DuraMAT
Durable Module Materials Consortium

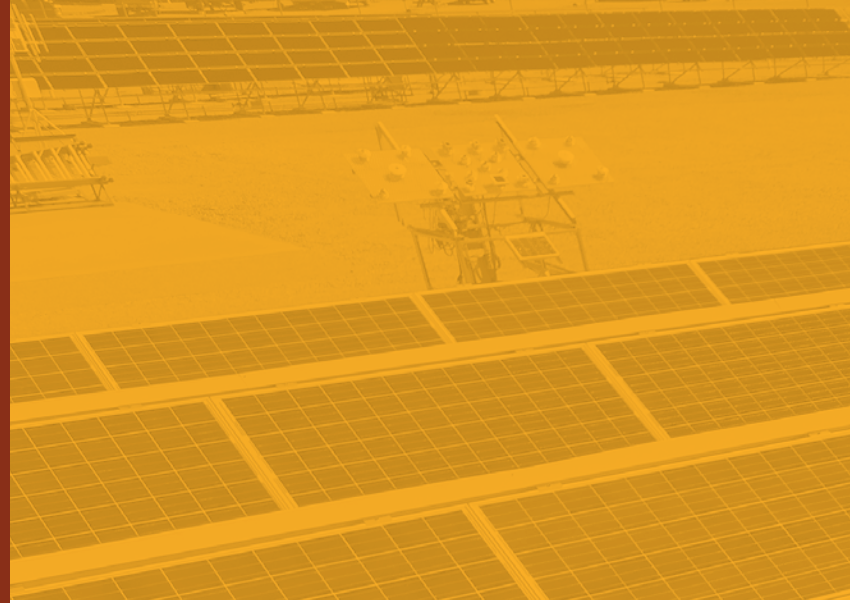
FY 2023

ANNUAL REPORT

TOWARD RELIABILITY FORECASTING

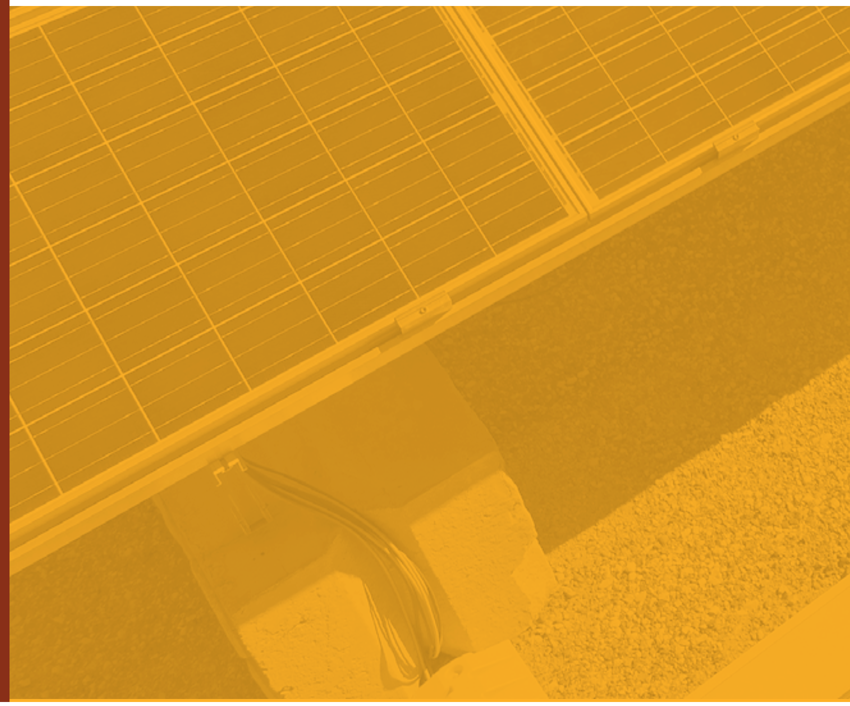
U.S. DEPARTMENT OF ENERGY
NREL Transforming ENERGY
Sandia National Laboratories
BERKELEY LAB

TABLE OF CONTENTS



About DuraMAT

The Durable Module Materials Consortium (DuraMAT) is a multi-lab consortium led by the National Renewable Energy Laboratory (NREL), with Sandia National Laboratories (Sandia) and Lawrence Berkeley National Laboratory (LBNL) as core research labs, funded by the U.S. Department of Energy's Solar Energy Technologies Office (SETO). DuraMAT's overarching goal is to accelerate a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035. We work in partnership with our 22-member industry advisory board (IAB) and the technical management team at SETO.



DuraMAT Director's Letter

2023 has been a wild ride in the solar industry. Photovoltaic (PV) manufacturing is coming back to the United States, and deployment is booming again. DuraMAT has a unique opportunity to support flourishing manufacturing and deployment over the next couple of years. Despite the industrywide changes, our primary mission stays the same—enabling reliable, durable PV for the energy transition.

DuraMAT's goals are to understand:

- Which materials and module designs will enable sustainable, high-energy-yield, 50-year modules, and how do we ensure that these new modules are not going to fail prematurely?
- What triggers wear-out, defined as a rapid increase in degradation at end of life, and what are the characteristics, rates, and mechanisms of long-term degradation in PV modules?

In fiscal year 2023 (FY23), DuraMAT introduced the idea of reliability forecasting and kicked off several new projects in this area. Reliability forecasting is the ability to predict future performance based on physical models, accelerated testing, tests to failure, detailed characterization, and statistical analysis—without reliance on past field performance. Module technology, changing environmental conditions, and rapidly accelerating deployment mean that we need to quantify future performance in a world where the past is not a great indicator. This is especially important for understanding long lifetimes and wear-out mechanisms that may not occur for 20–30 years.

We awarded six projects under our reliability forecasting call this year. Research areas include ultraviolet (UV)-induced degradation, glass fracture mechanics, fundamental degradation mechanisms in encapsulants, and faster analysis of failure data. DuraMAT also launched six complementary projects under an open call studying copper metallization, polymer degradation, field and indoor degradation correlation, and recycling. These projects help us better understand the potential weaknesses and risks of new designs and materials, and they help us spot those issues more quickly. The combination of modeling, indoor experimentation and characterization, and outdoor field studies helps build predictive capabilities for long module lifetimes. Outreach and communications efforts are ongoing, with invited and contributed talks at the PV Reliability Workshop (PVRW), the IEEE Photovoltaic Specialists Conference (PVSC), the Silicon Workshop, the International Photovoltaic Science and Engineering Conference (PVSEC), RE+, and many others. From 2017 through the end of FY23, DuraMAT produced 75 published journal articles and over 210 presentations. We will continue our hybrid webinars, presentations, and other events so we can remain accessible, inclusive, and open. In addition to traditional academic publications, DuraMAT has developed a suite of software tools and data sets for PV reliability studies for our stakeholders. These include mechanical models for materials, wind loading, fracture mechanics, moisture diffusion, irradiance, and others. All can be accessed from the DuraMAT Data Hub.

DuraMAT's goals are ambitious, and we remain focused on building predictive reliability capabilities that will accelerate PV deployment for the energy transition. DuraMAT remains a trusted resource for the PV industry as it deals with growing pains and a tremendous opportunity to decarbonize electricity generation.

We are looking forward to another productive year of research, and we really hope to see you all in person soon. 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

Key Results From FY23

Reliability Forecasting Strategy

- Forecasting is primarily forward-looking and focused on recently deployed and newer technologies where historical projections are likely inaccurate.
- Forecasting efforts start from fundamental research questions about how a material, interface, component, or module will change in the use environment over many years. Forecasting does not start with field observations of wide-scale problems after deployment.
- Forecasting studies may focus on whether or not an observed phenomenon is or will become a degradation or failure problem. This includes latent defects from manufacturing and damage during use.
- Forecasting seeks to quantitatively predict changes over long lifetimes rather than screen out known weaknesses based on prior observations.
- Forecasting requires the capability to develop scaling relationships between things that have already been studied for longer times and those that are newer.
- Forecasting requires rapid validation without waiting years for traditional field validation.

Quantifying the Impacts of Cell Cracks

- Newer modules with many busbars, half-cut cells, and glass-glass encapsulation are more tolerant of cracked cells and less likely to exhibit power loss.
- Impacts that damage cells in new modules with thin glass usually also break the glass.
- Module design changes such as rotating cells in the module can also make modules less sensitive to cell breakage. Interconnect breakage can lead to power loss, and DuraMAT continues to study interconnect durability.

High-Efficiency Modules

- UV-induced degradation appears to be a significant issue in modules made with high-efficiency cells. DuraMAT is starting new work to quantify this in FY24.
- Our small field study of bifacial modules continues to show higher degradation than expected, usually due to losses in short-circuit current.
- Hybrid encapsulants like EPE (EVA-POE-EVA), which is a combination of ethylene vinyl acetate (EVA) and polyolefin elastomer (POE), can have significant performance advantages, but the interface between the two polymers can be weak.
- The rear sides of bifacial cells appeared to be more susceptible to UV damage compared to the front sides. The increased degradation related to UV exposure in modern cell types may offset the gains predicted from increased UV/blue transmission to the cells. Long-term energy yield may be higher with a UV-blocking encapsulant despite the lower initial flash efficiency.

DuraMAT Communications Working Group

New discoveries, scientific results, and research outcomes can only be impactful if they are clearly and effectively communicated. The outcomes of DuraMAT are no exception. As researchers, we often default to peer-reviewed journals and scientific conferences to communicate our results. The DuraMAT industry advisory board (IAB) has always encouraged us to push outside of this comfort zone and expand the impact and influence of DuraMAT. In FY23, we formed a working group focused on improving and expanding our communications network. The working group was composed of DuraMAT researchers at various stages in their careers and Harrison Dreves from NREL's communications team. The working group met a number of times over the course of the year. Initial efforts focused on defining the different audiences we are trying to reach and identifying the most effective ways of communicating with them. The outcome of these efforts was presented in August at a public DuraMAT webinar titled "Reliable & Durable Communication: Consistently Connecting DuraMAT Messages with Target Audiences." A recording of this presentation can be found at the DuraMAT website: *www.duramat.org/news-and-events/webinars*. The final deliverable for the group was to develop and document an improved communications plan for FY24.

This year, we also revised the way we think about our working groups and implemented sunset dates for our groups. Having accomplished our main mission, the communications working group was closed at the end of the fiscal year to free up bandwidth for future working groups.

CONTACT:
Harrison Dreves, *harrison.dreves@nrel.gov*

What's next?

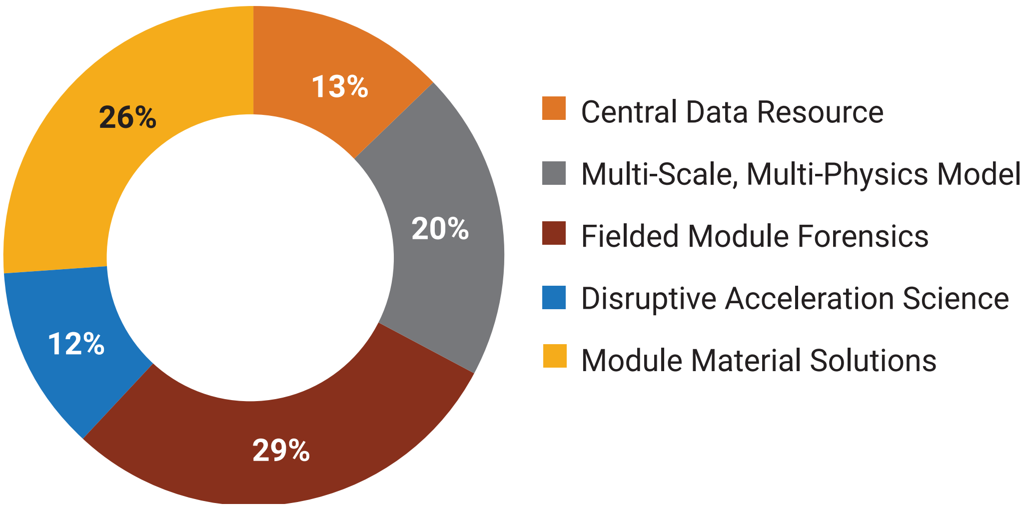
Topic: New applications of machine learning to solar research

CONTACT:
Anubhav Jain, LBNL, *ajain@lbl.gov*

DuraMAT Fiscal Year 2023 Financial Report

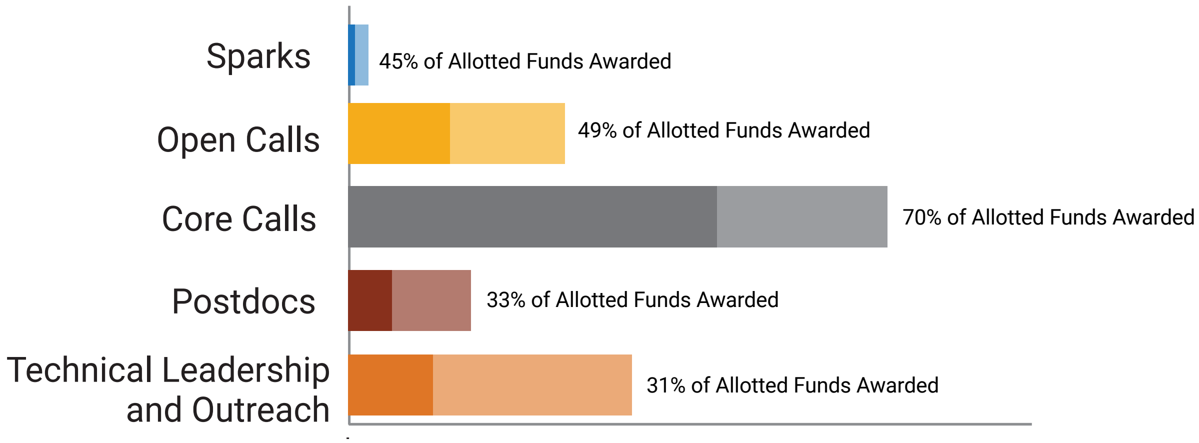
DuraMAT continues to partner with national labs, universities, and industry to fund research projects that offer solutions to critical barriers limiting PV module reliability and durability. To date, the DuraMAT program has funded 78 research projects and collected over $3.68 million in cost share.

Project Portfolio Organized by Core Objectives



The first figure on this page shows the current distribution of project funds among our five research objectives. A full list of projects and detailed descriptions of each project can be found on our website.

Percentage of DuraMAT Budget Awarded by Project Type



The second figure shows the total funding allotted for each project type, and the percentage of that funding that has been awarded thus far. As shown in the figure, the program is currently in the process of awarding $3.4 million through its next round of Open Call awards, where univerisity and industry partners are the prime recipents. Over the next 2 years, an additional $5.3 million in Core and Spark awards will go through the national laboratory network.

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:

- Demonstration of a central data resource, the DuraMAT Data Hub, that securely hosts multiple types of private and public data (released and online at *https://datahub.duramat.org*).
- Development of open-source software libraries for data cleaning (e.g., PVAnalytics), statistical analysis (e.g., PVPRO, PVARC, vocmax), and machine learning (e.g., clear sky detection, pvOps) to solve module reliability challenges, leveraging the data available in the Data Hub as well as industry data sets.
- Demonstration of applications of the data and software tools to address short-term commercial challenges that are beyond current industry capabilities as well as long-term research challenges; use of machine learning to disentangle the causal factors of degradation.
- Techno-economic analysis of the effects of more predictive accelerated testing, lower degradation, and resilient module designs and materials. For example, the simplified PV levelized cost of energy (LCOE) calculator allows for interactive modeling of installed system cost and LCOE in response to changing variables such as location, tracker system, and cell technology.

