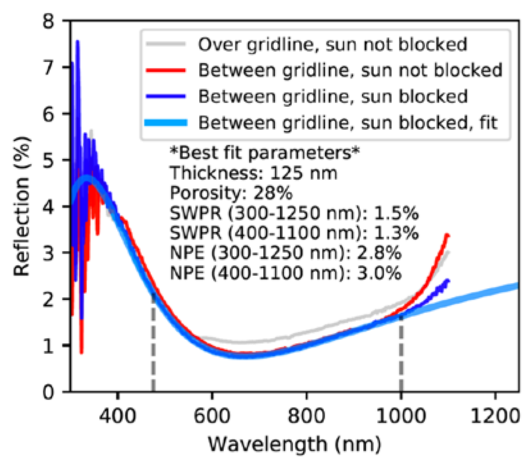


Figure 2: Outdoor measurement of anti-reflective coating characteristics on a commercial module. The reflectivity spectrum is fit to theoretical calculations and used to estimate film thickness and average porosity.

LEARN MORE

Karin, Todd, and Anubhav Jain. "Visual Characterization of Anti-Reflective Coating on Solar Module Glass." Presented at the 47th IEEE Photovoltaics Specialists Conference. Virtual. June 15–August 21, 2020. *https://www.youtube.com/watch?v=2v_GFQ6zm1U*.

GitHub. 2020. "pvarc." *https://github.com/DuraMAT/pvarc*.

Fielded Module Forensics

Core Objective

Key Result:

Digging into POE vs EVA Encapsulants' Role in the Durability of Glass/Glass Modules

PI: Laura T. Schelhas, NREL

Summary of Result: Glass/glass PV modules, where glass covers both the front and back of the module, are growing significantly in commercial popularity. This architecture is anecdotally expected to have greater durability than conventional glass/backsheet modules, yet little research has focused on the degradation mechanisms in glass/glass modules.

In this project, we aim to provide chemical, structural, and mechanical insights to enable cutting-edge understanding of the degradation processes at the material interfaces in glass/glass modules (Figure 1). We are developing and adapting module imaging, adhesion, and interfacial characterization methods specifically for glass/glass module structures. In phase 1 of our study, minimodules using polyolefin elastomer (POE) or ethylene vinyl acetate (EVA) encapsulants in glass/glass and glass/transparent backsheet architectures were stressed under damp heat with positive, negative, or no-voltage bias. Selected data shown in Figure 2 highlight the improved durability of modules with POE versus EVA encapsulants. The higher performance loss in EVA-containing modules is tentatively attributed to potential-induced degradation shunting and rear-side passivation polarization, where the degradation is worse in glass/glass versus glass/transparent backsheet structures.

These results reveal the importance of selecting materials compatible with the module construction, such as for glass/glass. Future mechanical and chemical characterization will complete the story of glass/glass module degradation, while further studies are planned to investigate glass/glass modules under sequential testing.

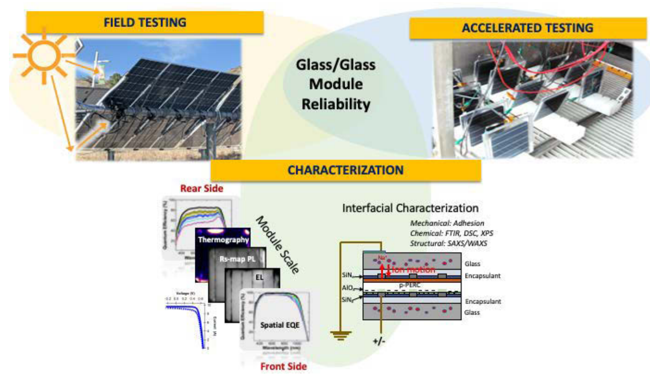


Figure 1: Schematic representation of project focus and approach

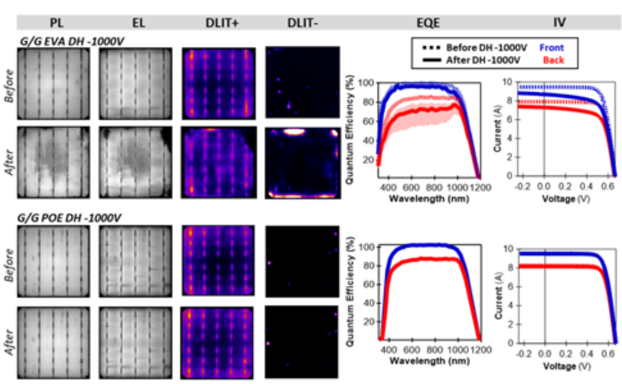


Figure 2: Select imaging, QE, and IV results for phase 1. Minimodule studies. The full study included minimodules exposed to damp heat (85°C/85% relative humidity) under both positive, negative, and no-bias conditions.

