FY 2019

Annual Report

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 Energy Materials Network. DuraMAT is a multi-lab consortium, led by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, with SLAC National Accelerator Laboratory 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 photovoltaic modules that increase performance, extend lifetime, and enable new applications. We work in partnership with our fifteen-member industry advisory board and the technical management team in the U.S. Department of Energy's Solar Energy Technologies Office.

DuraMAT Director's Letter

In 2019, DuraMAT undertook a significant reorganization, switching from a six-node capability network with demonstration projects to a simpler structure with five core objectives. These core objectives are focused on establishing and applying critical capabilities to address the big challenges for PV module durability.

For example, one of these big challenges is the PV community's inability to make predictions of service life and durability for modules using our current testing protocols and knowledge. It is incredibly difficult to make meaningful predictions of 30 years or more for the outdoor durability of cutting edge products with a six-month product development cycle! Improving PV modules' outdoor durability and our ability to predict it requires more durable materials and designs, better tests to screen for weaknesses, improved modeling, more materials and module characterization data, and a way to combine all of these data with historical performance data to extract meaningful results. Our vision is for DuraMAT's five core objectives to address broad challenges like these.

DuraMAT's five core objectives are:

Last year, DuraMAT also kicked off our final round of six lab-led projects totaling $4 million over three years. Additionally, DuraMAT awarded four industry-lab partnerships to DSM, the Electric Power Research Institute, SunPower, and Osazda Energy. Our Spark program, which supports innovative, early-stage ideas with small grants, continued with new awards to Sandia, NREL, and LBNL teams. We plan to award a final round of industry- and academic-led partnerships in fiscal year 2020. These new and continuing efforts ensure that we will continue to make progress on each of the core objectives through the next two years of DuraMAT and position us for a successful renewal in fiscal year 2021.

DuraMAT leverages the decades of experience, expertise, and world-class facilities of the national laboratories to create a "one-stop shop" for timely solutions to critical barriers that are limiting module reliability. We have become a trusted partner that the U.S. PV industry relies on for high-quality, relevant, timely, and impactful research. DuraMAT continues to study and validate improved materials, testing methods, modeling approaches, and big data management and analytics to reduce risk—and the levelized cost of energy—and increase the value of PV systems. 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

The DuraMAT Industry Advisory Board provides the Consortium with valuable industry perspectives, helping to guide DuraMAT's work so it is relevant and impactful for the American solar and electric industries.

Working with DuraMAT

"DuraMAT provides value to EPRI and the electricity industry through improved understanding of long-term solar PV module performance and its subsequent impact on PV plant performance. DuraMAT's body of research is helping bridge the knowledge gap between upfront capital cost and long-term energy production and the ways in which module performance can be predicted and analyzed."

– Michael Bolen, Principal Project Manager at Electric Power Research Institute

"DuraMAT's emphasis on reducing risk and improving the performance of PV technologies is critical to the continued advancement of the solar industry. By following and participating in DuraMAT projects, we improve the effectiveness of our renewable R&D portfolio."

– Will Hobbs, Principal Research Engineer at Southern Company

"Small, domestic startup companies, such as our team at Osazda Energy, often do not have all the resources necessary to quickly achieve our market goals. DuraMAT gives us access to key capabilities—like materials characterization, computational modeling for product optimization, and techno-economic analysis—filling a critical gap for startup companies in PV reliability."

— Dr. Sang M Han, Chief Technical Officer, Osazda Energy, LLC.

DuraMAT Fiscal Year 2019 Financial Report

DuraMAT kicked off its five-year research program early in Fiscal Year (FY) 2017 (late in the 2016 calendar year). To achieve our goal of discovering, developing, de-risking, and enabling the commercialization of new materials and designs for PV modules, DuraMAT solicits proposals and awards funding for high-impact work in the national labs and outside entities.

Funding was awarded for technical work in the national labs staring in mid-FY17. Similarly, funding was awarded for university- and industry-led work that began in early FY18. DuraMAT continues to award funding that supports the program's goals, through the beginning of FY20.

DuraMAT's spending can be divided into five broad categories: core work, capability development, industry-led projects, academic-led projects, and spark projects.

Core funding is a flat funding amount allocated to each of the four core labs to cover technical leadership, consortium management, and the DuraMAT postdoctoral researcher at each lab. Capability funding is awarded competitively to the laboratories to develop and demonstrate new capabilities. Academic- and industry- led projects are awarded competitively for work led by outside institutions in collaboration with the lab capabilities. Spark projects are small awards ($50k) for 6- to 9-month projects at the labs to test out new ideas or work directly with industry.

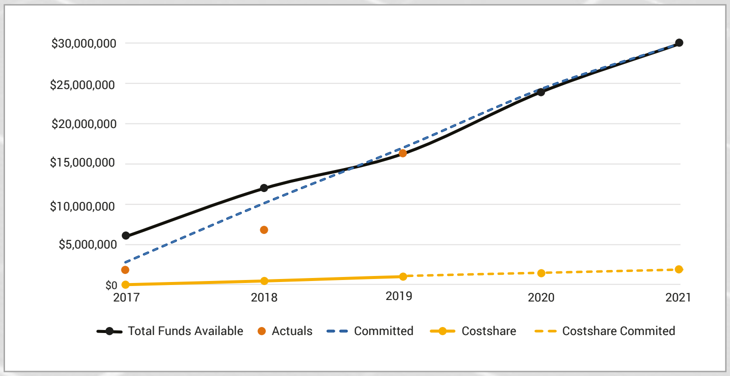


Figure 1 shows DuraMAT's total available funding of $30M, committed funding that has been awarded, actual spending totals, and actual/committed cost share through the end of FY19 (Sept. 30, 2019).

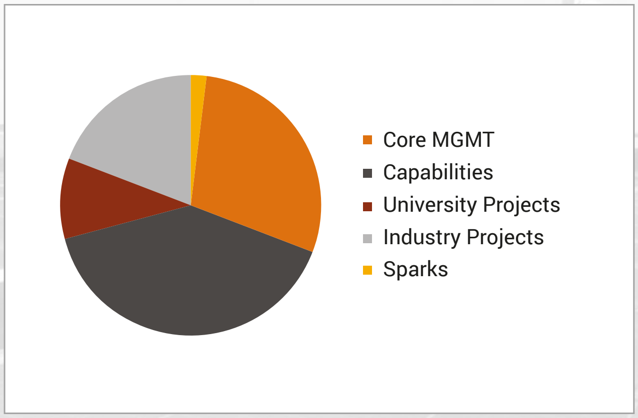


Figure 2 shows the distribution of funds within these five areas. Approximately 70% of the funding awarded stays in the laboratories in the form of core and capability funding. 28% is invested in university and industry-led work, but a portion of this funding actually returns to the labs to leverage the lab capabilities. Sparks funding accounts for 3% of the budget.

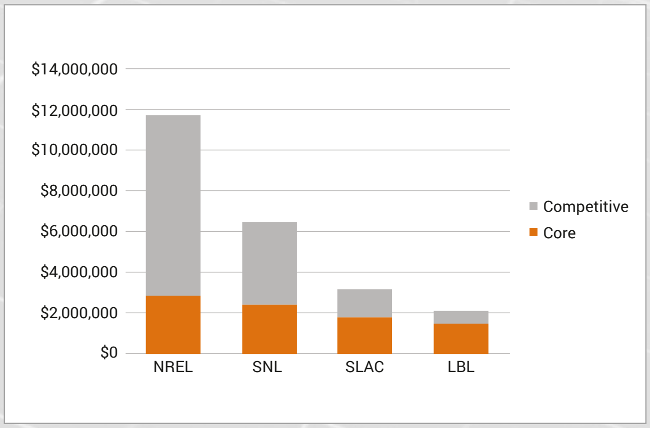
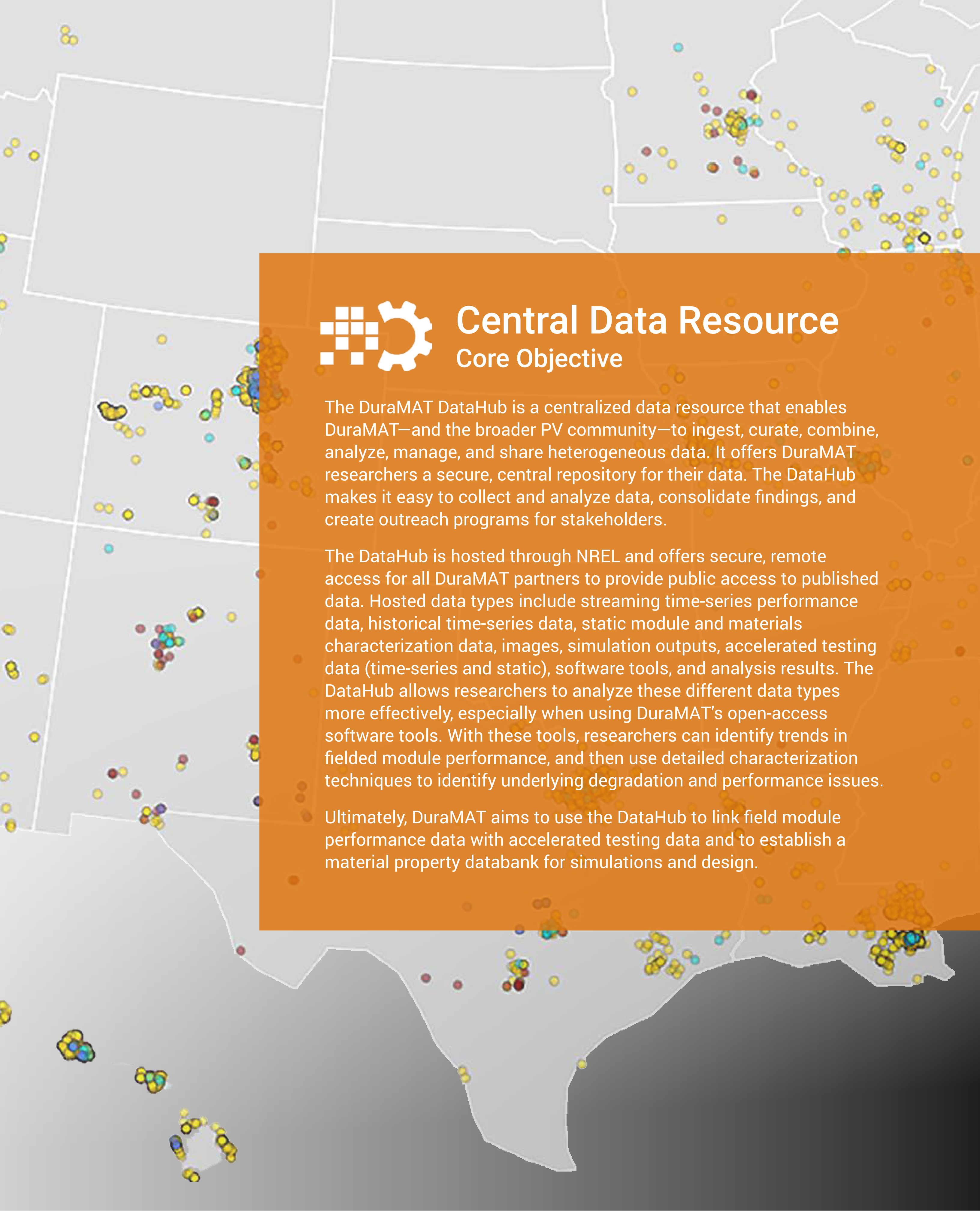