Central Data Resource

Core Objective

KEY RESULT

Techno-Economic Analysis Support for DuraMAT

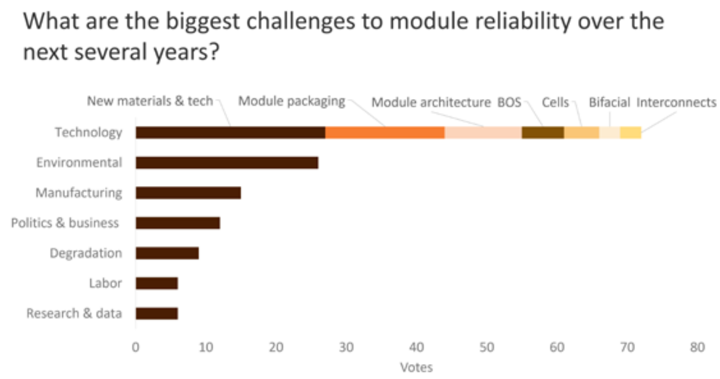
Techno-economic analysis (TEA) helps DuraMAT stakeholders by identifying promising research directions for improved PV module and system reliability, durability, and sustainability. This is achieved by quantifying the value of these improvements in terms of financial and environmental impact, and by synthesizing qualitative information about technology and reliability trends from industry and DuraMAT researchers.

PI: Michael Woodhouse, Brittany Smith (NREL)

Team Members: Jarett Zuboy (NREL)

Summary of Result: The TEA team synthesizes a range of sources (PV market reports, industry interviews, peer-reviewed literature) to identify likely and impactful near-term module and system technology trends and to assess the reliability implications of those trends. By deploying our bottom-up manufacturing and module testing cost modeling capabilities, TEA works to calculate the performance-cost trade-offs between technology approaches. We also model system power production over defined degradation profiles and useful lifetimes, in conjunction with levelized cost of energy (LCOE) modeling. This includes the online LCOE calculator sustained by DuraMAT, which can quantify the impacts of changing PV module degradation profiles and materials substitution, operations and maintenance expenses, and the value proposition of new materials and products. We also evaluate the costs and benefits of circular processes or initiatives and the sustainability of materials.

We hope to continue identifying opportunities for high-impact degradation science through sensitivity analyses of module and system lifetime economics, collect industry input on current and emerging technologies, provide an online LCOE calculator, and link new module technology trends with potential reliability impacts. We achieve high impact by communicating our analytical results to the broad community of solar and storage industry stakeholders through peer-reviewed journal publications, virtual and live webinar and conference presentations, and publicly available cloud-based cost modeling tools. TEA has also uncovered partnering opportunities between researchers and industry.



Sample results from polling at NREL's PV Reliability Workshop—one of multiple ways the reliability implications of module technology and market trends continued to be tracked in 2023.

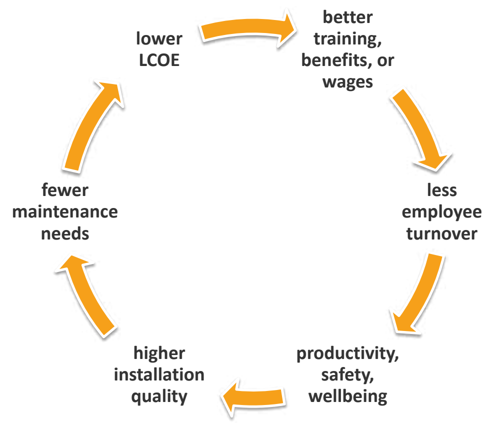


Illustration of installation and maintenance workforce factors that may affect PV project LCOE.

LEARN MORE

Online LCOE Calculator: *https://datahub.duramat.org/dataset/lcoe-calculator-tool*

Zuboy, J, et al. 2023. "Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes." *IEEE Journal of Photovoltaics*. *https://doi.org/10.1109/JPHOTOV.2023.3334477*

Central Data Resource

Core Objective

KEY RESULT

Assessing Factors Underpinning PV Degradation Through Data Analysis

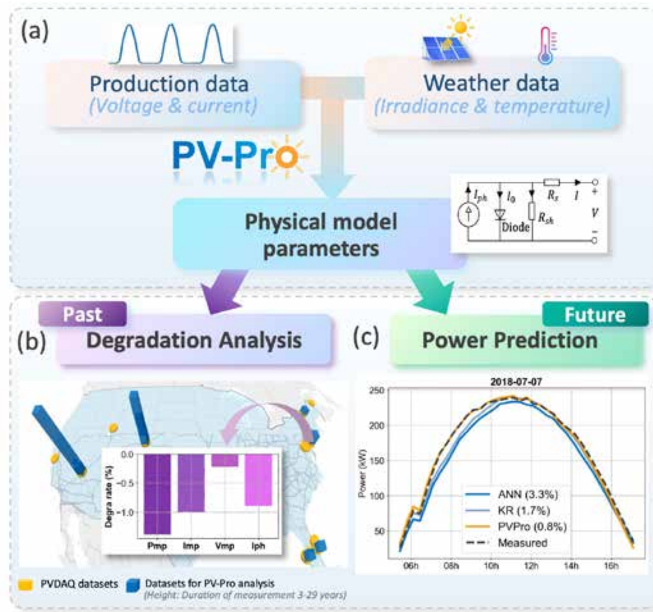
PVPRO builds precise physical models for degradation analysis and power prediction. Bill-of-materials analysis uncovers the design factors that influence power loss.

PI: Anubhav Jain (LBNL)

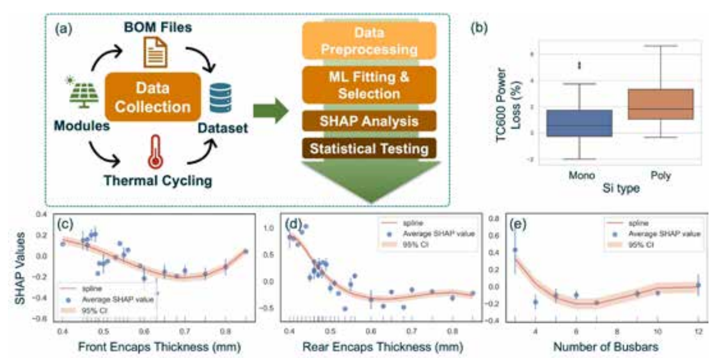
Team Members: Baojie Li, Xin Chen (LBNL)

Summary of Result: Modeling on-site PV systems typically requires specialized measurements. We propose the PVPRO method to construct an accurate physical model of a system leveraging only production and environmental data. PVPRO serves two primary functions: degradation analysis and power prediction. Using historical data, PVPRO can extract past and current single-diode model parameters and reconstruct the degradation trend for various parameters. We have successfully employed PVPRO in multiple PV systems, demonstrating its efficacy and practicality for identifying the root source of power loss. As for power prediction, PVPRO improves the irradiance-to-power conversion process with an error reduction of ~20%–30% compared to traditional models and machine learning techniques.

Another focus of the project is the bill of materials (BOM) of PV modules, which impacts the overall module durability. We used machine learning and Shapley Additive Explanations (SHAP) interpretation to discover the correlation between BOM features and degradation. We found that the cell type with busbar numbers and encapsulant thickness remain the top influential factors. This work could provide directions for future research on module design and optimization.



(a) PVPRO can extract physical model parameters using only production and weather data. (b) PVPRO calculates the degradation rate of multiple parameters and estimates the root source of power loss. (c) The physical model rebuilt by PVPRO also enables precise irradiance-to-power conversion with power error <1% and outperforms typical machine learning models.



(a) Workflow of the BOM study. (b) Dependence plot of the relation between numerical features and the SHAP value. (c) Distribution of power loss between monocrystalline and polycrystalline silicon cells.

LEARN MORE

Li, Baojie, et al. 2023. "Determining Circuit Model Parameters From Operation Data for PV System Degradation Analysis: PVPRO." *Solar Energy* 254: 168–181. *https://doi.org/10.1016/j.solener.2023.03.011*.

Online PVPRO software repository: *https://github.com/DuraMAT/pvpro/*

Central Data Resource

Core Objective

KEY RESULT

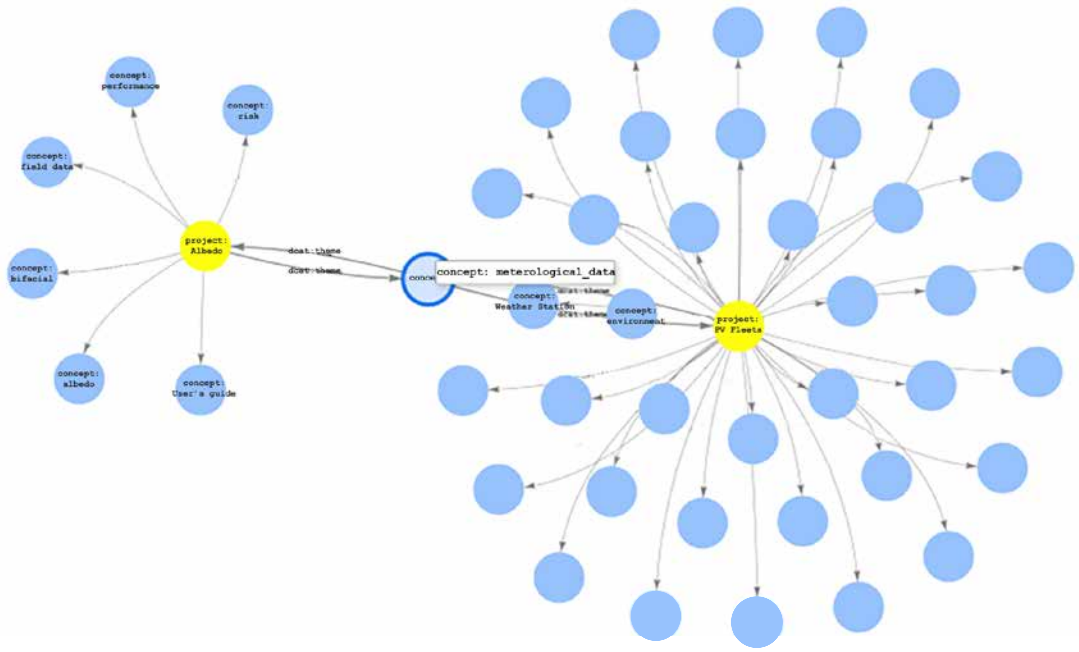
Learning How To Chat With the DuraMAT Data Hub

The DuraMAT Data Hub continues to operate after 6 years, attracting researchers and interested members of the public from around the globe. The number of consortium researchers, number of data products, and access by outside researchers continue to grow annually.

PIs: Robert White (NREL)

Team Members: David Rager, Sagi Zisman, Rachel Hurst, Nick Wunder, Nalinrat Guba, Ashley Vise (NREL)

Summary of Result: Over the past year, we have continued to expand the DuraMAT Data Hub. The Data Hub currently has 267 registered users working on 96 projects that encompass 12,107 files (an 11.5% increase from last year). We also identified future ways to improve researchers' and outside users' experience. This year, we identified a critical need to improve the search function for data and information in the Data Hub. As previewed at the 2023 DuraMAT Fall Workshop, we were able to express data in a visual knowledge graph and link it through a large language model system (e.g., ChatGPT) to provide a contextualized chat that could more effectively filter data for the user than the conventional method that is part of the current Data Hub platform. The prototype was well received at the fall workshop. In FY24, we plan to improve on the prototype and integrate it into the new Data Hub platform.



An example cut from the larger DuraMAT knowledge graph showing the knowledge nodes and the interconnection between two separate data sets. This will allow users to explore the Data Hub more effectively.

LEARN MORE

DuraMAT Data Hub: *https://datahub.duramat.org*

Multi-Scale Multi-Physics Model

Core Objective Lead: Martin Springer, Martin.Springer@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:

- Development of a converter software between COMSOL and Sierra to share finite element models across national laboratories, universities, and collaborators.
- Representation of crack geometries as one-dimensional vectors for parameterization and generation of new crack structures that will inform machine learning models to estimate power loss based on electroluminescence images.
- Publication of open-source Python library PVDeg, which allows for the collaborative development of degradation models and provides the necessary framework to perform geospatial analysis.
- Verification against experimental results of a structural mechanics model focused on hail impact, which enables accurate prediction of mechanical stresses during impact.
- Combination of previous aerodynamic modeling efforts into an open-source software package called PVade, which enables simulation of fluid-structure interactions of tracker-mounted PV systems.

Multi-Scale Multi-Physics Model

Core Objective

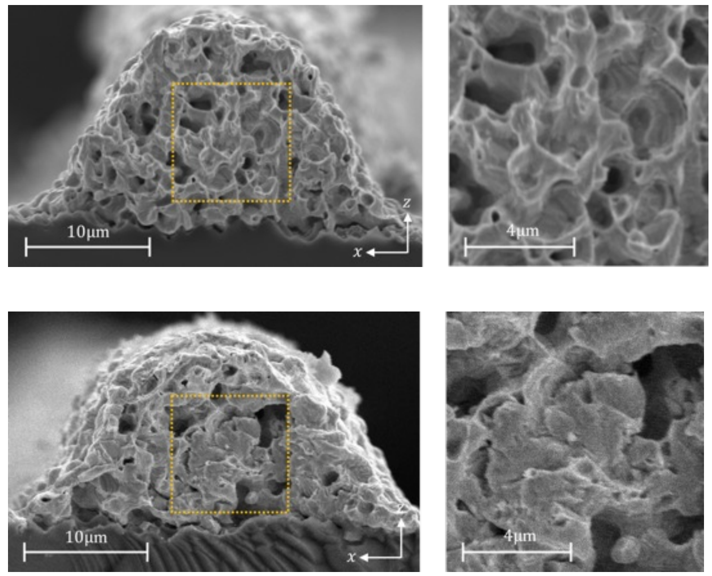
KEY RESULT

Gridline Bridging Is Quickly Reduced by Crack Surface Blunting

The electrical connections of fractured silicon PV cells are maintained by a rough fracture surface of the bridging gridlines. With even limited cell fragment movement, however, these fracture surfaces become smoother and significantly reduce the effective bridging distance.

Team Members: Salil Rabade, Tim Silverman, and Nick Bosco (NREL)

Summary of Result: Cracks in crystalline silicon solar cells can form for many reasons, from installation to weather conditions like wind oscillation, hail impact, and temperature changes. Crack generation does not lead to immediate power loss because gridlines electrically bridge cracks. However, repeated contact and separation between cracked gridlines during thermal and mechanical loading can eventually cause complete electrical isolation. Hence, it is important to study the relationship between the evolution of bridging behavior and dynamic mechanical loading to predict electrical failure.



Scanning electron microscopy fractography images of silver gridlines before (top) and after (bottom) limited cell fragment movement. Sharp features on the fracture surface that initially enable electrical bridging of the cell fragments are quickly blunted.