LEARN MORE

Publications in preparation:

Sinha, Archana, et al. 2020. "A Review of Degradation Modes of Glass/Glass Packaged Photovoltaic Modules" Invited to Journal of Physics D: Applied Physics.

Sulas-Kern, Dana B., et al. 2020. "Spatially-Resolved Characterization of Degradation Modes under Accelerated Stress in Bifacial Silicon Photovoltaics with Glass/Glass and Glass/Clear-Backsheet Packaging."

Conference presentation:"Investigating Interface Degradation in Glass/Glass Photovoltaic Modules." 2020. Presented at the PV Reliability Workshop, February 25–27.

Module Material Solutions

Core Objective Lead: Margaret Gordon, megord@sandia.go

Design, develop, and derisk innovative materials and module architectures to address PV reliability issues using DuraMAT capabilities.

Key Results:

- De-risk innovative materials using accelerated testing and materials forensics:
    - Characterize failure modes in ECAs; develop crack-tolerant metallization to increase reliability of cells; and design sustainable, reliable, recyclable backsheets.
- Enable new architectures including:
    - Flexible modules: define the technical requirement of each component in the flexible module as well as the overall material stack and develop a process to experimentally evaluate module performances; advance the reliability of bifacial modules through new transparent packaging materials.

Key Result:

Advanced *In Situ* Analysis of Electrically Conductive Adhesive Interconnects

PI: Zachary Holman, Arizona State University

Summary of Result: Electrically conductive adhesives (ECAs) are gaining market traction in the PV industry as an alternative to traditional solder interconnects; however, the long-term reliability of ECAs under PV operating conditions and environments is not well understood. Through our research, we demonstrated methods that can evaluate the quality of ECA interconnects through X-ray imaging techniques. X-ray projections can nondestructively image the ECA interconnects in a PV module. This technique provides qualitative insight into the alignment and shape of the ECA and can also image cracks within the ECA layer. Further, it gives a quantitative evaluation of the number and size of voids present in the ECA layer. X-ray tomography is a destructive imaging technique for more advanced analysis that produces a 3D rendering of the ECA-busbar overlap region, which details the precise location of voids and cracks; it can also evaluate the quality of the ECA-busbar interface.

We have demonstrated the capability of X-ray imaging techniques to provide a unique evaluation of the quality of the ECA interconnection, and we plan to further test a wide variety of ECA materials to give recommendations for maximizing the reliability of ECA-containing PV modules.

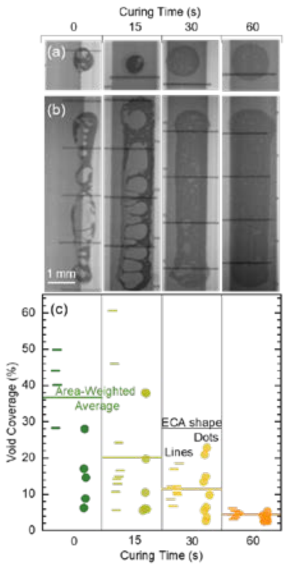


Figure 1: (a) and (b) X-ray projection of ECA segments in a shingled minimodule that were cured for varied times prior to lamination. (c) Plot depicting the percentage of void coverage in the ECA segments.

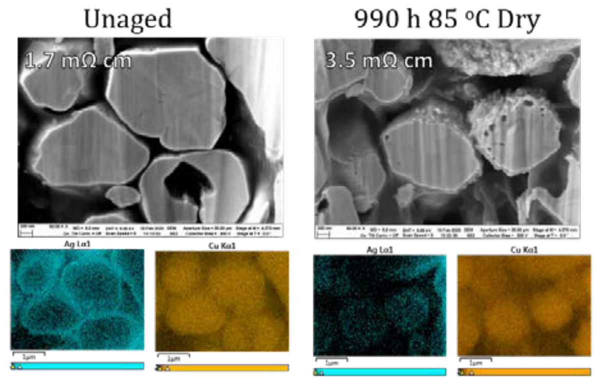


Figure 2: An ECA that contains Ag-coated Cu particles is shown before (left) and after (right) dry heat aging. The bulk resistivity increase appears to be due to the degradation of the Ag coating.

LEARN MORE

Hartweg, Barry, Kathryn Fisher, and Zachary Holman. 2020. "Failure Analysis of Electrically Conductive Adhesives in Shingled Solar Modules." Presented at the PV Reliability Workshop – Lakewood, CO, February 25–27, 2020.