Figure 3 shows the distribution of core and competitively-awarded (Capability, Project, and Spark) funding at each laboratory. Core funding is intended to enable the labs to start and manage DuraMAT work. The competitively awarded funding indicates how they have leveraged that initial investment to win competitive awards for work that benefits the PV industry and community.



Central Data Resource

Core Objective

The DuraMAT DataHub is a centralized data resource that enables DuraMAT—and the broader PV community—to ingest, curate, combine, analyze, manage, and share heterogeneous data. It offers DuraMAT researchers a secure, central repository for their data. The DataHub makes it easy to collect and analyze data, consolidate findings, and create outreach programs for stakeholders.

The DataHub is hosted through NREL and offers secure, remote access for all DuraMAT partners to provide public access to published data. Hosted data types include streaming time-series performance data, historical time-series data, static module and materials characterization data, images, simulation outputs, accelerated testing data (time-series and static), software tools, and analysis results. The DataHub allows researchers to analyze these different data types more effectively, especially when using DuraMAT's open-access software tools. With these tools, researchers can identify trends in fielded module performance, and then use detailed characterization techniques to identify underlying degradation and performance issues.

Ultimately, DuraMAT aims to use the DataHub to link field module performance data with accelerated testing data and to establish a material property databank for simulations and design.

Central Data Resource

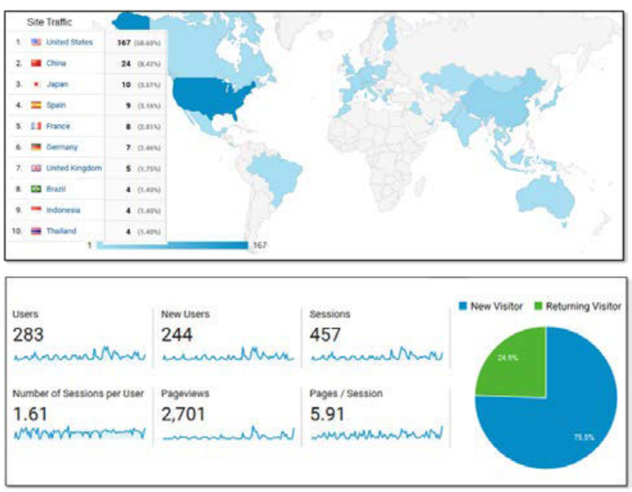
Core Objective

Key Result:

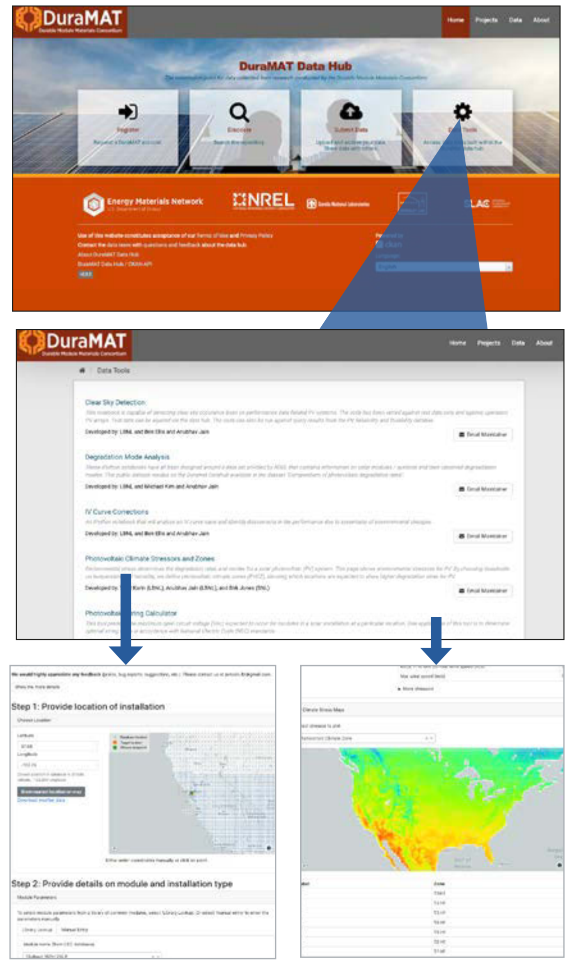
DuraMAT DataHub and Infrastructure

PI: Robert White, NREL

Summary of Result: We successfully developed, deployed, and continue to maintain a central data repository where DuraMAT researchers can share information and experimental data to support the Energy Materials Network partners. The work consisted of the creation of a central repository for basic data and the integration of time series data. The entire system is deployed in a FedRamp-approved cloud infrastructure.



Statistics on site usage: Both internal registered Data Hub research activity and external public activity (via Google Analytics)



Integration of two interactive tools through the Data Hub Data Tools repository. These tools directly address industry and research needs concerning system string size and possible PV stressors.

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DuraMAT Webinar Series, April 2019:
"An Introduction to the DuraMAT DataHub," presented by Robert White, NREL. *https://www.duramat.org/datahub-recording-text.html*

Creation of public site for time series data:
https://pvdata.duramat.org/

EXPECTED OUTCOMES

Ability to integrate data from across Data Hub to support advance analysis capabilities, particularly with the interconnection of accelerated testing with PV field performance data.

Next Steps:

1. Continued operations and tutorial outreach with DuraMAT researchers.
2. Prototype data tool extraction and upload for C-AST project and Cell Cracking projects.

Central Data Resource

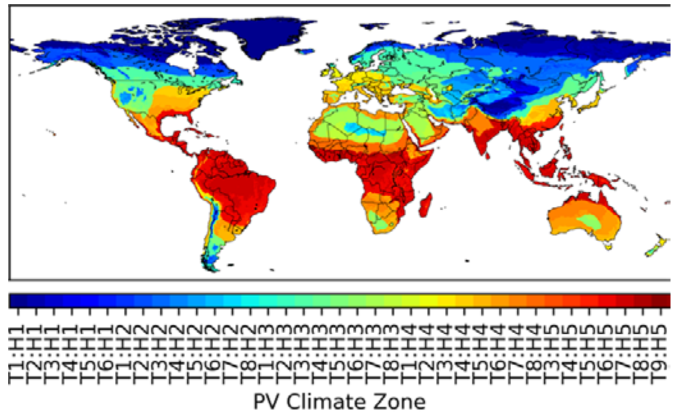
Core Objective

Key Result:

Climate Classification Targeted to Photovoltaic Degradation Through Data Analytics

PI: C. Birk Jones (Sandia), Todd Karin and Anubhav Jain (LBNL)

Summary of Result: We developed a climate zone classification system that is specific to PV module degradation. A large body of previous research indicates that climate affects PV degradation; however, the geographic distribution of climate stressors has not yet been characterized in a systematic way. Climate stressors are usually described using the Koppen-Geiger classification system, which uses temperature and rainfall to develop zones relevant for botany. This system lacks the ability to distinguish locations based on climate stressors more relevant to PV degradation. We developed the PVSCZ-2019 scheme by setting thresholds on individual climate stressors that affect PV, equivalent module temperature, and mean specific humidity (Figure 1). In this threshold classification, each stressor is given a letter key and a number describing the stressor intensity in a particular location. The classification scheme was applied to regions in the United States (presented in the PVSC paper) and the World (presented at EUPVSEC).



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Online web tool:
https://pvtools.lbl.gov/pv-climate-stressors

T. Karin, C. B. Jones, and A. Jain. "Photovoltaic Degradation Climate Zones." 46th IEEE Photovoltaic Specialist Conference (PVSC), Chicago, Il. June 2019.

T. Karin, C. B. Jones, and A. Jain. "Photovoltaic Climate Zones: The Global Distribution of Climate Stressors Affecting Photovoltaic Degradation." 36th European Photovoltaic Solar Energy Conference and Exhibition. Marseille, France. September 2019.

EXPECTED OUTCOMES

Create a standard climate zone scheme used for research on PV degradation.

Spark interest in the community to further study the effects of different climate stressors on PV degradation.