LEARN MORE

Mechanical Models for 50-Year Lifetime PV Modules webpage: *https://www.duramat.org/projects/mechanical-models-lifetime-pv-modules*

Bosco, N., M. Springer, and X. He. 2020. "Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging Materials for Direct Finite-Element Method Input." *IEEE Journal of Photovoltaics* 10 (5): 1424–40. *https://doi.org/10.1109/JPHOTOV.2020.3005086*.

Silverman, T., M. Bliss, A. Abbas, T. Betts, J. Walls, and I. Repins. 2019. "Movement of Cracked Silicon Solar Cells During Module Temperature Changes." 46th IEEE Photovoltaic Specialists Conference. *https://doi.org/10.1109/PVSC40753.2019.8981150*.

Bosco, N., A. Chavez, V. Upadhyaya, and S. Han. 2020. "Fatigue-Like Behavior of Silver Metallization Gridlines and Proposed Damage Mechanics Model." 47th IEEE Photovoltaic Specialists Conference. *https://doi.org/10.1109/PVSC45281.2020.9300893*.

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

Predicting Glass Failure During Hail Impact Using Simulation

In this research, we seek to develop a criterion that would allow for prediction of glass failure under hail impact from simulations alone.

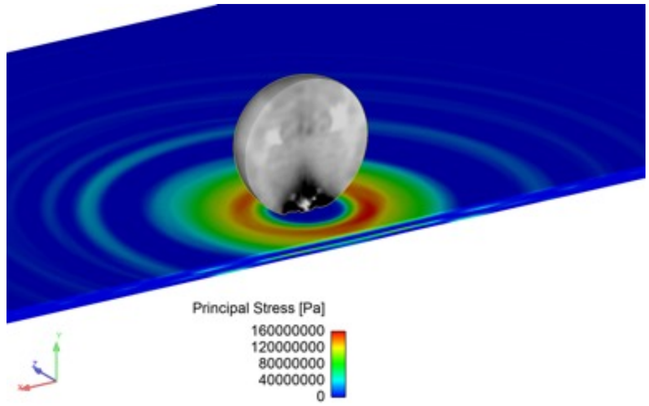
PI: James Hartley (Sandia)

Team Members: Colin Sillerud (CFV Labs), Jennifer Braid (Sandia)

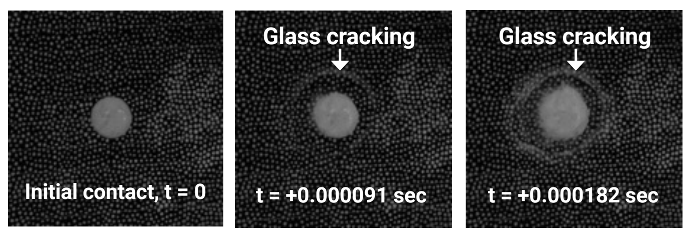
Summary of Result: Large hail events are a significant threat to PV deployments in many geographical regions. However, module survivability is difficult to quantify beyond a simplistic pass/fail criterion from physical test sequences. This leaves large uncertainty in the true risk of damage and complicates insurance-related decision-making, in turn raising costs.

In this research, we seek to develop a criterion that would allow for prediction of glass failure under hail impact from simulations alone. This could reduce testing overhead while also providing a more quantitative understanding of module hail robustness by showing whether survived impacts are approaching the failure criteria or still have margin. Additionally, the influence of module design variations on the probability of failure could be identified.

We are investigating glass stresses during impact, using a resolved ice material model to impose time-varying forces onto module models based on hail fracture and dispersion behavior. By cross-referencing simulated stresses against a database of more than 2,500 laboratory hail test results from this project and DuraMAT partners, we hope to identify the set of simulated features—such as a critical stress value, the affected area, and the length of time under stress—that explain a module glass failure.



Simulated glass stresses during ice ball impact, 75 microseconds post-contact. Predicted stresses are influenced by both ice fracture behavior and modeled module design.



High-speed video sequence of an ice impact, with digital image correlation features to derive deflections for simulation model validation. Observed failure timings also inform the simulated failure criteria.

LEARN MORE

Braid, J. L., P. Reu, J. Hartley, et al. 2023. "Digital Image Correlation Analysis of Hail Impacts on PV Modules." Presented at 2023 NREL Photovoltaics Reliability Workshop. Lakewood, CO. February 28, 2023. *https://pvrw.nrel.gov/past-proceedings*.

Hartley, J., J. Braid, C. Sillerud. 2023. "Analyzing Hail Impacts on PV Modules Using Computational Simulation." Presented at 2023 NREL Photovoltaics Reliability Workshop. Lakewood, CO. March 2, 2023. *https://pvrw.nrel.gov/past-proceedings*.

Hartley, J. 2023. "Hail Impact Damage on PV Modules." DuraMAT Webinar Series. December 18, 2023. *https://www.duramat.org/news-and-events/webinars*.

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

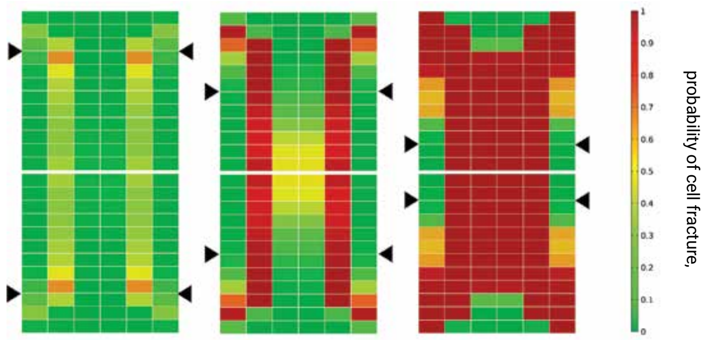
Cell Cracking? There's an App for That

WhatsCracking, a free, user-friendly app, accurately predicts cell fracture in crystalline silicon PV modules.

Team Members: Nick Bosco, Tim Silverman and Mike Deceglie (NREL)

Summary of Result: As silicon PV cells and modules grow in size, and more novel mounting schemes and thinner glass are considered, cell fracture has become a higher risk. Experimentally validating all combinations of module design, construction, framing, and mounting is not practical and can be burdensome within a narrow product development design window.

We released a predictive model for crystalline silicon PV module cell fracture as a user-friendly app, called WhatsCracking, that anyone can use for free without purchasing a software license or needing computer modeling expertise. WhatsCracking accurately predicts cell fracture in crystalline silicon PV modules.



Frame-by-frame video analysis of a 35-millimeter ice ball impacting a module, showing instantaneous displacements calculated from digital image correlation.

LEARN MORE

The WhatsCracking app is available for download from the DuraMAT Data Hub: *https://datahub.duramat.org/dataset/metadata/whatscracking-application*

A video tutorial for WhatsCracking is available on the NREL Learning YouTube channel: *https://www.youtube.com/watch?v=sfl3Q8uO7Sc&t=2s*

A DuraMAT webinar on February 13, 2023, introduced the app and presented several case studies: *https://www.duramat.org/webinars.html*

A PVRW presentation introduced the app and presented several case studies: *https://pvrw.nrel.gov/past-proceedings*

A PV Magazine trade article introduced the app and presented several case studies: *https://www.pv-magazine.com/magazine-archive/rotate-half-cells-for-stronger-modules/*

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

The Integration Pipeline for PV Degradation Analysis

An industry-facing PV degradation prediction tool and degradation database is designed to enable a 50-year module.

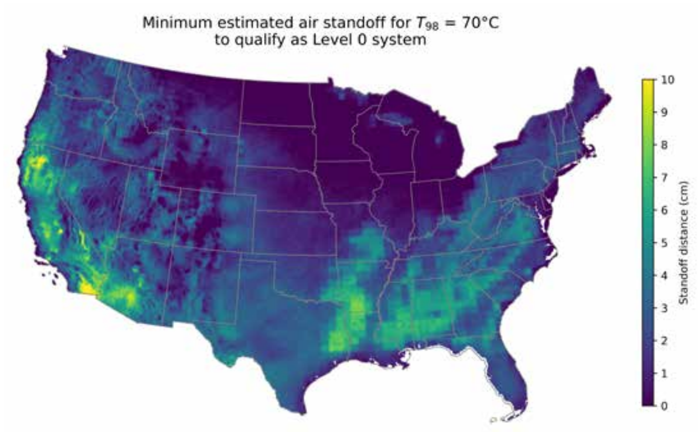
PI: Michael Kempe (NREL)

Team Members: Martin Springer, Silvana Ovaitt, Matt Brown, Tobin Ford (NREL)

Summary of Result: Extrapolating laboratory results to field durability insights requires coming up with a model and then comparing that model to environmental conditions. Getting the parameters for these models is difficult, but the models themselves are relatively simple. However, although the extrapolation mathematics are the same for all researchers in the PV field and are conceptually straightforward, they are also time-consuming, and many researchers fail to do this work properly because of the time needed and the fact that it is often outside of their expertise. We are creating a simple computational framework to minimize this work in hopes that PV researchers' extrapolations will be of higher quality.

Our open-source platform on GitHub is custom-tailored to PV applications. It interfaces with geospatial meteorological data, with Python functions organized for simple programming. A Python function wrapper is capable of simple automation of any degradation functions, and multiple nodes can be spun up on a remote supercomputer for fast, worldwide, geospatial meteorological calculations. We are standardizing the naming conventions for variables and computer code so that anyone can easily contribute their code to the GitHub repository.

This work will unify the PV industry's degradation computation efforts worldwide under a uniform set of programs and procedures—making the calculations quick and easy and helping people do higher-quality work with better accuracy.



This plot, created using the degradation tool, tells installers what the minimum standoff distance needs to be in order to be compliant with International Electrotechnical Commission (IEC) standards (in particular, IEC standard 63126).

Sources:

Kempe, M. et al. 2023. "Close Roof Mounted System Temperature Estimation for Compliance to IEC TS 63126." PVSC Proceedings 2023.

Fuentes, M. K. 1987. A Simplified Thermal Model for Flat-Plate Photovoltaic Arrays. *Albuquerque, NM: Sandia National Laboratories. SAND-85-0330. https://www.osti.gov/biblio/6802914.*

LEARN MORE

More information about the project can be found at *www.DuraMAT.org*, and all of the code can be accessed at *https://github.com/NREL/PVDegradationTools*.

Presentations on the project were given at the ATSM Workshop on Weathering and Durability Testing in Denver, Colorado, and the 2023 DuraMAT Workshop in Albuquerque, New Mexico.

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

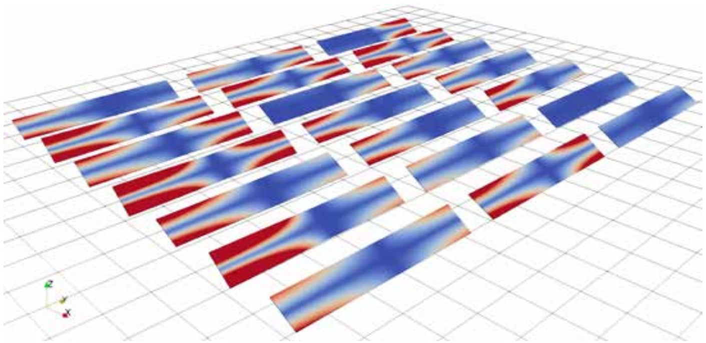
Finding Stability From the Wind

Single-axis tracker arrays can experience significant dynamic loading even at low wind speeds. A simulation and optimization framework helps manage wind-driven loading on PV systems.

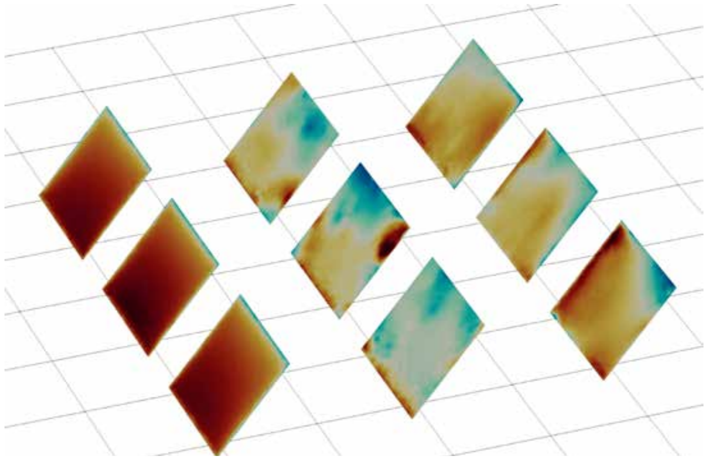
PI: Ethan Young (NREL)

Team Members: Walid Arsalane, Scott Dana, Chris Ivanov, Mike Deceglie (NREL)

Summary of Result: As PV modules continue to trend toward larger, thinner, and more flexible forms, they grow more susceptible to damage from dynamic wind loading. As a result, understanding the impact of wind on PV systems, particularly when mounted on compliant solar-tracking hardware, and identifying robust, stable array layouts and stow strategies is becoming increasingly important. We are developing an open-source software package, PV aerodynamic design engineering (PVade), to simulate the cascading fluid-structure interaction that occurs within solar-tracking arrays. This will enable researchers to test hardware, layout, and tracker control changes, leading to enhanced stability and a reduction in wind-driven damage. Early work on this project was focused on defining a simple user interface that allows users to easily define new system geometries, followed by implementation and numerical validation of the fluid, structure, and coupled solver physics. When finished, PVade will enable us to identify tracker alignments and stow strategies that minimize these dynamic loads and instabilities for a specific site's weather and test the effect of stability-enhancing hardware changes.



A small array oriented at 30° in an 8 m/s wind. Panels are mounted on a freely rotating torque tube but are rigidly fixed at approximately midspan. Red indicates larger displacements.



The instantaneous pressure induced on high-clearance agrivoltaics panels. Orange indicates positive pressure and blue indicates negative pressure.

LEARN MORE

For more information, contact Ethan Young (*ethan.young@nrel.gov*), or see our presentation from the 2023 PV Reliability Workshop: *https://www.nrel.gov/docs/fy23osti/85567.pdf*.

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

Enabling Multi-Physics and Multi-Scale Modeling Across Finite Element Codes

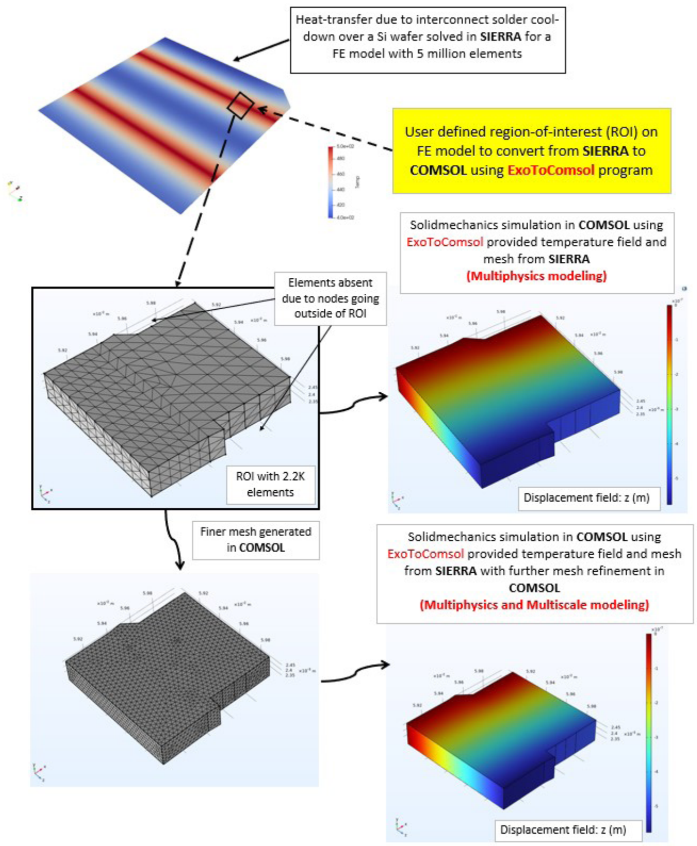
A new software program enables conversion between Sierra and COMSOL simulation codes.