Module Materials Solutions

Core Objective

Key Result:

Materials Engineering Innovations for Metallization:Bridging 50-Micron Gaps for the 50-Year Challenge

PI: Sang M Han, Osazda Energy and University of New Mexico (UNM)

Summary of Result: Osazda Energy, LLC and its team are on a path to commercialize a metal matrix composite paste (MetZilla™) capable of electrically bridging stress-induced cracks that appear in solar cells. MetZilla pastes, which consist of screen-printable silver paste and carbon nanotubes (CNTs), have shown increased ductility and fracture toughness while also offering self-healing to regain electrical continuity. However, integrating CNTs uniformly without agglomerations (see Figure 1) into various silver pastes designed for different cell architectures is no easy task with today's demand for thinner gridlines and flawless prints over hundreds of cells. To meet this challenge, Osazda Energy researchers have carried out a variety of different materials characterization techniques to continuously innovate product formulations to achieve enhanced fracture toughness of metallization. Our metallization can electrically bridge gaps ≥ 50 microns in cracked cells, potentially eliminating the cell-crack-induced degradation. Such crack tolerance would contribute toward a ≥ 50-year lifetime for PV modules.

With the help of Dr. Michael Woodhouse at the National Renewable Energy Laboratory, Osazda Energy has calculated that the CNT addition in MetZilla paste adds negligible cost ($0.0098/W) to module construction, while mitigating or potentially eliminating the cell-crack-related degradation.

The increased durability by reducing cell-crack-induced degradation would reduce module replacement costs, improving the operational lifetime and thus cashflow for utility-scale PV projects (see Figure 2).

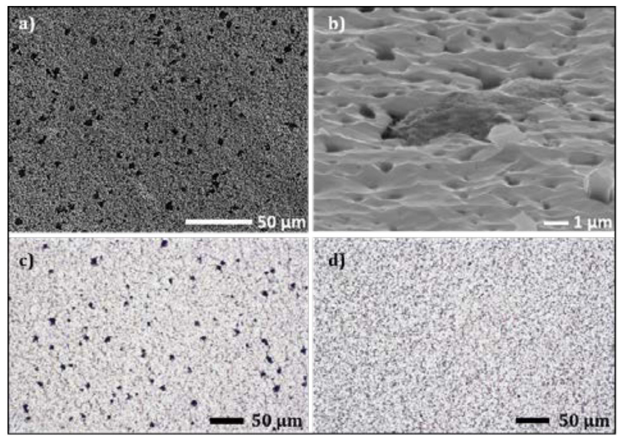


Figure 1: Scanning electron microscopy image (a) of CNT agglomerations (black dots) in unfired silver paste and (b) magnified view of CNT agglomeration on surface of fired silver paste. Optical microscope images of CNT agglomerations (c) before and (d) after optimal mixing.

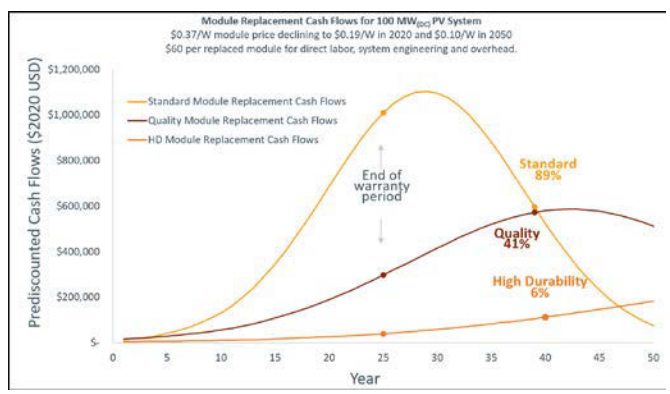


Figure 2: Module replacement cash flows for 100-MW PV system over 50 years. Courtesy of Michael Woodhouse and Henry Hieslmair.

LEARN MORE

Osazda Energy: *http://www.osazda.com/*.

YouTube. 2020. "American-Made Solar Price 90-Second Video." *https://youtu.be/dGnMenaamLI*.