Central Data Resource

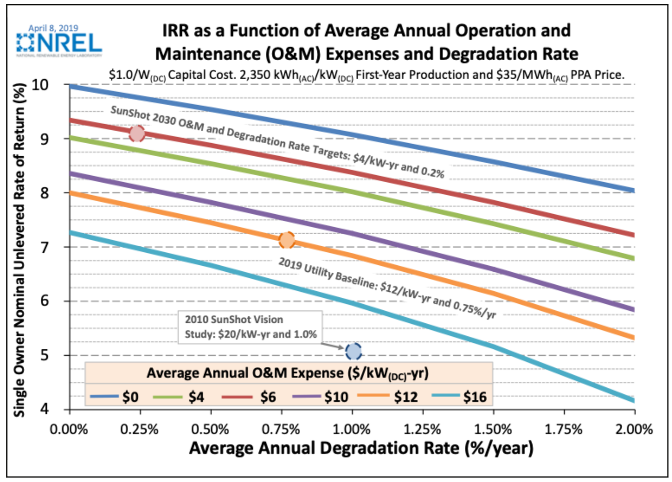
Core Objective

Key Result:

Techno-Economic Analysis

PI: Brittany Smith and Michael Woodhouse, NREL

Summary of Result: DuraMAT's techno-economic analysis supports DuraMat researchers, the industry advisory board (IAB), and the leadership team by developing customized lifecycle financial models for PV products and systems. This analysis is used to evaluate the market impact and overall value proposition of DuraMAT research projects. Under this project, we have developed pro forma PV project financial models to quantify the impact of technology improvements achieved by DuraMAT research. The benefits of this research and development program may include lower future operations and maintenance expenses, improved energy yield, lower degradation rates, and more favorable terms of project risk. The methodology and models that we utilize, and training to use the models, is available to all DuraMAT researchers, the leadership team, and the IAB. DuraMAT uses techno-economic analysis to identify and evaluate the potential impact of research including accelerated test development, materials solutions, and simulations.



Benefits for PV project economics derived from achievements of SETO reliability goals

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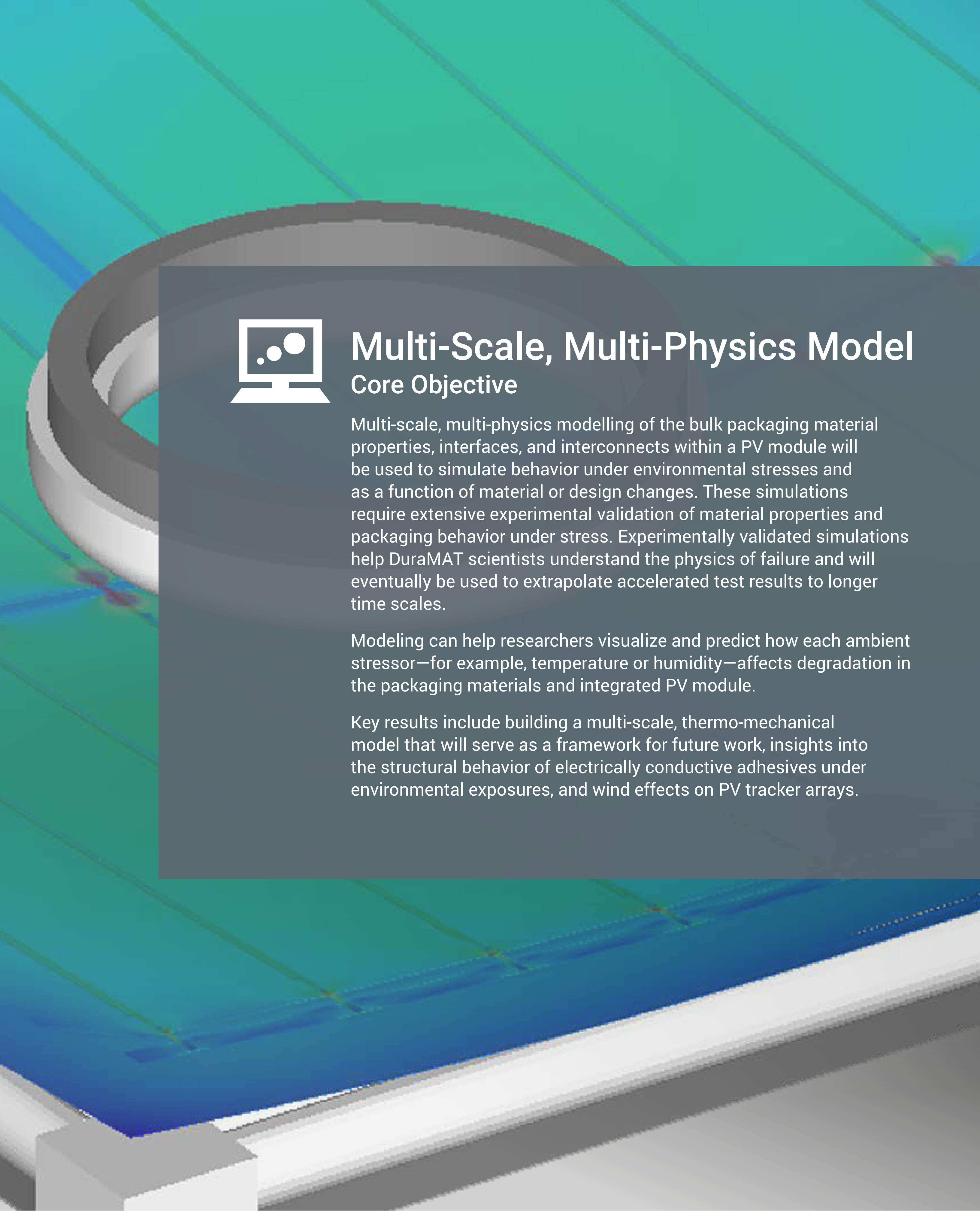
DuraMAT Webinar Series, February 2019: "The Role of Reliability and Durability in Photovoltaic System Economics," presented by Michael Woodhouse, NREL

EXPECTED OUTCOMES

Quantifying the impact of DuraMAT research on levelized cost of electricity and internal rates of return by analyzing module-related operations and maintenance, and degradation. Additionally, quantifying the value proposition of more rigorous module testing and climate-tailored degradation profiles for use in project pro forma models.



Multi-Scale, Multi-Physics Model

Core Objective

Multi-scale, multi-physics modelling of the bulk packaging material properties, interfaces, and interconnects within a PV module will be used to simulate behavior under environmental stresses and as a function of material or design changes. These simulations require extensive experimental validation of material properties and packaging behavior under stress. Experimentally validated simulations help DuraMAT scientists understand the physics of failure and will eventually be used to extrapolate accelerated test results to longer time scales.

Modeling can help researchers visualize and predict how each ambient stressor—for example, temperature or humidity—affects degradation in the packaging materials and integrated PV module.

Key results include building a multi-scale, thermo-mechanical model that will serve as a framework for future work, insights into the structural behavior of electrically conductive adhesives under environmental exposures, and wind effects on PV tracker arrays.

Multi-Scale, Multi-Physics Model

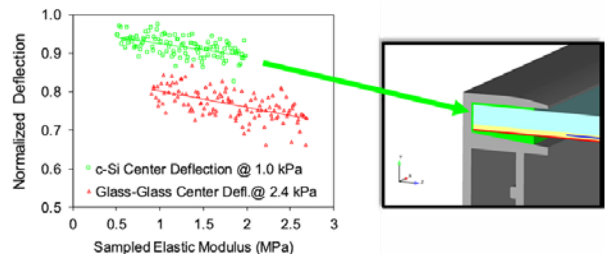
Core Objective

Key Result

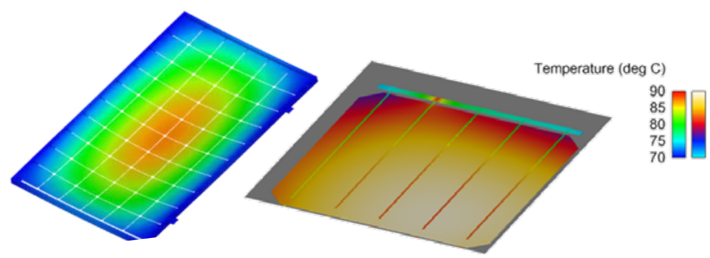
Elucidating the Effects of Module Materials and Design on Deformation Under Load

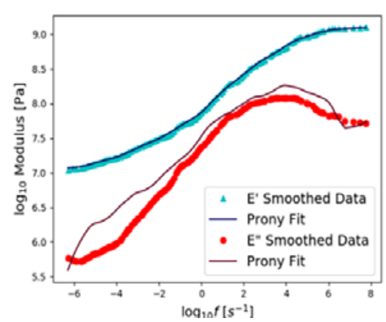
PI: James Hartley, Sandia

Summary of Result: Finite element models of two commercial module designs were developed and validated against experimental test data, demonstrating the ability to accurately predict module stress states under arbitrary external loads for both glass-glass and glass-backsheet design architectures. A sensitivity analysis was conducted on these validated models by running hundreds of simulations with parameter perturbations to identify correlations between design features and module stiffness. This study identified polymer materials, such as frame sealants and adhesives, as major contributors that could be optimized to improve module stiffness. This work demonstrated a methodology for design analysis and optimization using simulation and developed best practices for how to best model module-scale mechanical behavior. These computational module models may be explored to examine the effects of other environmental exposures on packaging integrity, such as how key degradation mechanisms are driven by thermal, mechanical, electrical, and combined stressors. Our models and workflows enable further insights into difficult-to-measure damage mechanisms and help quantify sensitivities to module design parameters.



Detailed cell-scale models receive boundary conditions from full module models and incorporate high-fidelity material and physics models to predict how interconnect degradation mechanisms are affected by exposure environments.