PI: Farhan Rahman, (Sandia)

Team Members: James Y. Hartley, (Sandia)

Summary of Result: Complete service life prediction of PV modules requires multi-physics and multi-scale modeling, which can be achieved through modeling capability sharing among DuraMAT partners. However, the absence of a converter tool between Sierra and COMSOL finite element analysis codes limits modeling capability sharing between Sandia and other DuraMAT partners. To address this, we developed a software called ExoToComsol that converts between Sierra and COMSOL file formats. This enables modeling results from a particular physics solve from one finite element code (Sierra/COMSOL) to be imported into another finite element code to solve for different physics, thus enabling the development of a multi-physics modeling chain. Moreover, users can define a particular region of interest on a large finite element model result from one finite element code, import it into another finite element code, and then perform mesh refinement to perform multi-scale modeling alongside multi-physics modeling.

The software program is written in Python and is open source. Code documentation and example use cases have been developed to illustrate main program utilities; these include Sierra-to-COMSOL two-way conversions of full models as well as model segments bounded by user-provided regions of interest. This open-source software program allows multi-physics and multi-scale modeling across Sierra and COMSOL software to improve DuraMAT's modeling capabilities.



The open-source converter program ExoToComsol enables multi-physics and multi-scale modeling across Sierra and COMSOL finite element codes.

LEARN MORE

The code and documentation for ExoToComsol will be available on GitHub, and an example data set to demonstrate the code functionality will be available in DuraMAT's Data Hub.

For more information, contact Farhan Rahman (*frahman@sandia.gov*).

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

Predicting the Electrical Impact of PV Cell Cracks

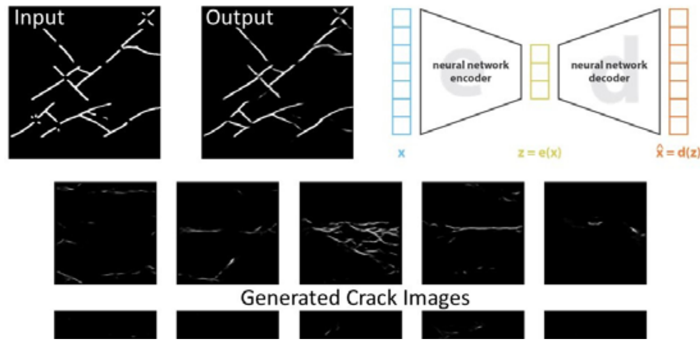
We're using machine learning to simplify representations and effects of cell cracks, so power loss can be predicted from electroluminescence images.

PI: Jennifer Braid (Sandia)

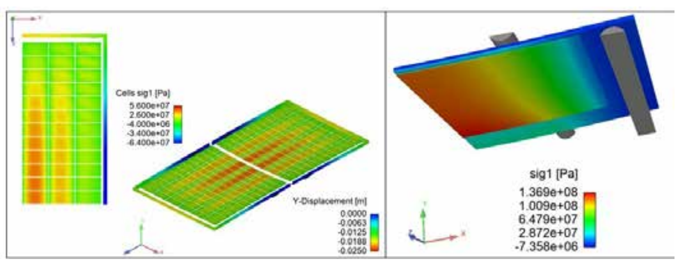
Team Members: James Hartley, Norman Jost, Emma Cooper, Benjamin Pierce (Sandia); Mariana Bertoni, Ian Slauch (Arizona State University)

Summary of Result: Quantifying the impact of silicon PV cell cracks on module performance is labor-intensive and provides only a point-in-time snapshot of module health. The effects of cracks on performance are probabilistic and highly variable in response to thermomechanical stressors. Our project accounts for the statistical and physical phenomena related to crack formation and the evolution of electrical behavior. Using dimension reduction and probabilistic machine learning techniques, we will predict present and future PV module power loss associated with real cell cracks from electroluminescence images.

Our framework is based on experimental measurements of *in situ* crack stress using X-ray topography coupled with electroluminescence and current-voltage measurements on encapsulated cells (Arizona State University). Crack geometries detected by electroluminescence are summarized and associated with electrical properties via variational autoencoder, which represents these features and quantities as a one-dimensional vector. Measured cracks will be replicated in finite element models to (a) determine the relationship between stress and crack electrical behavior, and (b) extend cell-level effects to full-size modules.



Variational autoencoder structure and results for representing crack geometries as one-dimensional vectors for parameterization and generation of new crack structures. This framework will also accept stress maps and electrical characteristics of the cell to learn the relationships between these variables and the crack geometry.



Finite element simulations of full-size modules and encapsulated cells to estimate the mechanical stress transferred to the cell and correlate it with X-ray topography measurements of cell deflection and crack movement. Full-size module simulations show that the geometry of stress to cells is similar to four-point bending of mini-modules.

LEARN MORE

We gave a poster at the 2023 PV Reliability Workshop and an oral presentation at the 2023 DuraMAT Fall Workshop.

We are also in the process of releasing a public repository for our variational autoencoder for crack parameterization, generation, and prediction.

Disruptive Acceleration Science

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

Conduct data-driven accelerated testing of PV material, component, module, and system specimens to enable development of degradation rate models and screening of design or material weaknesses with no *a priori* knowledge of failure modes.

Key Results:

- Demonstration of an accelerated testing method capable of identifying material damages and design field failures that are not captured by existing standardized steady-state or sequential tests.
  - The application-based, nonsubjective (e.g., derived from the diurnal cycle) combined-accelerated stress testing (C-AST) method was demonstrated to identify failure modes observed in PV installations, including backsheet cracking, interlayer delamination, interconnect corrosion, light- and elevated-temperature-induced degradation (LETID), light-induced degradation (LID), ultraviolet-induced degradation (UV-ID) of PV cells, and thermal runaway of balance of system components (connectors and fuses).
- Current study of contemporary cell interconnects (multiple busbars, low-temperature solder—including both conventional ribbon and copper wire—and electrically conductive tape), including accelerated stress tests, C-AST, outdoor aging (Mesa, Arizona, and Fairbanks, Alaska), and finite element analysis.
- Examination of the order in sequence (UV weathering, hot-humid, hot-dry) and stressor levels (irradiance, temperature, and humidity) for accelerated aging at packaging interfaces (e.g., encapsulant to cell). Additional material specimens and experiments will be used to develop a reaction rate kinetics model that may be applied to optimize the test protocol.
- Quantifying UV effects on the performance and degradation of (ethylene vinyl acetate [EVA], polyolefin elastomer [POE], EVA-POE-EVA [EPE]) and state-of-the-art cells (heterojunction, passivated emitter and rear contact [PERC], tunnel oxide passivated contact [TOPCon]).

Disruptive Acceleration Science

Core Objective

KEY RESULT

Why Bother With Solder When You Can Tape Cells Together To Interconnect Them Reliably?

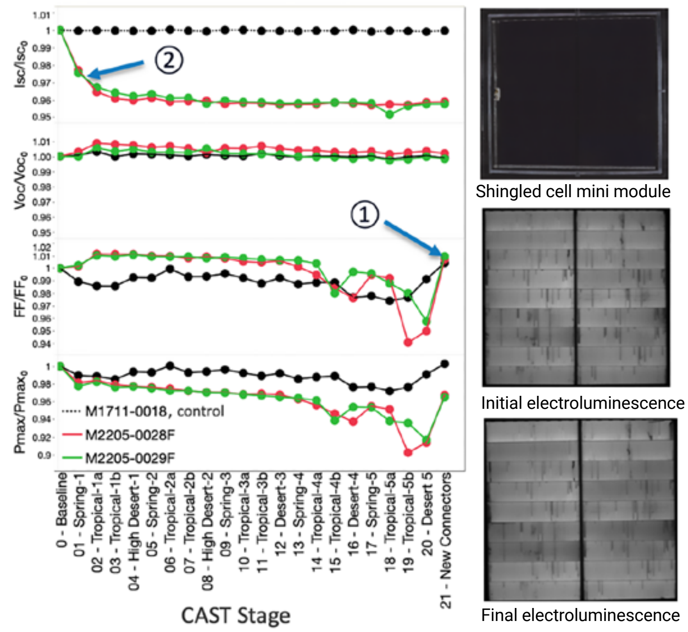
Combined-accelerated stress testing (C-AST) can enable rapid reliability prediction of emerging module interconnect technologies. In particular, electrically conductive adhesive tape for cell interconnection was found to be durable through C-AST, as evidenced by the negligible loss in fill factor. In this first trial, the fill factor reduction associated with contact resistance was initially about 1% absolute, which may be improved with greater conductive particle loading.

PI: Peter Hacke (NREL)

Team Members: Nick Bosco, David Miller (NREL); James Hartley (Sandia)

Summary of Result: The PV industry desires cell interconnect technology with features such as tight cell packing, no lead, low-temperature processing, reduced silver usage, low interconnect shadowing losses, higher voltage, lower current, high reliability, good manufacturability, and low series resistance losses. We are evaluating various novel interconnect technologies, including nickel-based electrically conductive tape (ECT), silver-based electrically conductive adhesive, PbSn-soldered multiwire, PbSnBi low-temperature soldered multiwire, laser-bonded interconnects, and low-temperature narrow gauge wire interconnects with SnBi solder attached to a transparent polymer foil.

The first technology examined in this project, the nickel-conductor-based ECT used for interconnecting shingled silicon heterojunction cells in 34.3-centimeter x 37-centimeter mini-modules, meets almost all the aforementioned goals for interconnects. It showed negligeable loss in performance through the challenging stress protocol of five C-AST cycles, where each cycle consisted of four climate sequences representing winter, spring, tropical, and high desert (see figure). Because C-AST is designed to evaluate all possible degradation modes, we concluded that there was (1) degradation in the module cable connectors, where power was restored when they were replaced; and (2) transmittance loss from solarization, verified with glass transmittance measurements performed after C-AST. Potential next steps for the ECT-based interconnection may include contact resistance reduction and testing in large module formats.



Degradation in fill factor that is restored after changing the connectors (1) and degradation of short-circuit current due to solarization of glass (2) in a mini-module with electrically conductive adhesive tape, showing high durability in the five cycles of C-AST. The results are confirmed by electroluminescence.

LEARN MORE

Hacke, P., D. Miller, D. Pierpont, and T. Wu. 2023. “Performance and Durability of Electrically Conductive Tape for Shingled Si Heterojunction Technology Cells.” *Prog Photovolt Res Appl.*: 1–11. *https://doi.org/10.1002/pip.3749*.

Hartman, K., P. Hacke, M. Owen-Bellini, et al. 2019. “Validation of Advanced Photovoltaic Module Materials and Processes by Combined-Accelerated Stress Testing (C-AST).” 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC), Chicago, IL. 2243–2248. *https://doi.org/10.1109/PVSC40753.2019.8980545*.

Spataru, S., P. Hacke, M. Owen-Bellini. 2018. “Combined-Accelerated Stress Testing System for Photovoltaic Modules.” 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC), Waikoloa, HI. 3943–3948. *https://doi.org/10.1109/PVSC.2018.8547335*.

KEY RESULT

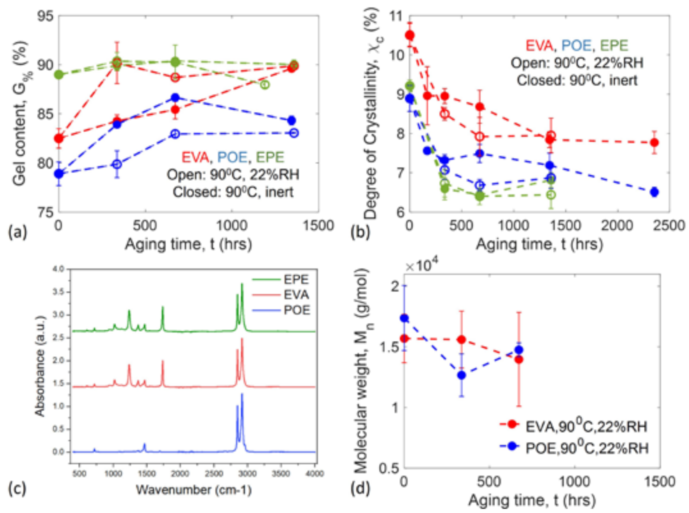
Hot Dry Aging at 90°C Reveals Thermal-Induced Crosslinking and a Decrease in Crystallinity in Polymeric Photovoltaic Encapsulants

Encapsulant delamination can be predicted with degradation modeling and accelerated testing. We observed an increase in the cross-linked gel content and a decrease in the percent crystallinity of ethylene vinyl acetate (EVA), polyolefin elastomer (POE), and EVA-POE-EVA (EPE) encapsulants from thermal aging, even in the absence of UV exposure and previously used peroxide initiators. We also developed a multi-scale fracture mechanics model that predicts changes in adhesion (G_c) of encapsulants and their interfaces under the most relevant accelerated aging conditions.

PI: Reinhold Dauskardt (Stanford University)

Team Members: Alan Liu (Stanford University); David Miller, Nick Bosco (NREL)

Summary of Result: Degradation of module encapsulant mechanical characteristics that lead to embrittlement and delamination remains a leading cause of failure in solar modules. Extending module lifetimes beyond 30 years requires advanced predictive modeling that includes the fundamental materials degradation pathways and their dependence on operating temperature, UV, and moisture. We develop a time-dependent multi-scale mechanics model based on detailed molecular degradation reaction kinetics that connects the encapsulant mechanical properties, including elastic modulus, yield strength, and adhesion energy, to the degrading molecular structure and interfacial bond density with adjacent solar cell and glass substrates. We are validating the model with experimental characterization of the encapsulants' molecular structure and mechanical properties with accelerated aging using differential scanning calorimetry (DSC), Fourier transform infrared spectroscopy (FTIR), Soxhlet extraction (gel content), gel permeation chromatography (GPC), nanoindentation, and adhesion characterizations (see figure). Interestingly, we observe an increase in gel content (cross-linking) and a decrease in crystallinity of EVA, POE, and EPE encapsulants under hot-dry aging conditions (90°C, little moisture) both in an open-air environment and a sealed inert environment, even in the absence of UV and cross-linking initiating agents (see figure). The current model predicts that moisture and UV are significant factors causing adhesion loss, and that high temperatures by themselves do not significantly impact G_c.