Module Materials Solutions

Core Objective

Key Result:

Novel and Traditional Backsheets Are Readily Distinguished from Their Material and Mechanical Characteristics

PIs: Kurt Van Durme and Nicola Siccheiri, DSM Innovation

Summary of Result: As the PV industry rapidly expands across the world, there has been a growing interest in increasing the lifespan and reliability of PV modules. Recent concern has emerged regarding module recyclability and their component materials, including fluoropolymer-based backsheets. This study examines seven traditional and emerging backsheets. In Figure 1(a), the unaged backsheets are readily distinguished from their material characteristics (e.g., phase transition temperatures and crystallinity). The semicrystalline polyethylene terephthalate (PET) core layer distinguishes traditional backsheets—BS-3, -5, and -7—which melt (255°C) and crystalize (195°C) at higher temperatures. In contrast, the polyolefin (PO)-based backsheets—BS-1, BS-2, and BS-4—show the lowest melt (165°C) and crystallization (130°C) behavior. The same components materials and their characteristics contribute to their distinct mechanical response in Figure 1(b). Here, the traditional PET-based backsheets have a greater ultimate tensile strength, whereas the emerging PO-based products have a much greater compliance (strain-at-failure).

The BACKFLIP project will compare the performance and durability of the backsheets through accelerated testing (damp heat, IEC TS 62788-7-2) and natural weathering.

We plan to compare additional characteristics, including discoloration (b*), gloss, macro and micro appearance, MiMo I-V performance, EL characteristics, DC breakdown voltage, crystalline structure (small- and wide-angle x-ray), and polymer chemistry (FTIR).

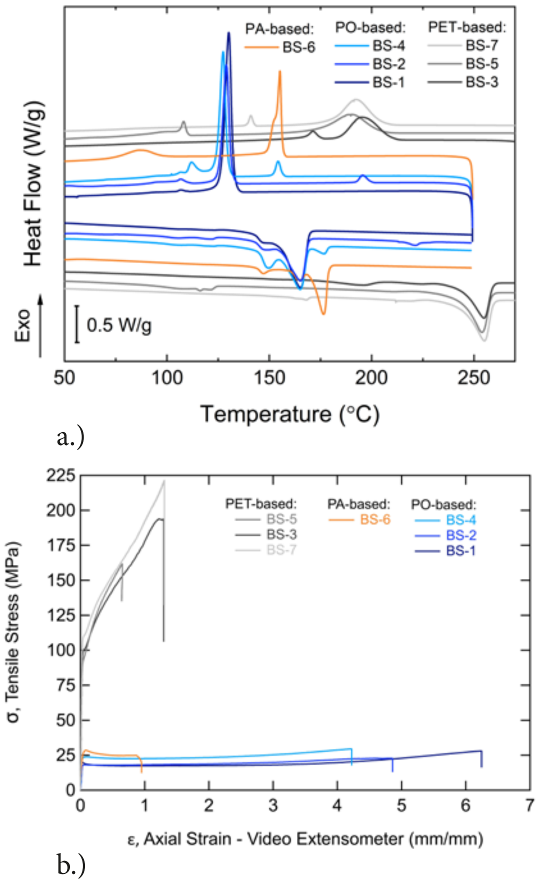


Figure 1: Comparison of the material and mechanical characteristics for the seven backsheets (unaged) in this study, including: (a) differential scanning calorimetry and (b) mechanical tensile response (stress/strain)

LEARN MORE

Sicchieri, Nicola, et al. 2020. "BACKFLIP: Determination of Backsheet Material Properties: A Comparison of Market-Benchmark BACKsheet Technologies to Novel Non-FLuoro-Based Co-Extruded Backsheet Materials and their Correlation and ImPact on PV Module Degradation Rates." DuraMAT. *https://www.nrel.gov/docs/fy20osti/76400.pdf*.

Key Result:

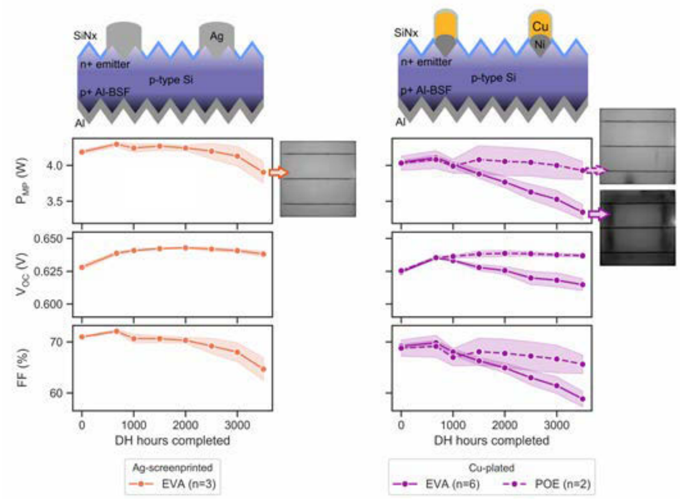
Testing to Enable Low-Cost, High-Performance Copper Contacts for Solar Cells

PI: Stuart Bowden, Arizona State University

Summary of Result: There are unanswered questions about the durability and long-term reliability of copper (Cu)-based contact schemes for silicon solar cells, and limited studies in the literature have specifically focused on the reliability of Cu contacts. Cu contacts are thought to be lower cost and higher performing than conventional silver-based contacts but have thus far achieved little market share.