Sensitivity analysis conducted over a suite of simulations show correlations between adhesive and edge seal material elastic modulus to module deflection for both glass-backsheet and glass-glass module architectures. These results show that module stiffness may be improved with careful selection of these materials.

LEARN MORE

DuraMAT Webinar Series, October 2019: "Multi-Scale, Multi-Physics Modeling Capabilities towards Predicting PV Reliability," presented by James Hartley, Sandia.

J. Y. Hartley et al., "Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load," 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL, USA, 2019, pp. 0511-0516.

EXPECTED OUTCOMES

A simulation workflow capable of providing insights into which deployment environments are the most damaging and why, and how material or design characteristics could improve robustness. Models and workflows would be applicable at full module, cell, or interconnection scales.

Multi-Scale Multi-Physics Model

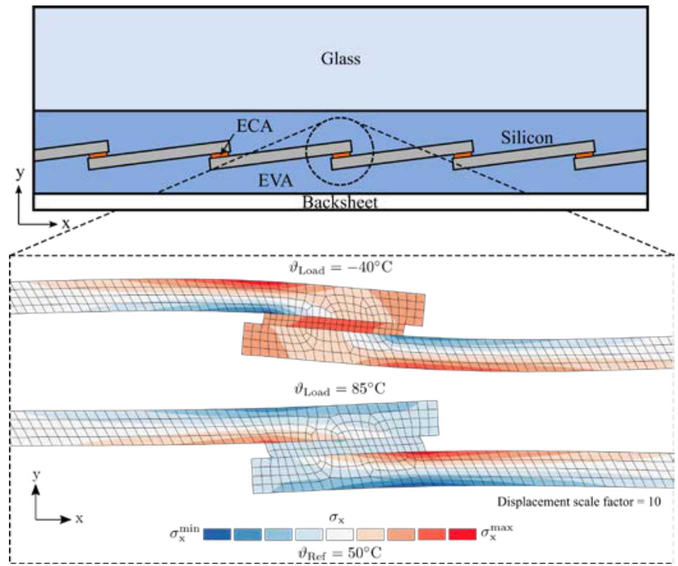
Core Objective

Key Result

A Unified Constitutive Model for the Degradation of Electrically Conductive Adhesives

PI: Nick Bosco, NREL

Summary of Result: The goal of this work is to develop the framework for a unified constitutive materials model for electrically conductive adhesives (ECA). This will include specific materials' characterization measurements and the analysis of those measurements to extract the parameters required for a high-fidelity constitutive model. This materials model will enable predictive simulation capabilities for ECA degradation as an electrical interconnect material in PV modules. In the first year, emphasis was on the structural behavior of the ECA, and a linear viscoelastic representation was found to describe the mechanical response sufficiently well. The effects of environmental exposure were investigated, and temperature-dependent material properties for a variety of ECAs were measured and prepared for use in numerical simulations. The obtained material models were used within a Finite Element simulation of a generic shingled cell module, and the differences between low and high-fidelity material models were discussed. A need for high-fidelity models was identified to obtain accurate predictions for the mechanical response of PV modules.



Finite Element model of a generic shingled cell model as an application for the ECA constitutive model. The resulting deformation figure is depicted for the silicon cell and the ECA.

LEARN MORE

Springer, M., and N. Bosco. "Linear viscoelastic characterization of electrically conductive adhesives used as interconnect in photovoltaic modules." Prog Photovolt Res Appl. 2020: 1–23. *https://doi.org/10.1002/pip.3257*

EXPECTED OUTCOMES

The constitutive model developed through the course of this work will have the ability to accurately predict ECA degradation as an electrical interconnect material in PV modules of any type or configuration and through any exposure, thus being able to relate accelerated to on-sun exposures.

Multi-Scale Multi-Physics Model

Core Objective

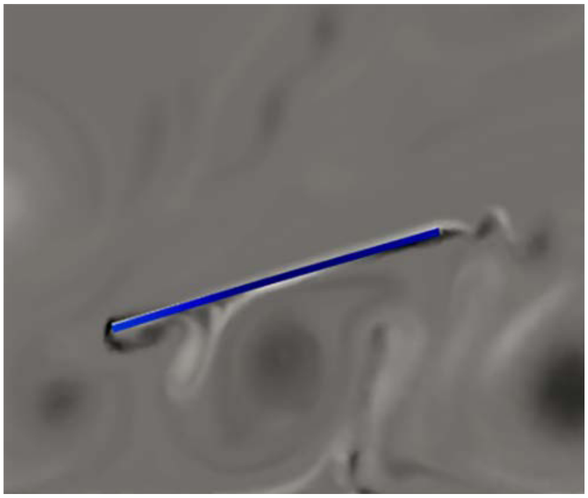
Key Result

Predictive Simulation for PV Trackers

PI: Dave Corbus, NREL

Summary of Result: The Predictive Simulation for PV Trackers project completed an open-source FEniCS model to create a high-level method to incorporate new physics and share codes to evaluate rigid body rotation around the torque tube of the PV array tracker. This model shows that spring connections are a reasonable way to model the actual physics of a tracker.

The result is an increased capability to model torsional galloping, a critical failure mode for PV trackers, leading to increased system resiliency. The relationship between fluid behavior and panel deformation lends itself to fluid-structure interaction algorithms, which enabled us to use an open-source code. The model results are being validated with field data taken at the NREL Flatirons campus, and this data will be made available on the DuraMat DataHub.



An example of the project's modeling of turbulence around a PV tracker, as shown in this visualization.

EXPECTED OUTCOMES

Next steps include: Incorporate higher-fidelity turbulence models; add dynamic behavior to the structure to capture effects of rigid body rotation and deformation; and refine the algorithm for 3D simulations. This project will carry over into FY20.

Disruptive Acceleration Science

Core Objective

Disruptive Acceleration Science is focused on understanding how PV materials, modules, and systems will perform outdoors based on relatively aggressive experimental conditions. Accelerated testing is essential for any product that needs to perform predictably outdoors for many years, and it is especially important for products like PV that are often deployed in harsh conditions.

All PV modules undergo extensive accelerated testing for known failure modes and safety issues in order to meet international industry standards. These tests provide a level playing field for module comparison, but there are always opportunities to make testing better, lower-cost, and faster.

DuraMAT focuses on acceleration science in order to develop new testing methods that don't require a priori knowledge of the failure mode and could eventually enable service life predictions.

This approach uses experimental conditions that mimic, but do not exceed, the extremes of the natural environment. This application of extreme, but realistic, stress allows us to detect weaknesses without provoking irrelevant failures.

The key results under this objective include the Combined Accelerated Stress Testing (C-AST) platform, which applies combinations of stresses as they are experienced outdoors, and the experimental validation of C-AST through a comparison of well-characterized backsheets. Future plans include feasibility studies of outdoor accelerated testing and low-cost accelerated testing.

Disruptive Acceleration Science

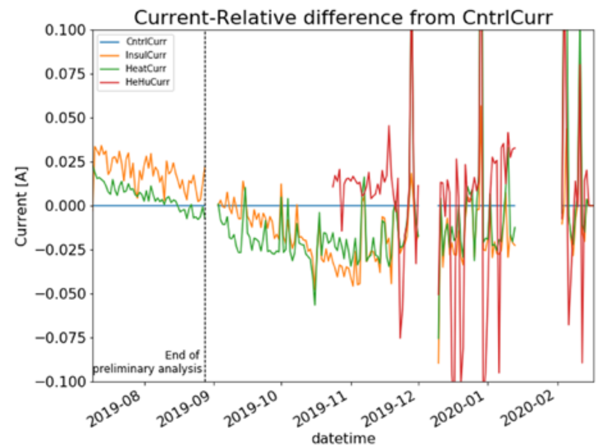
Core Objective

Key Result:

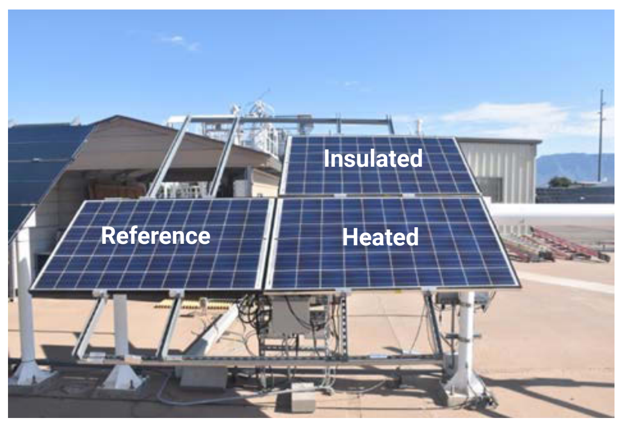
Outdoor Accelerated Testing of PV Modules

PI: Joshua S. Stein, Sandia

Summary of Result: This project aimed to prototype and test new, low-cost, and scalable methods for achieving acceleration of temperature and humidity in the outdoor array environment. These accelerated tests were performed while the modules were under sun, grid-connected, and producing power. Thus, correlations between aging and power losses were detectable. Four modules were installed outdoors at Sandia in New Mexico. The plot below shows the differences in the heated module currents from the reference. It appears that the heated modules may have degraded very slightly in the first four months but have since recovered. Indoor flash testing done after nine months of exposure did not show any measurable degradation.



We compared the currents measured in each module over time. The plot shows the difference in the heated module currents from the reference. It appears that the heated modules may have degraded very slightly in the first four months but have since recovered.



Four modules were installed outdoors at Sandia in New Mexico. One of the modules was a reference; one was insulated from the back; one was insulated and heated from the back; and one was heated and exposed to a high-humidity environment.

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Results of this project were presented in a poster at the 2020 PV Module Reliability Workshop in Lakewood, Colorado: "Challenges in Outdoor Accelerated Testing of PV."