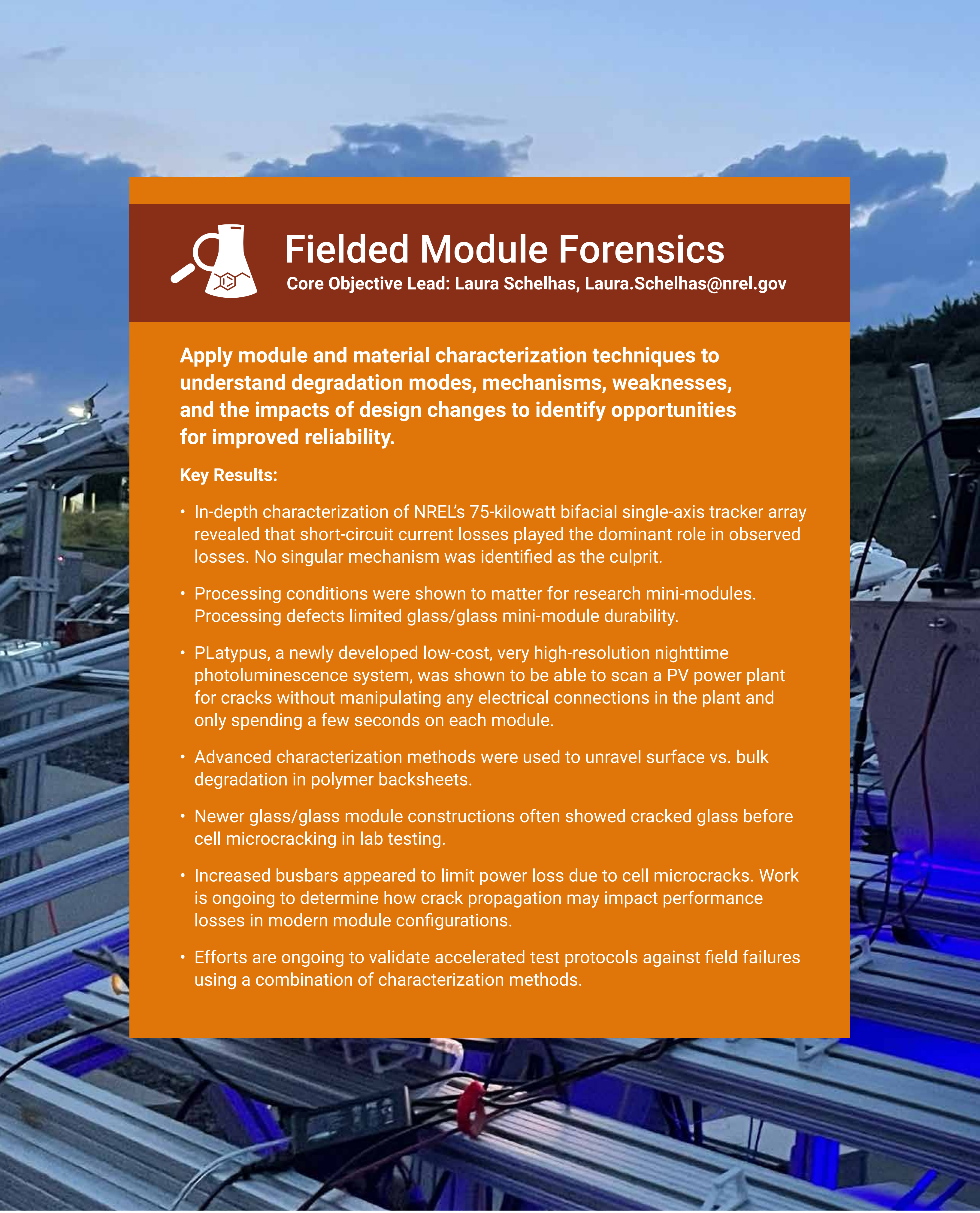


Model verification by analyzing encapsulants with: (a) Soxhlet extraction for the cross-linked gel content, (b) DSC for the degree of crystallinity, (c) FTIR for the polymer chemical structure, and (d) GPC for the number averaged molecular weight.

LEARN MORE

Liu, A., P. Thornton, D.R. D'hooge, R.H. Dauskardt. "Predicting Encapsulation Delamination in Photovoltaic Modules Using Photochemical Reaction Kinetics and Fracture Mechanics." *Progress in Photovoltaics*. In press.

Liu, A. and R.H. Dauskardt. 2023. "Predictive Fracture Mechanics and Photochemical Reaction Kinetics Modeling of PV Module Reliability." Materials Research Society Spring 2023 Meeting. *https://www.mrs.org/meetings-events/presentation/2023_mrs_spring_meeting/2023_mrs_spring_meeting-3817919*.



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 impacts of design changes to identify opportunities for improved reliability.

Key Results:

- In-depth characterization of NREL's 75-kilowatt bifacial single-axis tracker array revealed that short-circuit current losses played the dominant role in observed losses. No singular mechanism was identified as the culprit.
- Processing conditions were shown to matter for research mini-modules. Processing defects limited glass/glass mini-module durability.
- PLatypus, a newly developed low-cost, very high-resolution nighttime photoluminescence system, was shown to be able to scan a PV power plant for cracks without manipulating any electrical connections in the plant and only spending a few seconds on each module.
- Advanced characterization methods were used to unravel surface vs. bulk degradation in polymer backsheets.
- Newer glass/glass module constructions often showed cracked glass before cell microcracking in lab testing.
- Increased busbars appeared to limit power loss due to cell microcracks. Work is ongoing to determine how crack propagation may impact performance losses in modern module configurations.
- Efforts are ongoing to validate accelerated test protocols against field failures using a combination of characterization methods.

Fielded Module Forensics

Core Objective

KEY RESULT

Sequential Stress Testing Identifies Processing Defects in Bifacial PV Module Packaging That Limit Durability

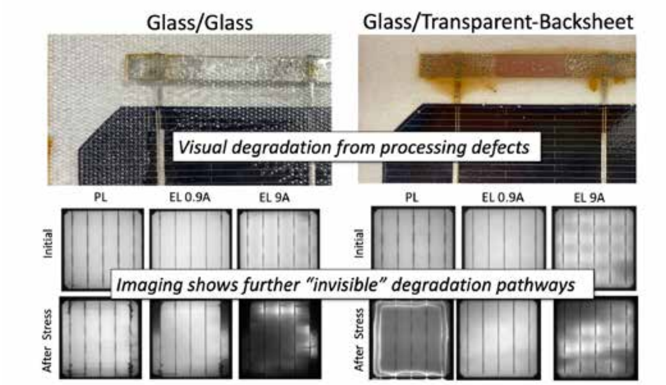
Here, we study degradation in glass/glass (G/G) bifacial PV with emerging encapsulants and half-cut cells. We validate a sequential stress testing procedure against outdoor exposure. We find that defects such as edge pinch and delamination may limit durability in non-optimized glass/glass modules, and that modules with particular transparent backsheets may fail severely with rear-side light exposure.

PI: Dana Kern (NREL)

Team Members: Steve Johnston, Paul Ndione, Dennice Roberts, Michael Owen-Bellini, Laura Schelhas, Soňa Uličná, John Mangum, Kent Terwilliger (NREL)

Summary of Result: Sequential stress testing can identify durability concerns for bifacial crystalline silicon PV modules beyond the design flaws screened via qualification testing. We find that lamination defects limit durability when processing is not optimal in bifacial structures. For example, edge pinch and delamination limit durability in non-optimized G/G modules, despite the promise of robust materials. Such defects in G/G modules may arise when lamination procedures created for glass/(transparent) backsheet (G/TB) packaging are implemented in G/G modules without appropriate further optimization. Indeed, modified lamination procedures that decrease edge pinch in G/G modules enhance G/G durability.

We also observe a possibility of catastrophic degradation in G/TB modules that surpasses loss in edge-pinch G/G modules when TBs are directly exposed to light. We test bifacial modules under a modified International Electrotechnical Commission 63209-2 sequential stress procedure, consisting of multiple iterations of damp heat (DH200), full-spectrum light exposure (A3-1000/2000), thermal cycling (TC50), and humidity/freeze (HF10). We validate degradation by comparison with outdoor exposure, which shows similar relative trends after 1.5 years outdoors compared to our first stress cycle. Subsequent stress cycles impart more severe damage than this short outdoor exposure. Our results highlight the utility of sequential stress to uncover PV degradation, and the importance of avoiding lamination defects for bifacial module durability.



Examples of degradation in G/G and G/TB mini-modules stemming from processing defects, including both visual photos and electro-optical imaging.

LEARN MORE

Uličná, Soňa. 2023. "Material Selection and Processing Defects in Bifacial Photovoltaic Module Packaging That Limit Durability." DuraMAT webinar, November 13, 2023. *https://www.duramat.org/news-and-events/webinars*.

Sinha, Archana, Dana Sulas-Kern, Michael Owen-Bellini, Laura Spinella, Soňa Uličná, Silvana Ayala Pelaez, Steve Johnston, and Laura Schelhas. 2021. "Glass/Glass Photovoltaic Module Reliability and Degradation: A Review." *Journal of Physics D*. *https://doi.org/10.1088/1361-6463/ac1462*.

Sulas-Kern, Dana, Michael Owen-Bellini, Paul Ndione, Laura Spinella, Archana Sinha, Soňa Uličná, Steve Johnston, Laura Schelhas. 2022. "Electrochemical Degradation Modes in Bifacial Silicon Photovoltaic Modules." *Progress in Photovoltaics: Research and Applications. https://doi.org/10.1002/pip.3530*.

Fielded Module Forensics

Core Objective

KEY RESULT

PLatypus Detects Cracked Cells in Seconds Without an Electrical Connection

PLatypus uses simple field photoluminescence with low cost and very high resolution to detect cracked cells in seconds.

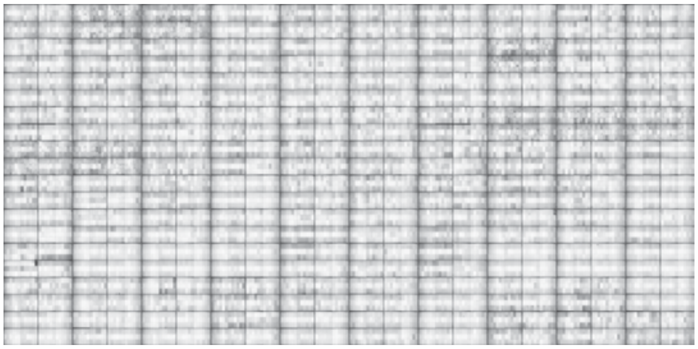
PI: Tim Silverman (NREL)

Team Members: Nicole Luna (NREL), Will Hobbs (Southern Company), Kelsey Horowitz (AES)

Summary of Result: PV system owners are concerned about cracked cells, which are invisible. Cracks can start out benign and later lead to power loss or safety failures. Early detection would help owners prepare for these changes. Detecting cracks usually requires cumbersome, expensive, or low-resolution electroluminescence technology. Electroluminescence either requires a power supply that produces a hazardous voltage to bias multiple modules at a time, or it requires operation of individual modules' connectors.

We built a low-cost, very high-resolution nighttime photoluminescence system. It can detect cracked cells in a module without making any electrical connection to it. The key is that it uses multiple cameras to piece together an image of the entire module. The array of cameras is mounted closer to the module than would be possible with a single camera. This allows high-power light-emitting diodes to be mounted between cameras, exciting photoluminescence in the module without making any electrical connection to it.

PLatypus can scan a PV power plant for cracks without manipulating any electrical connections in the plant and only spending a few seconds on each module. In a field trial using the first prototype, we collected photoluminescence images on 100 modules. By the end of the trial, we spent less than 30 seconds on each module and identified ways for future prototypes to move even faster.



A montage of photoluminescence images from a field trial shows the condition of 100 modules. The montage contains 800 photoluminescence images from PLatypus' multi-camera system.

PLatypus is a multi-camera photoluminescence imager with no electrical connections to the PV module. A half-size prototype is shown collecting a photoluminescence image on a fielded PV module.

LEARN MORE

Results from demonstrations and computer-aided design models are available on the DuraMAT Data Hub at *https://datahub.duramat.org/project/platypus*.

A YouTube video about this project is coming soon.

Fielded Module Forensics

Core Objective

KEY RESULT

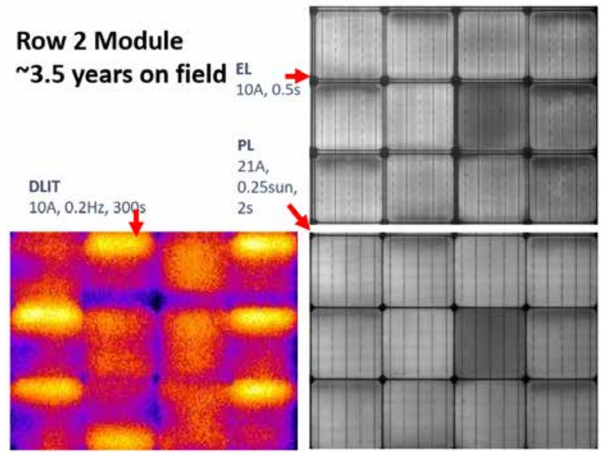
Investigating Degradation of Bifacial Technologies in the Field

Short-circuit current dominates bifacial degradation in various pre-2020 modules, but no single underlying cause has been identified.

PI: Silvana Ovaitt (NREL)

Team Members: Dirk Jordan, Dana Kern, Steve Johnston, Elizabeth Palmiotti, Peter Hacke, Chris Deline (NREL)

Summary of Result: In a comprehensive study conducted at NREL's 75-kilowatt bifacial single-axis tracked field, accelerated degradation was observed in four out of five bifacial technologies when compared to their monofacial counterparts. The investigation into the root causes of this accelerated bifacial degradation used various analytical tools and techniques. This included using RdTools™ to identify degradation rates, conducting measurements on fielded and control modules using infrared imaging, employing electroluminescence and photoluminescence techniques, conducting quantum efficiency analysis, assessing current-voltage curves, and utilizing handheld Raman and antireflective coat measurement instruments. The analysis revealed that changes in short-circuit current played a dominant role in the observed losses. Interestingly, the diverse methodologies identified distinct loss mechanisms across the different bifacial technologies, pointing to a lack of a singular culprit responsible for the accelerated degradation. The outcomes and methodologies employed in this investigation are being documented for publication in a journal paper. This study's significance is further emphasized by placing the findings within the broader context of the performance and degradation of various bifacial systems, as identified in the PV Fleets data.



For a weathered module compared to a control, overall luminescence intensity is down to about 55% of the control, suggesting a loss in voltage. There are dark edge patterns (top or bottom of cells) in high-current electroluminescence and photoluminescence and hotter dark lock-in thermography, suggesting that these areas have increased carrier recombination and perhaps a loss of passivation.

A novel handheld Raman instrument was used on NREL's 75-kilowatt bifacial field modules to measure front and rear encapsulant changes, among other techniques to pinpoint sources of degradation.

LEARN MORE

Ovaitt, S., D. Jordan, C. Deline, D. Kern, S. Johnston, E. Palmiotti. "Insights Into Bifacial Photovoltaic Module Degradation Dynamics." In preparation.

Bifacial field data and measurements are available at: *https://datahub.duramat.org/dataset/best-field-data*.