In this project, we fabricate crystalline silicon (c-Si) solar cells with Cu-plated contacts on both conventional and high-efficiency cell architectures (aluminum BSF, PERC, and, SHJ), then expose the cells to environmental stress based on standard qualification protocols. We investigate conventional and emerging encapsulants and module architectures (ethelyne vinyl acetate [EVA] versus polyolefin encapsulent [POE]; glass/backsheet versus glass/glass) to search for vulnerabilities introduced by Cu-plated contacts in a wide variety of conventional and forward-looking cell and module configurations.

We have published some of the first results on unique failures during qualification-style testing, indicating both when the failures seem related and unrelated to Cu contacts. In particular, we observe diode degradation with damp heat stress in diffused junction cells with Cu-plated contacts (see reference 2 below). This degradation is atypical for damp heat stress and suggests Cu contamination of the c-Si wafer. Further work on destructive forensic analysis of degraded



Degradation with increasing durations of damp heat stress for Ag-screen-printed (orange) and Cu-plated (purple) solar cell contacts. In Cu-plated contacts, degradation is minimized by POE encapsulants (dotted purple line), whereas EVA (solid purple line) results in diode degradation and lifetime loss at the cell edge.

LEARN MORE

Karas, Joseph, et al. 2020. “Damp Heat Induced Degradation of Silicon Heterojunction Solar Cells With Cu-Plated Contacts.” IEEE Journal of Photovoltaics 10, no. 1: 153–158. *https://ieeexplore.ieee.org/document/8878168*

Karas, Joseph, et al. 2020. “Degradation of Copper-Plated Silicon Solar Cells with Damp Heat Stress.” Progress in Photovoltaics 28, no. 11: 1175–1186. *https://doi.org/10.1002/pip.3331*.

Arizona State University Solar Power Lab: *https://pv.asu.edu/*

DuraMAT Workforce Development

Workforce development is central to DuraMAT's mission through our "DuraMAT Early Career Scientists" (DECS) program. The DECS program consists of early career scientists and postdoctoral researchers at the national laboratories who are primarily funded (>50%) to work on DuraMAT projects. We train these researchers in the skills they will need to work in the PV industry or national laboratories. They also serve as the "glue" that holds the consortium together. Each lab has one or two DECS participants each year who participate in both research and leadership roles throughout their appointments.

In the last year, the DECS have refined their approach to validating accelerated testing protocols against field aging and applied the method to new, precommercial materials. A highlight and summary of their recent progress can be found on page 32. Additionally, the DECS have expanded into new territory including cell cracking. Members of the DECS have published a number of papers in the last year as well as disseminated work at a number of international conferences.

This year, the DECS have added a number of new members, including Sona Ulicna (SLAC National Accelerator Laboratory [SLAC]), Martin Springer (National Renewable Energy Laboratory [NREL]), Thushara Gunda (Sandia National Laboratories [Sandia]), Dana Sulas-Kern (NREL), Laura Spinella (NREL), Bennet Meyers (SLAC), and Farhan Rahman (Sandia). The broader group meets monthly to discuss ideas and share their work. Additionally, Ashley Maes (Sandia) has completed her time at DuraMAT and made the move to the space solar industry.

In addition to the DECS, DuraMAT's university project serves as an additional venue for workforce development.

DuraMAT Workshop
Fall 2020, Zoomlandia

The Virtual DuraMAT Fall Workshop attracted 82 attendees from national labs, universities, and the PV industry. The workshop, scheduled over three half-days, focused on two objectives: first, providing a comprehensive review of all DuraMAT projects, and second, obtaining critical feedback on the progress and impact of DuraMAT's five core objectives. Combined, these reviews helped to assess how DuraMAT's efforts are addressing current and future issues in PV module material reliability.