EXPECTED OUTCOMES

In this project, we successfully demonstrated three methods for elevating the operating temperature of a fielded PV module. Humidity proved to be harder to control. After nine months of exposure, the modules were flash tested and did not show any detectable degradation.

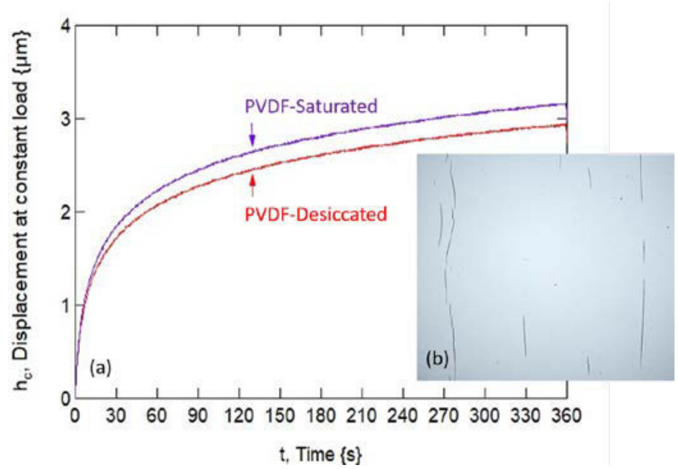
Key Result

Combined-Accelerated Stress Testing (C-AST) for PV Modules and Application for Evaluation of Backsheets

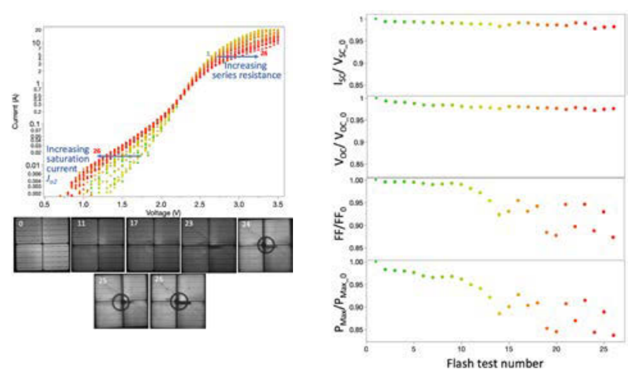
PI: Peter Hacke, NREL

Summary of Result: The Module Prototyping and Accelerated Stress Testing Capability Area has developed a toolset and protocol for C-AST that combines stress factors of the natural environment into a single test requiring fewer modules, fewer tests, and making it possible to discover weaknesses in new module designs that are not known a priori. This will help reduce risk, accelerate time to market and bankability, reduce costly overdesign, and estimate service life for PV modules.

In this project, we instrumented a weathering chamber for six mini-modules to apply five stress factors: temperature, full spectrum light, system voltage bias, mechanical pressure, and humidity (noncondensing and spray). We found the implementation of a multiseasonal, multiclimate stress protocol necessary to reveal the susceptibility to failure of certain backsheet materials. Backsheet failure, which developed as a result of exposure to tropical test conditions, was only revealed upon desiccation when replicating a high desert climate when the material embrittled. In addition to the development of the testing protocols, we are developing in-situ characterization capabilities, such as light-and dark-IV curve tracing and electroluminescence (EL) imaging.



(a) Creep-hold tests of a PVDF backsheet type following 24 weeks in C-AST followed by a moisture saturation or desiccation procedure show that the desiccated sample had a 13% greater hardness and 23% greater modulus of elasticity leading it to be more susceptible to cracking than the saturated sample; (b) micrograph of the cracked PVDF backsheet.



Degradation of a PERC module through C-AST, including effects of light-induced degradation and cell cracking. Left: EL images and in-situ dark I-V measurements showing the increase in series resistance and saturation current associated with the degradation. Right: Power degradation of this module through approximately eight months of testing.

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DuraMAT Webinar Series, May 2019:
"Development of Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules," presented by Peter Hacke, NREL.

EXPECTED OUTCOMES

Combined-accelerated stress testing is anticipated to be implemented over the entire PV value chain to de-risk and lower the cost of electricity. We will next demonstrate the protocol's ability to differentiate LID mechanisms and continue to identify various failure modes in PV modules.

Disruptive Acceleration Science

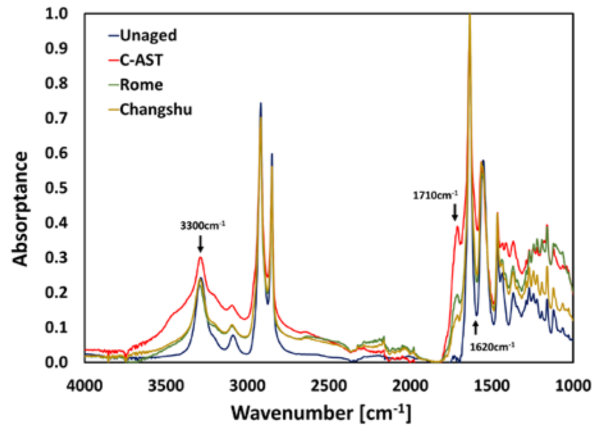
Core Objective

Key Result

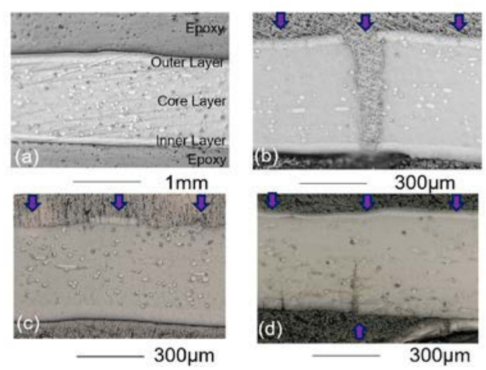
Correlation of Advanced Accelerated Stress Testing With Polyamide-Based PV Backsheet Field Failures

PI: Michael Owen-Bellini, NREL

Summary of Result: This key result was delivered by the DuraMAT Early Career Scientists (DECS) project, comprising postdoctoral researchers funded under DuraMAT and seeks to leverage all technical capabilities within our network. It brings together advanced characterization techniques, predictive simulation techniques, data analytics, and module prototyping and testing to form a cohesive project with the goal of supporting and validating the development of advanced accelerated stress testing and module materials. Polyamide-based AAA backsheet cracking has been reproduced through combined and sequential stress testing. Planar-and cross-sectional-optical microscopy, Fourier-transform Infrared spectroscopy (FTIR), and discrete scanning calorimetry (DSC) have been used to elucidate the mechanical and chemical changes leading to backsheet failure. Field-aged backsheet samples demonstrating failure in various climates (including locations in China and Italy) were also analyzed. Through the analysis, a comparison was made between the different stress testing protocols and field-aged samples to validate the relevance of the advanced stress tests. The changes induced through combined-accelerated stress testing (C-AST) were most representative of changes induced by the field, supporting the relevance of C-AST and providing validity for the test protocol.



Overlay of FTIR-ATR spectra for outer layer of unaged, C-AST aged, and field-aged AAA backsheet



Cross-sectional microscope images for: (a) unaged AAA backsheet; (b) C-AST parallel to the macrocrack observed above cell tabbing; (c) Changshu, China sample above cell tabbing; and (d) Rome sample above cell spacing. Purple arrows indicate possible UV exposure paths.

LEARN MORE

Owen-Bellini, et al., "Correlation of advanced accelerated stress testing with polyamide-based photovoltaic backsheet field-failures," IEEE PVSC. Chicago, Illinois, 2019.

Moffitt, et al., "Understanding PV Polymer Backsheet Degradation through X-ray Scattering," IEEE PVSC. Chicago, Illinois, 2019.

EXPECTED OUTCOMES

The project is expected to validate the relevance of advanced accelerated stress testing protocols and establish a comprehensive set of characterization techniques that can be used to more appropriately evaluate new materials for use within PV modules.

Fielded Module Forensics

Core Objective

Fielded Module Forensics refers to the quantification and characterization of module failure modes during outdoor exposure and the study of materials and performance properties changing over time during testing and deployment. One of the biggest challenges to studying degradation or failure in fielded modules is the frequent absence of a “reference” module or material. As a result, it is difficult to find out what went wrong when we don’t know what a failure-free module should look like.

This capability includes a wide variety of structural, chemical, morphological, electrical, mechanical, and compositional materials characterization tools and the development of reference libraries for module materials. This core objective will enable researchers to better understand PV material durability and explain degradation mechanisms, in addition to generating practical, multi-modal data that guides next steps in materials and module design.

Key results include a study of cell cracking in fielded modules, a non-destructive test method to monitor the generation and evolution of stresses in encapsulated cells and modules, and the development of an imaging protocol to identify degradation mechanisms in fielded modules.

Fielded Module Forensics

Core Objective

Key Result:

Degradation Mechanisms in Fielded Modules Characterized by Luminescence and Thermal Imaging

PI: Dana B. Sulas-Kern, NREL

Summary of Result: We studied fielded module failure by comparing current-voltage characteristics with spatially resolved electroluminescence, photoluminescence, UV-fluorescence, and dark lock-in thermography images. For 23 modules, we identified metallization failures causing a severe drop in fill factor and 8%-35% power loss. We showed a correlation (R2= 0.74) between the number of hot solder joints and increasing series resistance. We created resistance maps from injection-dependent electroluminescence, showing that hot solder joints are located at low-resistance areas within high-resistance cells. Our results demonstrate a unique example, using spatially resolved analysis to uncover causes of power loss, and our quantitative image processing provides methods for use on future systems.