Fielded Module Forensics

Core Objective

KEY RESULT

Cross-Sectional Characterization of Aged Polyethylene Terephthalate (PET)- and Polyolefin (PO)-Based Backsheets

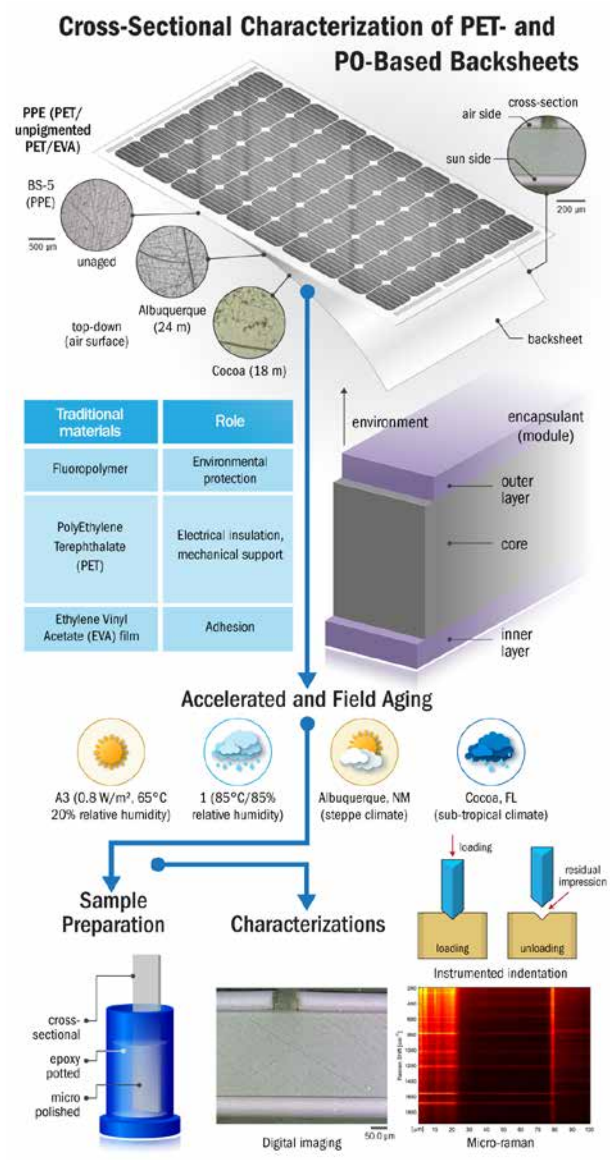
We conducted cross-sectional characterization of PPE and PO backsheets from accelerated and field aging. PPE surface degradation precedes through-thickness cracking under A3 UV weathering and field aging.

PI: Elizabeth Palmiotti (NREL), Jennifer Braid (Sandia)

Team Members: David Miller (NREL); Jessica Kopatz, Christine Roberts, Bruce King (Sandia); Peter Pasmans, Chris Thellen (Endurans/Worthen)

Summary of Result: PV backsheets are the traditional rear surface material in a PV module. Backsheets are typically multi-layer composites of different polymer materials that each address purposes such as electrical insulation or environmental durability. Each layer is further complicated by manufacturer-specific pigments, additives, and processing steps, as well as separate degradation mechanisms. Backsheets are typically characterized by bulk or surface techniques, which may miss defects in interior layers or interfaces between layers.

In this work, we investigated cross sections of a PPE backsheet (polyethylene terephthalate [PET]/unpigmented PET/ethylene vinyl acetate [EVA]) and a polyolefin (PO) backsheet subjected to accelerated aging (85°C/85% relative humidity and A3) and field aging (24 months in Albuquerque, New Mexico and Cocoa, Florida) from the previous DuraMAT BACKFLIP (Comparison of Market-Benchmark Backsheet Technologies to Novel Non-Fluoro-Based Co-Extruded Materials and Their Correlation and Impact on PV Module Degradation Rates) project. Samples were cross-sectioned then imaged by digital microscopy to characterize individual layer thicknesses and physical degradation. Micro-Raman spectroscopy was conducted along each cross section in 1-micrometer steps to study chemical and phase changes. Nano-indentation was used to verify the mechanical integrity of each layer.



Cross-sectional characterization of PET- and PO-based backsheets.

LEARN MORE

Information on the original backsheets may be found in previous publications from BACKFLIP. This work was presented at the DuraMAT Fall Workshop and was submitted to the PV Reliability Workshop for presentation, and a journal article is actively being written.

Fielded Module Forensics

Core Objective

KEY RESULT

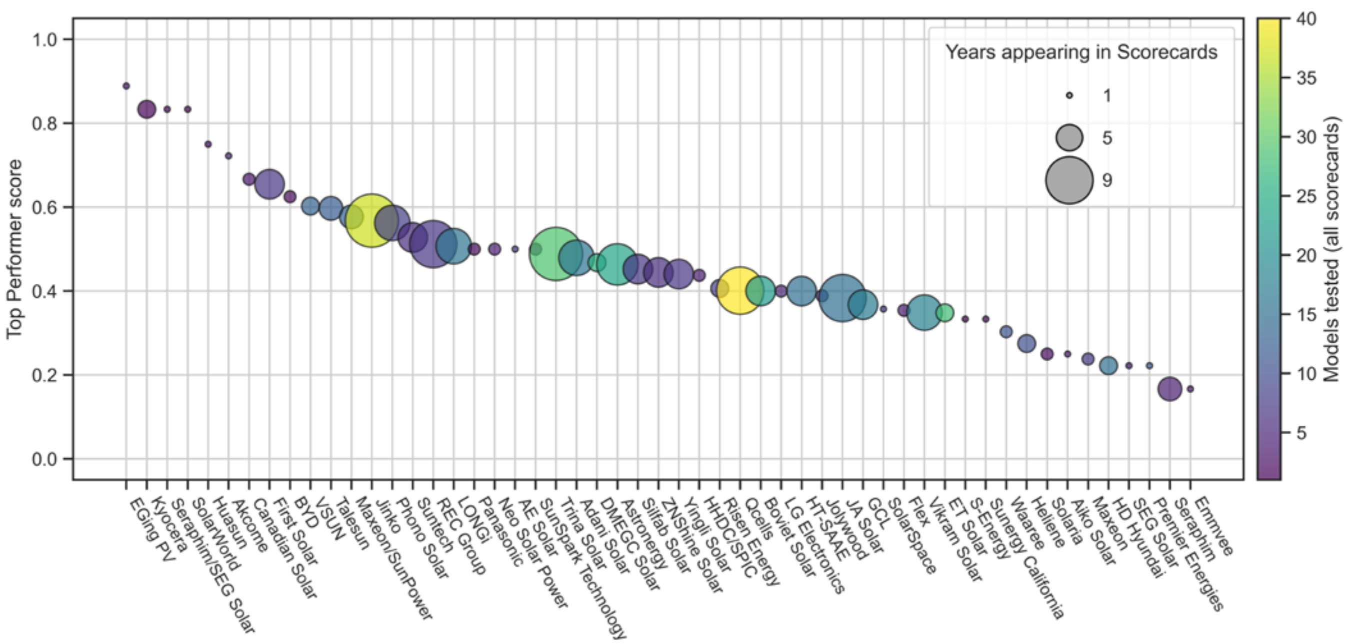
Historical PV Module Test Data: Now Available for You to Use!

A user's guide to historical PV module testing data is now available, complete with a database of more than 500 model names, test results, and bill-of-materials (BOM) information. We benchmarked BOMs of recently deployed PV modules to associate specific BOMs with field performance trends.

PI: Joe Karas (NREL)

Summary of Result: In this project, we built upon previous work that has identified bill-of-materials (BOM) variation as a key driver of degradation in historical PV modules. However, in this work, we aimed to proactively identify systems that exemplify recent and forthcoming technological trends and BOM changes in PV modules, laying the groundwork for monitoring triggers and mechanisms of degradation. Prior work has found that BOM lists often evolve, and may include several different options and evolutions for each element of a PV module (e.g., glass, encapsulant, cells, perhaps leading to hundreds of variations that can behave differently in the field. Rigorous third-party testing and verification of specific BOMs is necessary to mitigate this risk.

PV Evolution Labs (PVEL) is an independent PV module testing lab that publishes an annual PV Module Reliability Scorecard. The scorecard designates "Top Performers" in a number of test categories. PVEL also performs BOM verification, which makes the scorecards valuable tools for associating field performance with test data on specific BOMs. This DuraMAT project began with an effort to comb historical scorecards and create a publicly available database of PVEL-tested PV modules, with notes on features and recent technological changes. This database is available on the DuraMAT Data Hub.



Top Performer score, the fraction of PVEL "Top Performer" designations achieved by a PV module manufacturer out of the total tests performed on its modules. Most manufacturers' modules achieve "Top Performer" status in ~40%–60% of total tests.

LEARN MORE

See the DuraMAT Data Hub to access the PV module scorecard database as well as a user's guide with supporting information: *https://datahub.duramat.org/dataset/pvel-module-reliability-scorecard-data*.

The main results from this work were presented at the 2023 DuraMAT Fall Workshop in Albuquerque, New Mexico. The presentation slides can be found on the DuraMAT Data Hub.

Fielded Module Forensics

Core Objective

KEY RESULT

Linkage Between Cell Cracks, Stress Testing, and Real-World Module Performance

Linking lab-based accelerated stress testing for cell cracks to field performance will have a high impact across the industry and provides a method to understand the effect of cell cracks on module power loss and degradation in modern modules.

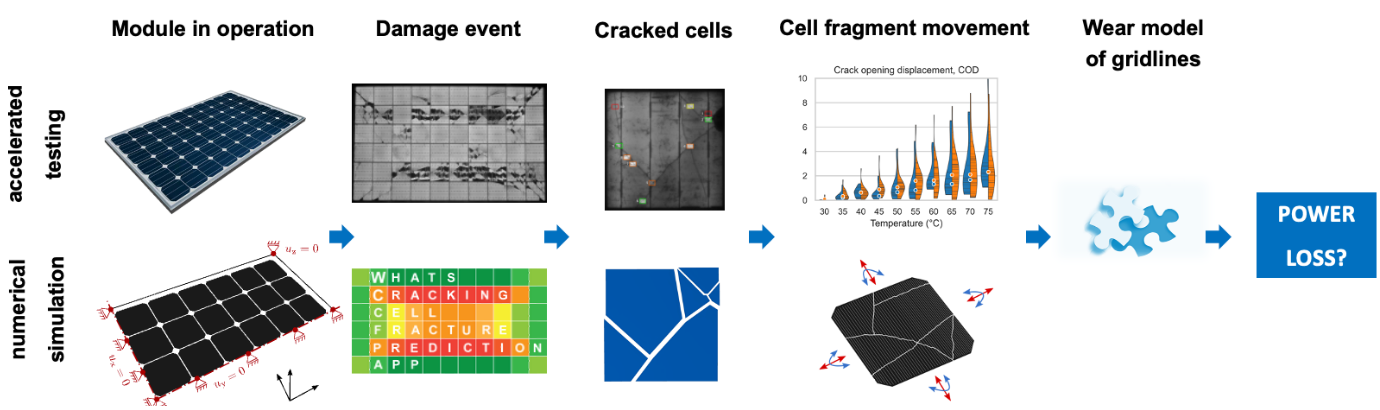
PI: Viral Parikh (Electric Power Research Institute [EPRI])

Team Members: Martin Springer, Tim Silverman, Mike Deceglie (NREL); Michael Gostein, (Atonometrics); Will Hobbs (Southern Company); Jim Rand (Core Energy Works); Srikar Vavilala, Thiago Seuaciuc-Osorio, Wayne Li, Robert Flottemesch (EPRI)

Summary of Result: Environmental stressors, such as wind loading, thermal cycling, and exposure to colder temperatures, can make benign PV cell cracks turn into harmful cracks that can be linked to substantial power loss and safety issues.

EPRI, in partnership with NREL, is seeking to understand the direct correlation between lab-based accelerated stress testing of cell cracks using NREL's state-of-the-art dynamic mechanical accelerated testing (DMX) device and real-world aging of cell cracks/modules deployed at EPRI's outdoor test facility in Colorado. Four sets of modules, two with a glass/glass (G/G) configuration and two with a glass/backsheet configuration, will be used for this study. Inducing cell cracks in G/G modules without glass breakage is difficult. However, the University of Central Florida has shown that a brief exposure to very low temperatures can increase the fracture probability of silicon solar cells. We plan to use this technique for inducing cell cracks in G/G modules. Further physics-based modeling will be used to correlate cell crack features to module power loss. For detailed analysis, tracking angle, *in situ* current-voltage, electroluminescence, module temperature, and plane of array irradiance data will be collected.

EPRI's outdoor test facility near Denver, Colorado, showing dedicated tracker rows to be used for field studies.



Physics-based modeling to correlate cell crack features and operating conditions to module power loss.

LEARN MORE

2023. "Effect of Cell Cracks on Module Power Loss and Degradation: Modern Module Architectures." Presented at the DuraMAT Fall Workshop, Sep. 26–27, 2023.

Project webpage: *https://www.duramat.org/projects/modern-pv-module-architectures*.

"NREL Breaks Solar Panels" video: *https://www.youtube.com/watch?v=aK8Sw8iMGMI*.

Fielded Module Forensics

Core Objective

KEY RESULT

Microcracks No Longer a Problem on Glass/Glass Modules

Prior generations of glass/backsheet modules were very susceptible to cell microcracks that affect power generation. For new modules with glass/glass modules and/or high numbers of busbars, microcracks aren't a big concern, according to a multi-year study of crack-induced degradation in fielded PV modules.

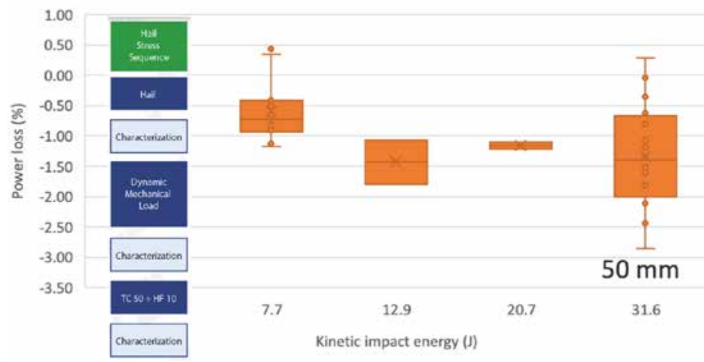
PI: Todd Karin (PV Evolution Labs [PVEL], Member of Kiwa Group)

Team Members: Anubhav Jain, Baojie Lie (LBNL); Tristan Erion-Lorico, Fabrizio Farina, David DeLong (PVEL)

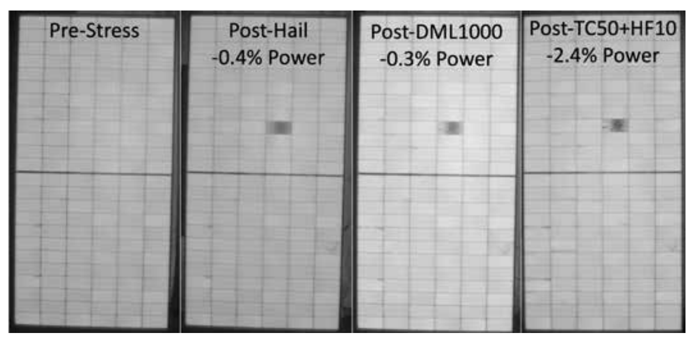
Summary of Result: The PV industry, including manufacturers, project owners, and insurance providers, is operating on an outdated understanding of the effect of cell microcracks on PV system production. In older modules with thicker cells, glass/backsheet construction, and 3–5 busbars, cell microcracks were easy to create and had real effects on power production.