The workshop held live overview presentations of each of the five core objectives and in-depth presentations of one highlighted project from each core objective. Prerecorded poster presentations of 5–10 minutes of all the projects were available for viewing for two weeks. In all, 21 projects (14 lab-led, 2 university-led, and 4 industry-led) were evaluated using a survey with questions about technical merit, outreach, and impact on the core outcomes. Each project was scored from 0–100, with 10–15 survey responses per project and fields for comments on strengths and weaknesses. On average, the projects scored an 82 in technical merit with a spread of 63–88, and 77 in communications/outreach with a spread of 61–85. Compared to last year, our projects were rated more highly on both technical merit and communications/outreach by 5–6 points. This indicates that DuraMAT projects on the whole are responding to Industry Advisory Board (IAB) and community feedback. The DuraMAT leadership team works with our PIs to coordinate between projects, improve communications, facilitate outreach, and provide targeted support as needed to ensure that the overall impact of the DuraMAT portfolio is greater than the sum of its parts. DuraMAT's focus in FY20 was on improving external communications and outreach, which was definitely a challenge in a fully virtual environment. Our efforts were bolstered by researchers spending more time publishing in lieu of travel, and we will continue to highlight and promote their excellent research results.

Live breakout sessions during the 2020 workshop focused on our core objectives. Rather than impose a structured set of questions, breakout leads (an IAB member and an early career researcher) were provided more open-ended questions to start the discussion, including questions about the most important topics DuraMAT should address in the upcoming year and in the next five years. The virtual format enabled us to run the breakouts in series, and each had about 30 industry participants and researchers discussing the work of each core objective and how it could benefit the PV community. A major outcome of these breakout sessions was the formation of two working groups for FY21: one investigating cell cracks in the PV module, and the second investigating

DuraMAT Workshop (Cont.)

reliability issues specific to glass/glass module designs. The DuraMAT consortium has funded a few efforts in each of these topic areas. The two working groups, through voluntary monthly meetings, connect these related DuraMAT research projects and also invite external researchers with insights to share, fostering a collaborative community informed by industry and focused on answering pressing PV stakeholder questions.

In our final session with the IAB, they indicated again that the structure and project portfolio of DuraMAT was aligned with our goals and making excellent progress. Our outreach has improved over 2019, and the IAB encouraged us to push for more communication, especially to diverse stakeholders from supply chain to foreign module manufacturers.

We look forward to our next workshop, in person, in the fall of 2021. We hope you will join us!

- Margaret, Teresa, and Laura

Publication and Research Output

https://www.duramat.org/publications.html

JOURNAL ARTICLES

1. Bosco, Nick, Martin Springer, and Xin He. 2020. "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite-Element Method Input." IEEE Journal of Photovoltaics *10, 5. 1424–1440. 10.1109/JPHOTOV.2020.3005086.*

2. Bosco, Nick, Stephanie L. Moffitt, and Laura T. Schelhas. 2019. "Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface." Progress in Photovoltaics: Research and Applications 27, 4. 340–345. *10.1002/pip.3106.*

3. Ellis, Benjamin H., Michael Deceglie, and Anubhav Jain. 2019. "Automatic Detection of Clear-Sky Periods from Irradiance Data." IEEE Journal of Photovoltaics 9, 4. 998–1005. *10.1109/JPHOTOV.2019.2914444.*

4. Hartley, James Y., Michael Owen-Bellini, Thomas Truman, Ashley Maes, Edmund Elce, Allan Ward, Tariq Khraishi, and Scott A. Roberts. 2020. "Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load." IEEE Journal of Photovoltaics 10, 3. 838–843. *10.1109/JPHOTOV.2020.2971139*

5. Jean, Joel, Michael Woodhouse, and Vladimir Bulović. 2019. "Accelerating Photovoltaic Market Entry with Module Replacement." Joule 3, 11. 2824–2841. *10.1016/j.joule.2019.08.012.*

6. Karas, Joseph, Archana Sinha, Viswa Sai Pavan Buddha, Fang Li, Farhad Moghadam, Govindasamy TamizhMani, Stuart Bowden, and André Augusto. 2019. "Damp Heat Induced Degradation of Silicon Heterojunction Solar Cells with Cu-Plated Contacts." IEEE Journal of Photovoltaics 10, 1. 153–158. *10.1109/JPHOTOV.2019.2941693.*

7. Karin, Todd, and Anubhav Jain. "Photovoltaic String Sizing Using Site-Specific Modeling." 2020. IEEE Journal of Photovoltaics 10, 3. 888–897. *10.1109/JPHOTOV.2020.2969788*.

8. Kumar, Rishi E., Guillaume von Gastrow, Joswin Leslie, Rico Meier, Mariana I. Bertoni, and David P. Fenning. 2019. "Quantitative Determination of Moisture Content in Solar Modules by Short-Wave Infrared Reflectometry." IEEE Journal of Photovoltaics 9, 6. 1748–1753. *10.1109/JPHOTOV.2019.2938108.*

9. Meng, Xiaodong, Kathryn C. Fisher, Lennon O. Reinhart, Wyatt S. Taylor, Michael Stuckelberger, Zachary C. Holman, and Mariana I. Bertoni. 2019. "Optical Characterization of Curved Silicon PV Modules with Dichroic Polymeric Films." Solar Energy Materials and Solar Cells 201. 110072. *10.1016/j.solmat.2019.110072.*

10. Meng, Xiaodong, Michael Stuckelberger, Laura Ding, Bradley West, April Jeffries, and Mariana Bertoni. 2018. "Quantitative Mapping of Deflection and Stress on Encapsulated Silicon Solar Cells." IEEE Journal of Photovoltaics, 8, 1. 189–195. *10.1109/JPHOTOV.2017.2768959*.