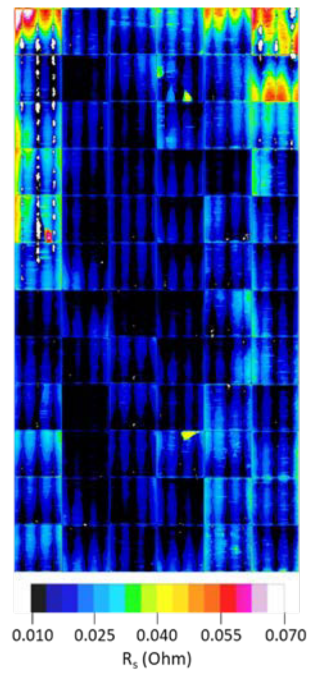


Figure 1. Example of quantitative series resistance map overlaid with heating at solder points in white, showing heating at low resistance spots within cells having high resistance areas.

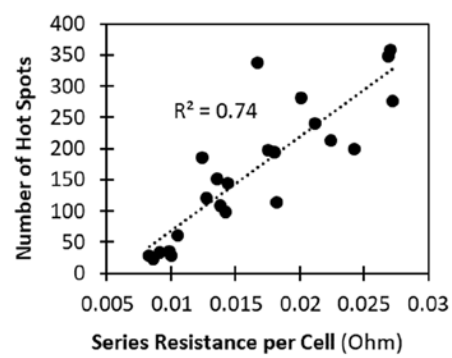


Figure 2. Number of hot solder points per module from dark lock-in thermography correlates with increasing series resistance from fitting of current-voltage curves.

LEARN MORE

Sulas-Kern, D.B., S. Johnston, and J. Meydbray. "Fill Factor Loss in Fielded Photovoltaic Modules Due to Metallization Failures, Characterized by Luminescence and Thermal Imaging" in IEEE 46th Photovoltaic Specialists Conference (PVSC), pp. 2008-2012, 2019.

https://doi.org/10.1109/PVSC40753.2019.8980840

EXPECTED OUTCOMES

This project shows the importance of combining multiple spatially resolved imaging techniques to uncover detailed reasons for fielded module degradation. Linking power loss to degrading module components and their location within the module informs methods for improving module durability.

Fielded Module Forensics

Core Objective

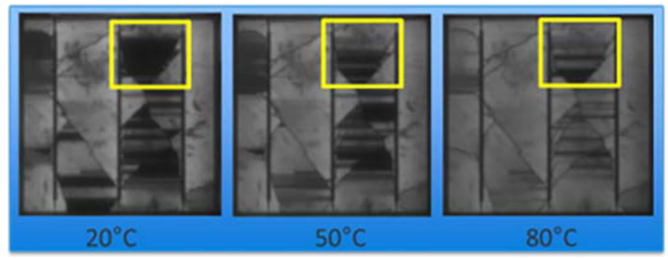
Key Result

Project Title: Effect of Cell Cracks on Module Power Loss and Degradation

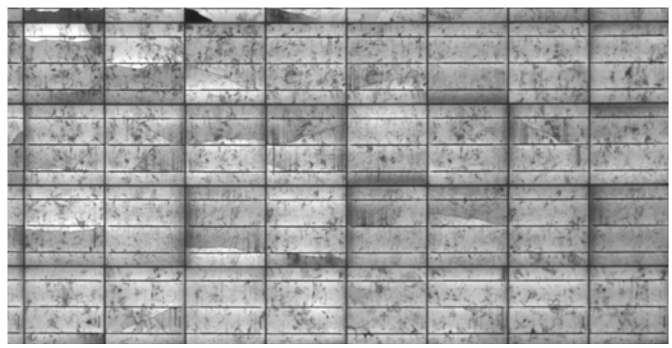
PI: Cara Libby, EPRI

Summary of Result: Temperature-dependent electroluminescence: We developed a prototype of a temperature-dependent electroluminescence (EL) system. The system applies bias to a module inside an environmental chamber to automatically capture EL images of the full module at arbitrary temperatures. This is important for understanding how cell fragments move within a module as temperature changes and how that, in turn, affects electrical connectivity.

Finite element method modeling for understanding crack damage evolution: We developed an initial full-module finite element method (FEM) model to understand how environmental exposure affects broken cell fragments inside a module. This will enable us to design field-relevant accelerated tests for this project, which will run in parallel to three field deployments. We have also shown that the nonuniform loads experienced by a module due to wind can be approximated by a linear load profile over the surface of the module and that this can be accurately reconstructed in the FEM model from a time series of two displacement measurements on the module laminate surface.



Temperature-dependent EL showing changing electrical connectivity of a cell fragment within a module



EXPECTED OUTCOMES

- Predictive modeling provides technical basis for PV plant owners to set crack thresholds.
- Machine-learning algorithms advance the state of the art in module performance prognosis.
- Improved qualification and lifetime test procedures based on FEM modeling informs manufacturer development of new module designs.

Fielded Module Forensics

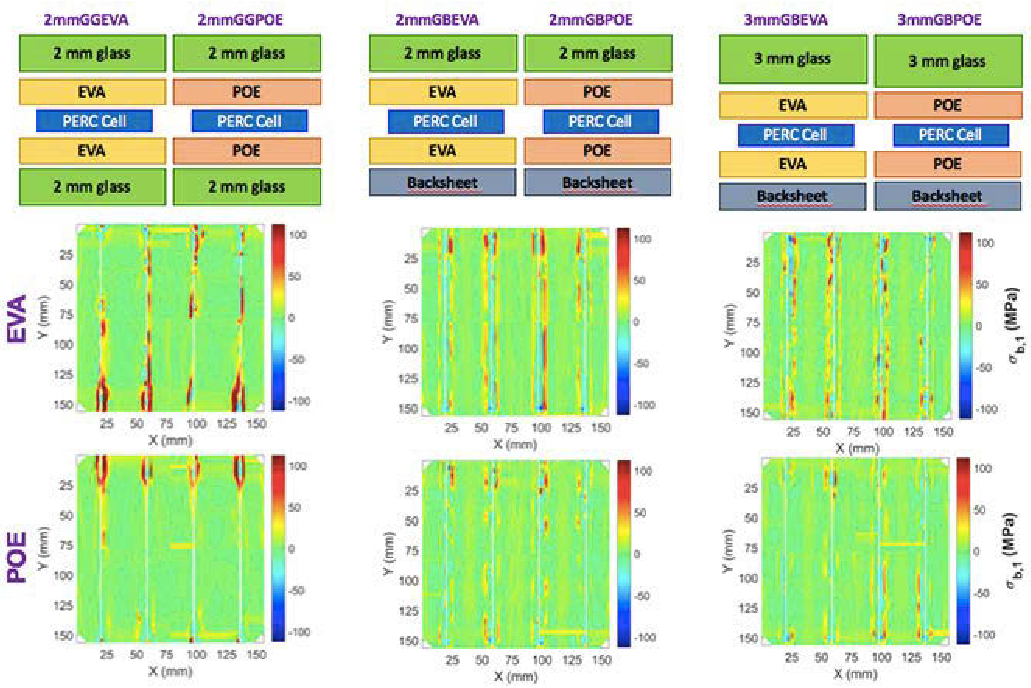
Core Objective

Key Result:

Project Title: Direct Imaging of Stress in Crystalline Silicon Modules

PI: Maria Bertoni, Arizona State University

Summary of Result: This project focuses on developing laboratory-based X-ray topography (XRT), as a nondestructive and reliable way to monitor the generation and evolution of deflection and related stresses in solar cells under encapsulation. The goals are fourfold: (1) extend the XRT method to map full cells inside minimodules; (2) build the physical model to transform deflection measurements into stress; (3) measure deflection and stress maps for a variety of encapsulants and backsheets configuration; and (4) evaluate the effect of accelerated testing.



Stress distribution on PERC cells encapsulated in glass/glass, 2 mm glass/backsheet, and 3 mm glass/backsheet configurations with EVA and POE. Note the high stress values at the end of the ribbons in the glass/glass modules.

EXPECTED OUTCOMES

Understand the stresses that the solar cell sees under encapsulation with different bills of materials, how the degradation of these materials affects the stress evolution, and, ultimately, understand the role of these stresses in module failure and failure rates.

Next Steps:

- Remeasure all minimodules glass/glass and glass/backsheet after DH1000
- Finite element model from Sandia showing stress distribution
- Submit paper on stress distribution in glass/glass and glass/backsheet modules using EVA and POE

Module Material Solutions

Core Objective

The Materials Solutions core objective leverages our technical capabilities across all of DuraMAT's partners to design, develop, and de-risk materials that address the current reliability challenges in PV systems.

Depending on specific project goals, work may focus on electrically conductive adhesives, backsheets, anti-soiling coatings, flexible packaging, cell cracking, or moisture barriers, among other topics. This cross-cutting objective will generate results that link all other objectives as materials solutions are the foundation for advances in reliability and degradation.

Key results under this objective are the development of a self-healing, conducting composite that regains electrical continuity across cracks and the generation of new concepts for module encapsulation and barrier technologies.