We are studying the effects of cell cracks on power production in modern modules with thinner cells, new solder processes, glass/glass construction, and 12–20 busbars. We are damaging modules and measuring the outcome on power production and fire risk. In attempting many creative ways to damage glass/glass modules, we have found that it is exceedingly difficult to create cell microcracks in glass/glass modules; typically, the glass breaks before the cells do. We have also found that when modules receive 11 shots of 50-millimeter hail, power loss is typically surprisingly small: on the order of 0.5%–3.0%.

These findings will recalibrate the PV industry's understanding of how microcracks affect performance, leading to lower insurance costs.



Summary of power loss in PVEL's hail stress sequence. After being subjected to 50-millimeter hail and subsequent cycling to propagate cracks, modules typically only lost −0.6%–2.0% power.



Electroluminescence of a module through the PVEL hail stress sequence. It takes time (and thermal or mechanical cycling) for the power loss due to a cell crack to become fully realized.

LEARN MORE

What happens when installers walk on PV modules? See: *https://www.youtube.com/watch?v=Zti4gLvlxXM*.

2023. "Performance Impacts of Cell Cracks on Modern High-Busbar Count PV Modules." DuraMAT Fall Workshop. September 26, 2023.

Module Material Solutions

Core Objective Lead: Bruce King, bhking@sandia.gov

Design, develop, and de-risk innovative materials, module architectures, and processing methods to address PV reliability.

Key Results:

- Novel use of laser processing was implemented throughout the PV module life cycle.
  - Femtosecond laser processing was used to demonstrate hermetic sealing of glass/glass modules. Modules are polymer-free and easily recyclable.
  - Surface patterning with a femtosecond laser was used to produce multifunctional surfaces with both antireflective and antisoiling properties. High-throughput processing was used for rapid screening of 10,000 different combinations to discover optimal morphologies.
  - Laser processing was used to demonstrate separation and recovery of intact PV module front glass for reuse or recycling.
- Copper screen printing pastes—an abundant and low-cost alternative to silver—were demonstrated on encapsulated PERC cells. The cells, produced using traditional screen printing and high-fire processing in air, demonstrated stability in damp heat tests.

KEY RESULT

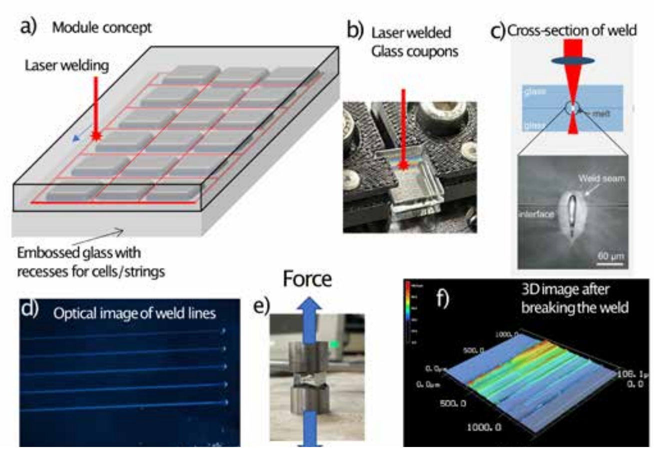
Glass/Glass Laser Welding Enables Polymer-Free, Hermitically Sealed Modules

Tests and simulations predict that polymer-free, femtosecond-laser-welded glass/glass modules will pass static load tests, enabling hermitically sealed and easily recycled modules.

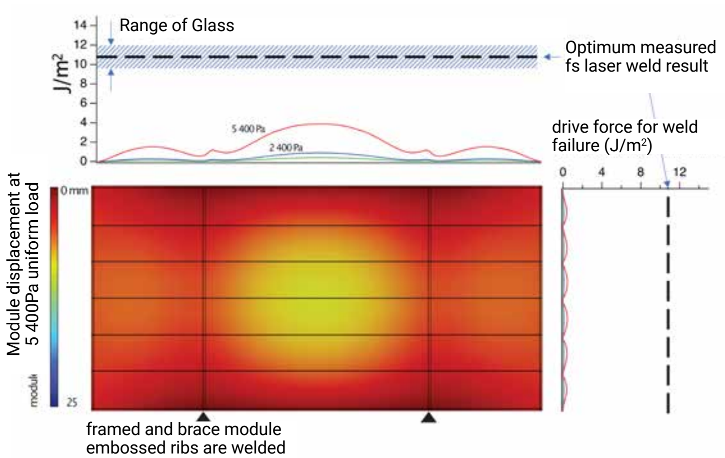
PI: David Young (NREL)

Team Members: Nick Bosco, Tim Silverman (NREL)

Summary of Result: The goal of this project is to explore the use of industrial femtosecond lasers to weld glass/glass modules together to form a strong, hermitic seal and to enable polymer-free, 50-year module designs that are easily recycled. Our industrial laser partners welded module glass coupons using a variety of laser conditions. The weld strength was measured using the double edge notch test to calculate the intrinsic stress-intensity factor (KI) and the energy per unit fracture surface area (J-integral). These values were inputs to a COMSOL finite element model, which allowed a full-area module (1 meter x 2 meters) simulation under static load (5,400 pascals). The tests showed that under optimum conditions, the laser welds were nearly as strong at the surrounding glass. The simulations showed that a femtosecond-laser-welded glass/glass module with embossed ribs will pass the static load test with a safety factor of over two.



Concept schematic of laser-welded module with embossed glass recesses for cell and strings. (b) Laser welding fixture. (c) Cross-sectional image of typical femtosecond laser weld between glass pieces. (d) Optical image of weld lines. (e) Stress intensity factor measurement jig. (f) 3D optical image of glass surface after weld failure with jig in (e).



Top and side graphs show J-integral for bulk glass and optimum measured value of laser weld in this project. The bottom left shows a simulated displacement heat map of full-area glass/glass module laser welded along thin black lines under a uniform static load test of 5,400 pascals. The COMSOL model predicts that the module passes the International Electrotechnical Commission static load test.

LEARN MORE

Initial results were presented at the 2022 DuraMAT Workshop. Final results were presented at the 2023 Photovoltaic Reliability Workshop and will be presented in a journal publication (TBD). Contact *David.young@nrel.gov* for more information.

Module Materials Solutions

Core Objective

KEY RESULT

Accelerating Discovery of Self-Cleaning, Antireflective Glass Topologies Using High-Throughput Laser Processing

We developed a new high-throughput laser fabrication and rapid screening method for discovery of multifunctional engineered self-cleaning and antireflective glass surfaces for PV applications. This research identified multiple unique surface topologies that yield self-cleaning and transparent morphologies applicable to glass top sheets, which are currently under further testing for durability.

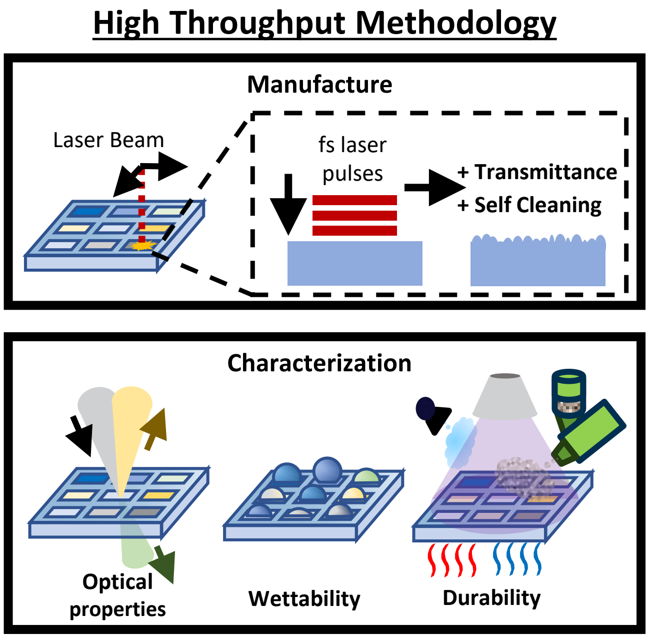
PI: Vassilia Zorba (LBNL)

Team Members: Jake Carter, Minok Park (LBNL)

Summary of Result: Multifunctional antireflective coatings provide improved light transmission through reflection reduction when compared to bare glass, and through elimination of soiling particles that block incident sunlight. State-of-the-art coatings only last between 1 and 15 years, and their benefits subside after a small fraction of the solar module's overall lifespan.

This project used high-throughput laser processing to screen 10,000 morphologies on glass and identify surfaces that provide transparency and the potential for self-cleaning. One of the advantages of this approach is that these structures are directly manufactured into the glass and not chemically bonded to the glass substrate. We developed custom tools to manufacture and characterize the wetting and optical performance of hundreds of unique textures per hour. Long-term durability was measured as an effect of brush abrasion, and an accelerated aging chamber is in development that will simulate many aspects of environmental stress following the combined-accelerated stress testing protocol.

This work has discovered multiple surface topologies that retain a high degree of transparency while inducing superhydrophilicity. Further exploration of the parameter space and screening of aged samples should identify optimal structures to maximize light capture over the lifespan of a PV module.



High-throughput screening methodology: Custom tools allow for the production and screening of ~300 samples per hour for wettability and optical properties. Accelerated aging protocols are in development for additional screening of high-performance samples.

(a) Highly transparent 10 x 10 grid of textured glass containing a superhydrophilic pattern (boxed). (b) Morphology of highlighted area. (c) Identical droplets placed on the highlighted area and the adjacent bare-glass surface.

LEARN MORE

See LBNL's Laser Technologies Group webpage: *https://laser-research.lbl.gov,* or *email vzorba@lbl.gov*.

Module Materials Solutions

Core Objective

KEY RESULT

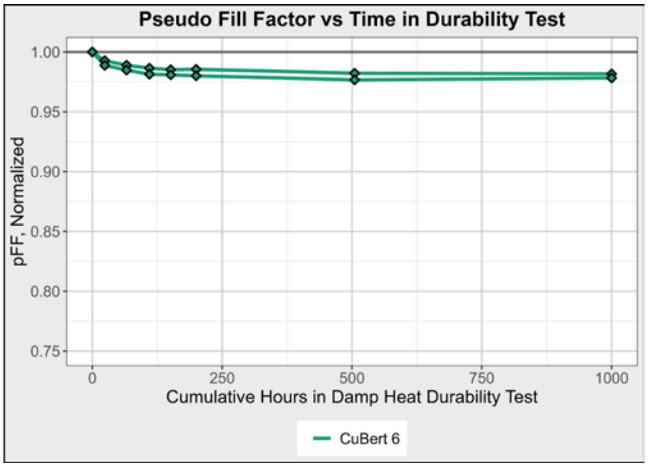
Stable Copper-Fired Pastes in Damp Heat: Durability of Modules Utilizing Screen Printed Copper Contacts

Encapsulated passivated emitter and rear contact (PERC) cells that were screen printed with a copper paste and fired in air maintained a stable pseudo fill factor and open-circuit voltage through a 1,000-hour damp heat test.

PI: Thad Druffel (Bert Thin Films LLC)

Team Members: Ajeet Rohatgi (Georgia Institute of Technology), Paul Stradins (NREL)

Summary of Result: The solar industry currently consumes over 10% of the global supply of silver. As the market continues to grow, silver metallization will become increasingly expensive and potentially unsustainable. However, the current metallization method of screen printing and firing is preferred for its simplicity. Potential replacements for silver with alternative metals like copper must follow the industry's preferred process. However, because copper both oxidizes and diffuses into silicon at high temperatures, any solution must address these two issues. To demonstrate to the industry that copper pastes can replace silver, we must show that the pastes can be fired in air at high temperatures and that they can survive industry-standard stability tests, namely the damp heat test. The team is preparing pastes designed with variable etching rates, which are then fired in air at different temperatures. Some of these cells are then encapsulated and placed into damp heat testing. Understanding the impact of etching rate during the damp heat test will assist with paste optimization for durable products. Demonstrating durability will de-risk this technology for the industry, potentially saving about $10 million per gigawatt of production and making the metallization process sustainable.



Demonstration of the stable pseudo fill factor (pFF) of encapsulated devices in a 1,000-hour damp heat test.

LEARN MORE

More information about the pastes can be found at *www.bertthinfilms.com*. The work has also been presented at the Metallization Workshop and the DuraMAT Workshop.

Module Materials Solutions

Core Objective

KEY RESULT

Silicon Module Recycling by High-Power Lasers

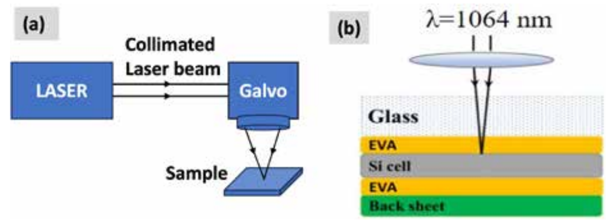
Successful glass recovery from end-of-life solar modules is demonstrated using high-power laser technology.

PI: Mool Gupta (University of Virginia)

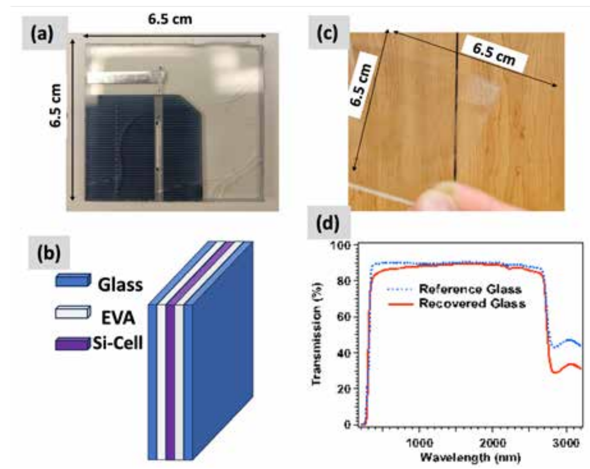
Team Members: Pawan Kanaujia (University of Virginia); David Young, Michael Owen-Bellini, Michael Woodhouse (NREL)

Summary of Result: Due to the rapid growth in solar power generation, an increasing amount of solar module waste is being generated. The waste must be handled in an environmentally friendly manner, and component recovery is required for recycling. However, the disposal of end-of-life PV modules presents substantial challenges. Conventional disposal methods involve either landfilling or crushing the modules for material recovery. Landfilling contributes to environmental degradation, whereas material recovery often involves economically inefficient and environmentally harmful processes. To address these challenges, we have demonstrated an innovative, nondestructive, and eco-friendly approach to material recovery using high-power lasers.

The laser approach is based on the breaking of chemical bonds or thermal melting/decomposition to recover glass without cracking. A significant advantage of this technique is its ability to recover flawless glass, free from defects and with optical transparency comparable to pristine glass. This high-quality recovered glass will have valuable applications, especially in the production of new solar modules, greenhouses, and other applications. This promotes sustainability within the solar energy industry. By addressing environmental concerns and making it cost-effective, the eco-friendly laser-based approach stands as a promising and socially responsible advancement for the rapidly growing solar energy sector.