11. Miller, David C., Michael Owen-Bellini, and Peter L. Hacke. 2019. "Use of Indentation to Study the Degradation of Photovoltaic Backsheets." Solar Energy Materials and Solar Cells 201. 110082. *10.1016/j.solmat.2019.110082*.

12. Moffitt Stephanie L., Laura T. Schelhas, Sunjay Melkote, and Michael F. Toney. 2019. "7 - Multifunctional Optical Coatings and Light Management for Photovoltaics." Advanced Micro- and Nanomaterials for Photovoltaics, 153–173. *10.1016/B978-0-12-814501-2.00007-4.*

13. Moffitt, Stephanie L., Robert A. Fleming, Corey S. Thompson, Charles J. Titus, Eungi Kim, Leon Leu, Michael F. Toney, and Laura T. Schelhas. 2019. "Advanced X-Ray Scattering and Spectroscopy Characterization of an Antisoiling Coating for Solar Module Glass." ACS Applied Energy Materials 2, 11. 7870–7878. *10.1021/acsaem.9b01316*.

14. Nayshevsky, Illya, Qian Feng Xu, Gil Barahman, and Alan M. Lyons. 2020. "Fluoropolymer Coatings for Solar Cover Glass: Anti-Soiling Mechanisms in the Presence of Dew." Solar Energy Materials and Solar Cells 206. 110281. *10.1016/j.solmat.2019.110281.*

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15. Nayshevsky, Illya, Qian Feng Xu, and Alan M. Lyons. 2019. "Hydrophobic-Hydrophilic Surfaces Exhibiting Dropwise Condensation for Anti-Soiling Applications." IEEE Journal of Photovoltaics 9, 1. 302–307. *10.1109/JPHOTOV.2018.2882636.*

16. Nayshevsky, Illya, Qian Feng Xu, Jimmy M. Newkirk, Daniel Furhang, David C. Miller and Alan M. Lyons. 2019. "Self-Cleaning Hybrid Hydrophobic-Hydrophilic Surfaces; Durability and Effect of Artificial Soilant Particle Type." IEEE Journal of Photovoltaics 10, 2. 577–584. *10.1109/JPHOTOV.2019.2955559*

17. Newkirk, Jimmy M., Illya Nayshevsky, Archana Sinha, Adam M. Law, QianFeng Xu, Bobby To, Paul F. Ndione, Laura T. Schelhas, John M. Walls, Alan M. Lyons, and David C. Miller. 2021. "Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First Surfaces." Solar Energy Materials and Solar Cells 219. 110757. *10.1016/j.solmat.2020.110757*.

18. Owen-Bellini, Michael, Peter Hacke, David C. Miller, Michael D. Kempe, Sergiu Spataru, Tadanori Tanahashi, Stefan Mitterhofer, Marko Jankovec, and Marko Topic. 2020. "Advancing Reliability Assessments of Photovoltaic Modules and Materials using Combined-Accelerated Stress Testing." Progress in Photovoltaics. 1–19. *10.1002/pip.3342*.

19. Owen-Bellini, Michael, Dana B. Sulas-Kern, Greg Perrin, Hannah North, Sergiu Spataru, and Peter Hacke. 2020. "Methods for In Situ Electroluminescence Imaging of Photovoltaic Modules Under Varying Environmental Conditions." IEEE Journal of Photovoltaics 10, 5. 1254–1261. *10.1109/JPHOTOV.2020.3001723*.

20. Rolston, Nicholas, Adam D. Printz, Florian Hilt, Michael Q. Hovish, Karsten Brüning, Christopher J. Tassone, and Reinhold H. Dauskardt. 2017. "Improved Stability and Efficiency of Perovskite Solar Cells with Submicron Flexible Barrier Films Deposited in Air." Journal of Materials Chemistry A 44, 5. 22975–22983. *10.1039/C7TA09178H*.

21. Springer, Martin, and Nick Bosco. 2020. "Linear Viscoelastic Characterization of Electrically Conductive Adhesives Used as Interconnect in Photovoltaic Modules." Progress in Photovoltaics 28, 7. 659–681. *10.1002/pip.3257*.