Module Material Solutions

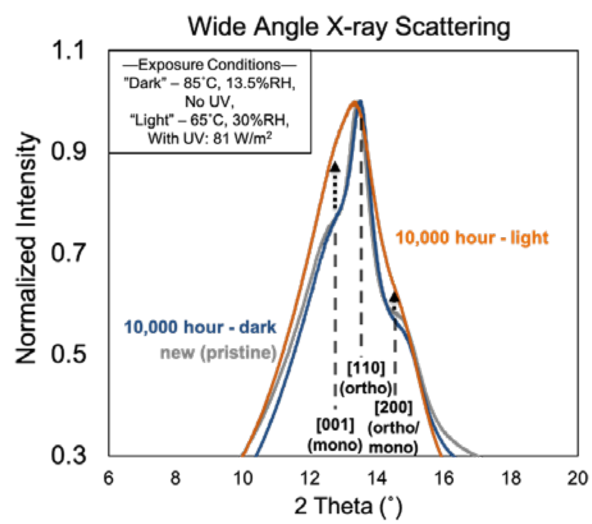
Core Objective

Key Result:

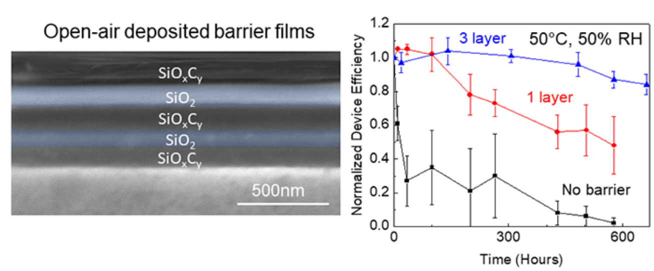
Demonstrating New Concepts for Module Encapsulation and Barrier Technologies

PI: Reinhold Dauskardt, Stanford University

Summary of Result: This project focused on the development of industrially relevant new concepts in solar module encapsulation and moisture barrier technologies to accelerate state-of-the-art module performance, reliability, and manufacturability with new module materials and interfaces, demonstrated using accelerated testing and reliability models. This project was divided into two interrelated thrusts. The first thrust focused on encapsulant reliability characterization using wide-angle X-ray scattering and FTIR-ATR of delaminated EVA (collaboration with SLAC), resulting in an improved understanding of fundamental degradation pathways. The second thrust focused on advanced in-situ moisture barrier technologies, utilizing open-air plasma-deposition of submicron multilayer barrier films to improve moisture barrier properties under accelerated aging conditions.



WAXS revealed that the peak ratios shifted when exposed to 10,000 hours in "Light" conditions but not in "Dark" conditions, with increases in the Monoclinic crystalline phase relative to the Orthorhombic phase.



Cross-section SEM image of the multilayer barrier structure and graph demonstrating the improved efficacy of the multilayer barrier compared to single-layer barrier

LEARN MORE

DuraMAT Webinar Series, December 2019: "Demonstrating New Concepts for Reliable Low-Cost Module Encapsulation and Moisture Barrier Technologies," presented by Reinhold Dauskardt, Stanford.

EXPECTED OUTCOMES

Thrust 1—Sophisticated characterization of degraded encapsulant layers to understand the fundamentals of the degradation pathways.

Journal publication submitted entitled "Fundamental Degradation Mechanisms for Reliability of PV Module Encapsulants."

Thrust 2—Development of novel thin film moisture barriers.

Journal publication submitted entitled "Open-Air, Plasma-Deposited Multilayer Thin Film Moisture Barriers."

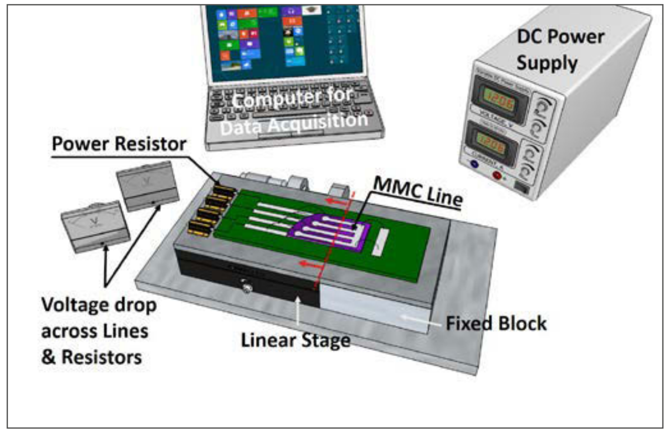
Key Result

Low-Cost Advanced Metallization to Reduce Cell-Crack-Induced Degradation for Increased Module Reliability

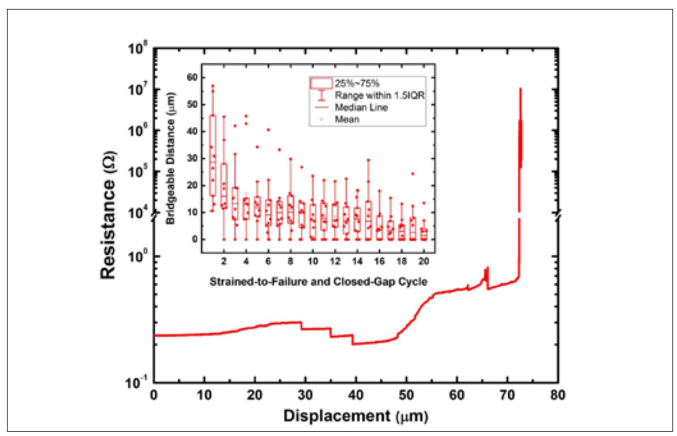
PI: Sang M Han, Osazda Energy and University of New Mexico

Summary of Result: Osazda Energy, LLC and its team possess unique capabilities to conduct electromechanical testing on gridlines and busbars, as well as accelerated mechanical stress testing on mini modules. Resistance Across Cleaves and Cracks (RACK) testing, in particular, can measure the conductance through grid fingers as they are tensilely strained at micrometer increments to failure. The module-level mechanical stress testing and simultaneous electroluminescence imaging allow visualizing the cracks forming in silicon substrates and electrically isolated regions. This combination of characterization tools proves exceptionally useful for rapid product development of new, crack-tolerant, screen-printable silver pastes that would improve the lifetime of silicon PV modules against cracks.

Osazda Energy's specialized metal matrix composites (Metzilla™) have shown increased ductility and fracture toughness. Additionally, Metzilla pastes can electrically bridge stress-induced cracks that appear in solar cells; the composites also self-heal to regain electrical continuity. Accelerated thermal-stress testing on Al-BSF mini modules conducted at NREL show cells processed with Metzilla paste degrade at a slower rate than cells processed with conventional metallization, further elucidating the crack tolerance of Metzilla paste.



Resistance Across Cleaves and Cracks (RACK) testing setup to measure the conductance through grid fingers as they are strained at micrometer increments to failure.



Gap bridging and self-healing capability demonstrated on PERC cells. MetZilla bridges 20 to 30 um gaps on the average and > 70 um maximum gap for the first crack opening. The self-healable gaps start from 30 um on the average and eventually plateau at a few microns as the gridlines are repeatedly strained to complete electrical failure.

LEARN MORE

DuraMAT Webinar Series, November 2019: "Low-Cost, Crack-Tolerant Metallization: A Materials Engineering Solution to Module Reliability," presented by Sang Han, University of New Mexico.

EXPECTED OUTCOMES

Providing a materials engineering solution (low-cost, advanced metallization) to electrically bridge cell cracks and extend the module lifetime well beyond 30 years.

DECs at the DuraMAT workshop in Vail, CO (Left to right): Stephanie Moffitt (SLAC), Laura Schelhas (SLAC), Archana Sinha (SLAC), Don Jenket (NREL), James Hartley (Sandia), Ashley Maes (Sandia), Todd Karin (LBL), Michael Owen-Bellini (not pictured).