22. Yuen, Pak Yan, Stephanie L. Moffitt, Fernando D. Novoa, Laura T. Schelhas, and Reinhold H. Dauskardt. 2019. "Tearing and Reliability of Photovoltaic Module Backsheets." Progress in Photovoltaics 27, 8. 693–705. *10.1002/pip.3144.*

23. Zhao, Oliver, Yichuan Ding, Ziyi Pan, Nicholas Rolston, Jinbao Zhang, and Reinhold H. Dauskardt. 2020. "Open-Air Plasma-Deposited Multilayer Thin Film Moisture Barriers." ACS Applied Materials and Interfaces 12, 23. 26405–26412. *10.1021/acsami.0c01493*.

PATENT APPLICATIONS AND PATENTS AWARDED

Hacke, Peter. "Method for Mechanical Load Testing of Photovoltaic Modules with Concurrently Applied Stressors and Diagnostic Methods." U.S. Patent Application No. 16/938,268. **2019**.

Han, Sang M. David M. Wilt, Omar K. Abudayyeh, and Andre Chavez. "Low-Cost, Crack-Tolerant, Screen-Printable Metallization for Increased Module Reliability." WO 2020/009936 A1. **2019**.

Han, Sang M., Omar K. Abudayyeh, David M. Wilt, and Andre Chavez. "Materials Engineering to Increase Crack-Tolerance of Screen-Printable Metal Paste." **2018**. Provisional patent application.

Zhu, Yu, Bryan D. Vogt, Clinton Taubert, Kun and Chen. "Electrical Conductive Adhesives with Multiple Filler System." USPTO: 62/914,761. **2019**.

Accelerated Applications

Industry-Relevant Research and Tools from DuraMAT

The DuraMat Data Hub

The DuraMAT Data Hub has now been operational for three years. It is deployed on an AWS federal government cloud hosted at the National Renewable Energy Laboratory (NREL) *https://datahub.duramat.org/*. It currently has 160 registered users working on 66 projects that encompass 4,942 files (a 726% increase from last year). Public data sets cover areas from soiling maps to albedo measurements and beyond. The Data Hub is providing a central point for researchers to archive, search, and obtain experimental and reference data, analysis tools, tutorials, and reports.

Contact — Robert.White@nrel.gov

PVAnalytics

A collaborative research team from Sandia National Laboratories (Sandia) and NREL have launched the first collaborative public software library—PVAnalytics—to organize and distribute reusable code for data preparation: *https://github.com/pvlib/pvanalytics*. This resource provides functions for quality control, filtering, feature labeling, and other tools supporting the analysis of PV system-level data.

Contact — cwhanse@sandia.gov

Thermo-Mechanical Modeling

Thermo-mechanical modeling of full-size glass-glass and glass-backsheet modules is underway at Sandia. The modeling tool can compare the behavior of different module designs, encapsulants, edge sealants, adhesives, and other materials on stiffness and mechanical response to external loads. The tool has applications in cell cracking and module deflection.

Contact — jkyuan@Sandia.gov

High-Throughput Optical Mapping Tool

Spatial quantification can reveal insights about degraded PV materials and modules not realized from bulk-or single point-measurements. The team at NREL has created a custom optical mapping instrument that can be used to quantify the transmittance and reflectance of a variety of material, coupon, and MiMo specimens. The team is interested in receiving samples for further testing in the next year. Contact david.miller@nrel.gov.

Contact – david.miller@nrel.gov

Combined-Accelerator Stress Testing (C-AST)

C-AST is a novel accelerated testing approach that uses a combination of real-world stress conditions to identify module design and material weaknesses without a priori knowledge of expected failure modes. C-AST has been validated through studies on backsheets and has now been applied to study a variety of module materials and components.

Contact – Peter.Hacke@nrel.gov

Fielded Module Study

The DuraMAT fielded module study has established a collection of modern PV modules selected for technological interest and commercial relevancy to study material degradation and to develop and validate nondestructive field forensics methodologies. In parallel with destructive characterization, the team is developing a method to nondestructively identify backsheet composition from field FTIR measurements.

Contact – bhking@sandia.gov

DuraMAT
Durable Module Materials Consortium

The DuraMAT—or Durable Module Materials—Consortium brings together the national lab and university research infrastructure with the PV and supply-chain industries for a grand goal: to discover, develop, de-risk, and enable the commercialization of new materials and designs for PV modules—with the potential for a levelized cost of electricity of less than 3 cents per kilowatt-hour.

ANNUAL **REPORT**

FY 2020

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