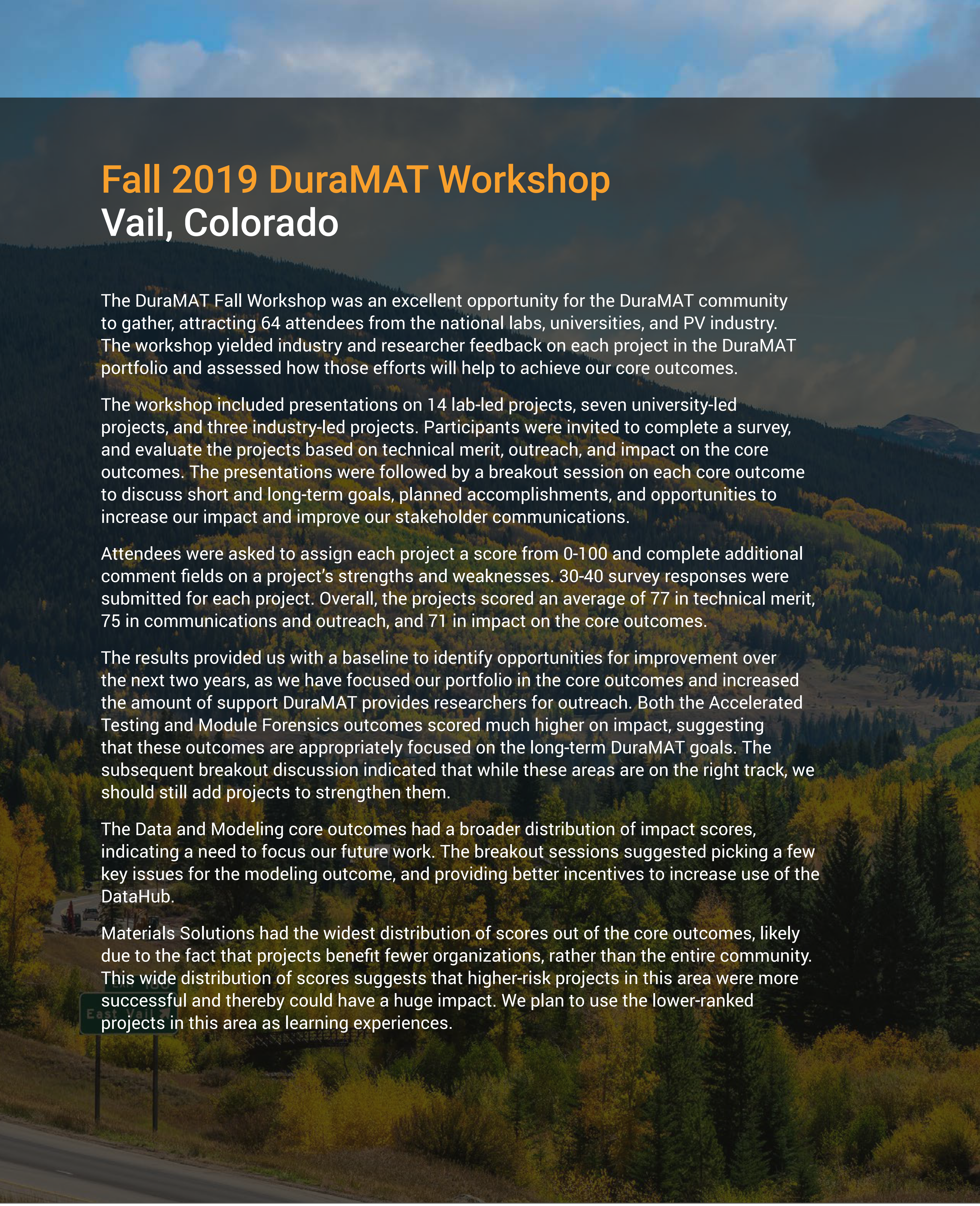
DuraMAT Workforce Development

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 that are primarily funded (>50%) to work on DuraMAT projects. We train these researchers in the skills needed to work in the PV industry or national laboratories. These researchers 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 continued efforts in their joint project focused on validating accelerated testing protocols against field aging. This work has highlighted each lab's unique capabilities, resulting in a unique approach to solving one of PV module reliability's most challenging questions. A highlight and summary of their recent progress can be found on page 16. The team continues their biweekly teleconferences and frequent visits to each other's labs to increase knowledge transfer and collaboration. Members of the DECS can also be found presenting at many of the large PV conferences around the world.

This year, the DECS has added two new members: Todd Karin of LBL and Archana Sinha of SLAC. Additionally, two members of the team have completed their time at DuraMAT and moved onto new positions: Stephanie Moffitt from SLAC is continuing her work in PV at the National Institute of Standards and Technology, and Ben Ellis from LBL has made the move to industry.

In addition to the DECS, DuraMAT's university project serve as an additional venue for work force development.



Fall 2019 DuraMAT Workshop
Vail, Colorado

The DuraMAT Fall Workshop was an excellent opportunity for the DuraMAT community to gather, attracting 64 attendees from the national labs, universities, and PV industry. The workshop yielded industry and researcher feedback on each project in the DuraMAT portfolio and assessed how those efforts will help to achieve our core outcomes.

The workshop included presentations on 14 lab-led projects, seven university-led projects, and three industry-led projects. Participants were invited to complete a survey, and evaluate the projects based on technical merit, outreach, and impact on the core outcomes. The presentations were followed by a breakout session on each core outcome to discuss short and long-term goals, planned accomplishments, and opportunities to increase our impact and improve our stakeholder communications.

Attendees were asked to assign each project a score from 0-100 and complete additional comment fields on a project's strengths and weaknesses. 30-40 survey responses were submitted for each project. Overall, the projects scored an average of 77 in technical merit, 75 in communications and outreach, and 71 in impact on the core outcomes.

The results provided us with a baseline to identify opportunities for improvement over the next two years, as we have focused our portfolio in the core outcomes and increased the amount of support DuraMAT provides researchers for outreach. Both the Accelerated Testing and Module Forensics outcomes scored much higher on impact, suggesting that these outcomes are appropriately focused on the long-term DuraMAT goals. The subsequent breakout discussion indicated that while these areas are on the right track, we should still add projects to strengthen them.

The Data and Modeling core outcomes had a broader distribution of impact scores, indicating a need to focus our future work. The breakout sessions suggested picking a few key issues for the modeling outcome, and providing better incentives to increase use of the DataHub.

Materials Solutions had the widest distribution of scores out of the core outcomes, likely due to the fact that projects benefit fewer organizations, rather than the entire community. This wide distribution of scores suggests that higher-risk projects in this area were more successful and thereby could have a huge impact. We plan to use the lower-ranked projects in this area as learning experiences.

Finally, participants indicated that the DuraMAT postdoc and early career network (the "glue" for the consortium), scientific impact, and our ability to study new, practical, and effective ideas are our greatest strength, while outreach to a more diverse group of stakeholders, underutilization of the DataHub, and insufficient integration to the larger reliability research community, are among our greatest opportunities for improvement.

Since receiving this feedback, the DuraMAT leadership team has made substantial progress in many of these areas. This includes diversifying our Industry Advisory Board (IAB) to improve outreach, directly coaching and incentivizing researchers to upload to the DataHub and publish, expanding our webinar promotion, and developing a consortium outreach strategy for high-level talks and publications.

Further discussions at the closing session with the IAB revealed that many thought the workshop itself offered one of our most useful outreach tools by providing networking opportunities. People talk to each other and learn a lot when they are trapped in a hotel together for two days!

Additionally, as our IAB noted, real progress has been made on all of our core outcomes. The most significant improvements were made in our module forensics capabilities. We are making some progress on DataHub use and will be focused on increasing that progress through fiscal year 2020.

Finally, we identified the need to increase our work in accelerated testing—both in foundational science and applied testing—since this area is so critical to the industry.

We look forward to our next workshop in the fall of 2020. We hope you will join us!

-Teresa, Margaret, and Laura

Publications

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1. 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. *https://doi.org/10.1002/pip.3106*

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

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10. 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. *https://doi.org/10.1109/JPHOTOV.2019.2955559*

11. 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. *https://doi.org/10.1002/pip.3144*

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1. Abudayyeh, Omar K., Andre Chavez, John Chavez, Sang M. Han, Francesco Zimbardi, Brian Rounsaville, Vijay Updadhyaya, Ajeet Rohatgi, Byron McDanold, and Timothy Silverman. "Development of Low-Cost, Crack-Tolerant Metallization for Solar Cells." Institute of Electrical and Electronics Engineers (IEEE) 46th Photovoltaics Specialists Conference (PVSC). Chicago, Illinois. June 16-21, 2019. *https://doi.org/10.1109/PVSC40753.2019.8980800*

2. Hartley, James Y., Ashley Maes, Michael Owen-Bellini, Thomas Truman, Edmund Elce, Allan Ward, Tariq Khraishi, and Scott Roberts. "Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load." IEEE 46th PVSC. Chicago, Illinois. June 16-21, 2019. *https://doi.org/10.1109/PVSC40753.2019.8980842*

3. Hartman, Katy, Peter Hacke, Michael Owen-Bellini, Yang Jin, Malcolm Cummings, Al Taylor, Jaco Pretorius, and Les Fritzemeier. "Validation of Advanced Photovoltaic Module Materials and Processes by Combined-Accelerated Stress Testing (C-AST)." IEEE 46th PVSC. Chicago, Illinois. June 16-21, 2019. *https://doi.org/10.1109/PVSC40753.2019.8980545*

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11. Karas, Joseph, Archana Sinha, Viswa Sai Pavan Buddha, André Augusto, Govindasamy TamizhMani, and Stuart Bowden. "Reliability of Modules with High Efficiency Solar Cells with Copper Plated Contacts." PVRW. Lakewood, Colorado. Feb 26-28, 2019.*

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All PVRW presentations can be found in the full PVRW Proceedings PDF at https://www.nrel.gov/docs/fy19osti/74405.pdf. (Note: please allow time for this large file to download.)

Accelerated Applications

Industry-Relevant Research and Tools from the DuraMAT

The DuraMat DataHub

The DataHub provides a central point for researchers to archive, search, and obtain experimental and reference data, analysis tools, tutorials, and reports. It is deployed on a federally approved implementation of Amazon Web Services at datahub.duramat.org. It currently has 103 registered users working on 53 projects that encompass 1,978 files and 61 publicly available datasets. The public data sets cover areas from soiling maps to albedo measurements.

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Photovoltaic Climate Zone (PVCZ) Tool

This tool describes a set of climate zones based on temperature, humidity, and other characteristics that are known to stress PV systems around the world. This is an alternative to the traditional Koppen Geiger zones developed for agriculture. PVCZ can be used for degradation analysis, system performance assessments, and other applications. Developed by Lawrence Berkley National Laboratory and Sandia National Laboratories, the tool is available at https://pvtools.lbl.gov/pv-climate-stressors.

Contact — toddkarin@lbl.gov

Thermo-Mechanical Modeling of Modules

Thermo-mechanical modeling of full-size glass-glass and glass-backsheet modules is underway at Sandia National Laboratories. 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.

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Wind Loading Modeling on Single-Axis Trackers

DuraMAT researches applied FEniCS—an open-source software tool—to model dynamic instabilities and other effects of wind loading on single-axis trackers. The NREL Flatirons Campus conducted detailed field tests measuring inflow conditions (e.g., wind speed and turbulence intensity) and loads on the tracker system. This data is being used to validate the model. Results have included recommendations to industry on higher stow angles to prevent dynamic instability conditions. Implementing these recommendations at the NREL test site has prevented instability conditions in the 40-80 mile per hour wind speed range in which they had previously occurred.

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Combined Accelerated Stress Testing (C-AST)

This novel, accelerated testing approach employs a combination of real-world stress conditions to identify weaknesses in module designs and materials without prior knowledge of expected failure modes. C-AST has been validated through studies on backsheets in which it successfully replicated the field performance of different materials.

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Fielded Module Forensics

Fielded module forensics that can identify causes of module power loss are critical for repair planning, warranty claims, and future system performance estimates. This project showed that spatially resolved thermal imaging combined with injection-dependent electroluminescence can detect unrecoverable back-side metallization failure as the source of resistive performance loss in fielded modules. Photoluminescence and UV fluorescence can be added to study other degradation modes as needed.

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DuraMAT
Durable Module Materials Consortium

The DuraMAT—or Durable Module Materials—Consortium brings together the national lab and university research infrastructure with the photovoltaic (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.

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