Schematic of (a) experimental setup for laser debonding, and (b) laser focusing on various interfaces of a solar module.



(a) Image of a small-format solar module. (b) Schematic representation of a tested solar module. (c) Recovered glass from a solar module. (d) Optical transmission spectra of recovered glass compared with reference glass.

LEARN MORE

This work was presented at the 2023 DuraMAT Workshop in Albuquerque, New Mexico, and an abstract has been submitted to the 2024 SPIE Defense + Commercial Sensing Conference. Also see U.S. patent applications PCT/US2023/076447 and 63/538,209.

DuraMAT Early Career Scientists

The DuraMAT Early Career Scientists (DECS) program aims to connect early career scientists, foster collaboration across institutions, and enable professional development and networking opportunities. Additionally, a goal of DECS is to create community between postdocs, students, and interns at conferences and workshops. The DECS program is revitalizing this year after a brief hiatus. Meetings are held on the second Wednesday of each month with a range of proposed topics, including exploring different career paths embodied by DuraMAT (industry, academia, startups, and national labs); developing workshopping skills; and honing scientific communication skills. A major focus of the group is writing a DECS-led proposal for future lab calls and supporting other proposal development, as this is a means to hone science communication skills, network, and synthesize observations across current DuraMAT projects.

This September's DuraMAT workshop included a DECS-IAB session connecting industry members to students and providing insight into career development and issues important to industry. We hope to further spark this connection with a "DECS Day" ahead of PVRW, which will be specific to early career scientists and which we hope can become a semiannual connection point rotating between different DECS member institutions. This year, DECS participants continue to represent DuraMAT through research presentations at the European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), RE+, PVSC, PVRW, and more! Additional contributions include acting as session chairs and publishing papers.

DECS Leadership:

Elizabeth Palmiotti,
Elizabeth.Palmiotti@nrel.gov
Dennice Roberts,
Dennice.Roberts@nrel.gov

DuraMAT Workshop

The 2023 DuraMAT Fall Workshop took place September 26-27, 2023 in Albuquerque, New Mexico, Chaired by Cliff Hansen of Sandia. Sixty attendees, mostly in person and representing a broad spectrum of researchers and industry, engaged in energizing discussions about current work, unmet needs, and future challenges to engineering reliable PV modules.

Technical sessions addressed:

- Data, software, and analytic tools
- Use of accelerated aging to advance PV reliability
- Bill of materials impacts: trends, analytics, and forensic analysis
- Advancements in module materials and recycling
- Cracks: they're still not good; performance loss as damage evolves
- Modeling: mechanical loading and degradation tools.

In an invited plenary session, Jim Crimmins of CFV Labs explained how PV plant underperformance (the observed gap between modeled and actual performance) is "always and everywhere relative." Underperformance can result from component degradation, environmental effects such as soiling, hardware or system failures, optimistic or incomplete modeling, or combinations of all of these. Dylan Colvin of Florida State University outlined a strategy for comprehensive module characterization that envisions linking laboratory, field, and forensic techniques across levels of detail and sophistication to provide a holistic assessment of a module's potential lifecycle.

Technical highlights included:

- Anubhav Jain (LBNL) presented recommended practices for projects that produce open-source software.
- Todd Karin (PV Evolution Labs) surprised us with laboratory experiments showing that glass-glass modules (with 2.0-mm glass) are more likely to suffer glass fracture than cell cracking after hail-like impacts. It is difficult to damage the cells of these modules without breaking the module's glass.
- James Hartley (Sandia) described progress toward a model for probability of damage due to hail impacts.
- Elizabeth Palmiotti (NREL) described detailed characterization of accelerated and field-aged module backsheets.
- On behalf of Peter Hacke (NREL), James Hartley (Sandia) described how low-temperature solder wire interconnects (LTSWIs) are identified, through C-AST procedures and modeling, as a vulnerability in modules incorporating that manufacturing approach.

Publication and Research Output

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

JOURNAL ARTICLES

1. Palmiotti, Elizabeth C., Christine C. Roberts, and Bruce H. King. 2023. "Thermal Behaviors of Ethylene Vinyl Acetate Encapsulants in Fielded Silicon Photovoltaic Modules." Journal of Applied Polymer Science 140 (35). *10.1002/app.54337*.
2. Woodhouse, Michael. 2023. "Uncertainty in Degradation Affects Financial Modelling Results Differently for ITC and PTC." In ***Solar Risk Assessment Report***. Beaverton, OR: kWh Analytics. *https://www.kwhanalytics.com/solar-risk-assessment*.
3. Jordan, Dirk C., and Clifford Hansen. 2023. "Clear-Sky Detection for PV Degradation Analysis Using Multiple Regression." ***Renewable Energy*** 29: 393–400. *10.1016/j.renene.2023.04.035*.
4. Hacke, Peter, Michael Owen-Bellini, Michael D. Kempe, Dana B. Sulas-Kern, David C. Miller, Marko Jankovec, Stefan Mitterhofer, Marko Topič, Sergiu Spataru, William Gambogi, and Tadanori Tanahashi. 2023. "Acceleration Factors for Combined-Accelerated Stress Testing of Photovoltaic Modules." ***Solar RRL*** 7 (12). *10.1002/solr.202300068*.
5. Haegel, Nancy M., Pierre Verlinden, Marta Victoria, Pietro Altermatt, Harry Atwater, Teresa Barnes, Christian Breyer, Cjros Case, Stefaan De Wolf, and Chris Deline. 2023. "Photovoltaics at Multi-Terawatt Scale: Waiting is Not an Option." ***Science*** 380 (6640): 39–42. *10.1126/science.adf6957*.
6. Li, Baojie, Todd Karin, Bennet Meyers, Xin Chen, Dirk Jordan, Clifford Hansen, Bruce King, Michael Deceglie and Anubhav Jain. 2023 "Determining Circuit Model Parameters From Operation Data for PV System Degradation Analysis: PVPRO." ***Solar Energy*** 254: 168–81. *10.1016/j.solener.2023.03.011*.
7. Chen, Xin, Todd Karin, Cara Libby, Michael Deceglie, Peter Hacke, Timothy J. Silverman, and Anubhav Jain. 2023. "Automatic Crack Segmentation and Feature Extraction in Electroluminescence Images of Solar Modules." ***IEEE Journal of Photovoltaics*** 13 (3): 334–42. *10.1109/JPHOTOV.2023.3249970*.
8. Miller, David C., Katherine E. Hurst, Archana Sinha, Jiadong Qian, Stephanie L. Moffitt, Soňa Uličná, Laura T. Schelhas, and Peter Hacke. 2023. "Quantifying Optical Loss of High-Voltage Degradation Modes in Photovoltaic Modules Using Spectral Analysis." ***Progress in Photovoltaics*** 31 (8): 840–61. *10.1002/pip.3690*.
9. Libby, Cara, Pauydal Bijiaya, Xin Chen, William B. Hobbs, Daniel Fregosi, and Anubhave Jain. 2023. "Analysis of PV Module Power Loss and Cell Crack Effects Due to Accelerated Aging Tests and Field Exposure." ***IEEE Journal of Photovoltaics*** 13 (1): 165–73. *10.1109/JPHOTOV.2022.3228104*.
10. Arent, Douglas J., Peter Green, Zia Abdullah, Teresa Barnes, Sage Bauer, Andrey Bernstein, Derek Berry, Joe Berry, Tony Burrell, and Birdie Carpenter. 2022. "Challenges and Opportunities in Decarbonizing the US Energy System." ***Renewable and Sustainable Energy Reviews*** 169. *10.1016/j.rser.2022.112939*.
11. Springer, Martin, Dirk C. Jordan, and Teresa M. Barnes. 2022. "Future-Proofing Photovoltaics Module Reliability Through a Unifying Predictive Modeling Framework." Progress in Photovoltaics 31 (5): 546–53. *10.1002/pip.3645*.
12. Hartweg, Barry, Kathryn Fisher, Sridhar Niverty, Nikhilesh Chawla, and Zachary Holman. 2022. "Analysis of Electrically Conductive Adhesives in Shingled Solar Modules by X-Ray Imaging" Techniques." Microelectronics Reliability 136. *10.1016/j.microrel.2022.114627*.
13. Jordan, Dirk, Nancy Haegel, and Teresa Barnes. 2022. "Photovoltaics Module Reliability for the Terawatt Age." Progress in Energy 4 (2). *10.1088/2516-1083/ac6111*.
14. Sinha, Archana , Jiadong Qian, Stephanie L. Moffitt, Katherine Hurst, Kent Terwilliger, David C. Miller, Laura T. Schelhas, and Peter Hacke. 2023. "UV-Induced Degradation of High-Efficiency Silicon PV Modules With Different Cell Architectures." Progress in Photovoltaics 31 (1): 36–51. *10.1002/pip.3606*.
15. Spinella, Laura, Soňa Uličná, Archana Sinha, Dana B. Sulas-Kern, Michael Owen-Bellini, Steve Johnston, and Laura T. Schelhas. 2022. "Chemical and Mechanical Interfacial Degradation in Bifacial Glass/Glass and Glass/Transparent Backsheet Photovoltaic Modules." Progress in Photovoltaics 30 (12): 1423–32. *10.1002/pip.3602*.
16. Karin, Todd, Mason Reed, Jim Rand, Robert Flottemesch, and Anubhav Jain. 2022. "Photovoltaic Module Antireflection Coating Degradation Survey Using Color Microscopy and Spectral Reflectance." Progress in Photovoltaics 30 (11): 1270–88. *10.1002/pip.3575*.
17. Miller, David, Greg Perrin, Kent Terwilliger, Joshua Morse, Chuanxiao Xiao, Soňa Uličná, Bobby To, Chun-Sheng Jiang, Laura T. Schelhas, and Peter Hacke. 2022. "Development of Fixtures and Methods To Assess the Durability of Balance of Systems Components." IEEE Journal of Photovoltaics 12 (6): 1341–48. *10.1109/JPHOTOV.2022.3205154*.
18. Hacke, Peter, Akash Kumar, Kent Terwilliger, Paul Ndione, Sergiu Spataru, Ashwini Pavgi, Kaushik Roy Choudhury, and Govindasamy Tamizhmani. 2022. "Evaluation of Bifacial Module Technologies With Combined-Accelerated Stress Testing." Progress in Photovoltaics. *10.1002/pip.3636*.

Publication and Research Output

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

19. Silverman, Timothy J., Nick Bosco, Michael Owen-Bellini, Cara Libby, and Michael G. Deceglie. 2022. "Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells." IEEE Journal of Photovoltaics 12 (4): 1090–93. *10.1109/JPHOTOV.2022.3177139*.

20. Thornton, Patrick, Stephanie L. Moffitt, Laura T. Schelhas, and Reinhold H. Dauskardt. 2022. "Dependence of Adhesion on Degradation Mechanisms of Ethylene Co-Vinyl Acetate Encapsulants Over the Lifetime of Photovoltaic Modules." Solar Energy Materials and Solar Cells 244. *10.1016/j.solmat.2022.111818*.

21. Chen, Xin, Todd Karin, and Anubhav Jain. 2022. "Automated Defect Identification in Electroluminescence Images of Solar Modules." Solar Energy 242: 20–29. *10.1016/j.solener.2022.06.031*.

22. Sulas-Kern, Dana B., Michael Owen-Bellini, Paul Ndione, Laura Spinella, Archana Sinha, Soňa Uličná, Steve Johnston, and Laura T. Schelhas. 2022. "Electrochemical Degradation Modes in Bifacial Silicon Photovoltaic Modules." Progress in Photovoltaics 30 (8): 948–58. 1*0.1002/pip.3530*.

23. Karas, Joseph, Benjamin Phua, Alvin Mo, Nafis Iqbal, Kristopher Davis, Stuart Bowden, Alison Lennon, and André Augusto. 2022."Copper Outdiffusion From Copper-Plated Solar Cell Contacts During Damp Heat Exposure." ACS Applied Material Interfaces 14 (1): 12149–55. *10.1021/acsami.1c21218*.

24. Springer, Martin and Nick Bosco. 2021. "On Residual Stresses and Reference Temperatures in Thermomechanical Simulations of Photovoltaic Modules Using the Finite Element Method." IEEE Journal of Photovoltaics 12 (3): 853–59. *10.1109/JPHOTOV.2022.3143458*.

25. Kumar, Rishi E., Guillaume von Gastrow, Nicholas Theut, April M. Jeffries, Tala Sidawi, Angel Ha, Flavia DePlachett, Hugo Moctezuma-Andraca, Seth Donaldson, Mariana I. Bertoni, and David P. Fenning. 2022. "Glass vs. Backsheet: Deconvoluting the Role of Moisture in Power Loss in Silicon Photovoltaics with Correlated Imaging During Accelerated Testing." IEEE Journal of Photovoltaics 12 (1): 285–92. *10.1109/JPHOTOV.2021.3122878*.

26. Khan, Imran S., Joshua Morse, Robert R. White, and David C. Miller. 2022. "A Custom High-Throughput Optical Mapping Instrument for Accelerated Stress Testing of PV Module Materials." IEEE Journal of Photovoltaics 12 (1): 73–80. *10.1109/JPHOTOV.2021.3122925*.

27. Thuis, Michael, Naila M. Al Hasan, Rachael L. Arnold, Bruce King, Ashley Maes, David C. Miller, Jimmy M. Newkirk, et al. 2022. "A Comparison of Emerging Nonfluoropolymer-Based Coextruded PV Backsheets to Industry-Benchmark Technologies." IEEE Journal of Photovoltaics 12 (1): 88–96. *10.1109/JPHOTOV.2021.3117915*.

28. Woodhouse, Michael, David Feldman, Vignesh Ramasamy, Brittany Smith, Timothy Silverman, Teresa Barnes, Jarett Zuboy, and Robert Margolis. 2021. Research and Development Priorities To Advance Solar Photovoltaic Lifecycle Costs and Performance. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-80505. *docs/fy22osti/80505.pdf*.

29. Ulicna, Sona, Archana Sinha, Martin Springer, David C. Miller, Peter Hacke, Laura T. Schelhas, and Michael Owen-Bellini. 2021. "Failure Analysis of a New Polyamide-Based Fluoropolymer-Free Backsheet After Combined-Accelerated Stress Testing." IEEE Journal of Photovoltaics 11 (5): *1197–1205. 10.1109/JPHOTOV.2021.3090152*.

30. Springer, Martin, James Hartley, and Nick Bosco. 2021. "Multiscale Modeling of Shingled Cell Photovoltaic Modules for Reliability Assessment of Electrically Conductive Adhesive Cell Interconnects." IEEE Journal of Photovoltaics 11 (4): 1040–47. *10.1109/JPHOTOV.2021.3066302*.

31. Sinha, Archana, Dana B. Sulas-Kern, Michael Owen-Bellini, Laura Spinella, Sona Ulicna, Silvana Ayala Pelaez, Steve Johnston, and Laura T. Schelhas. 2021. "Glass/Glass Photovoltaic Module Reliability and Degradation: A Review." Journal of Physics D: Applied Physics 54. *10.1088/1361-6463/ac1462*.

32. Abudayyeh, Omar K., Andre Chavez, Sang M. Han, Brian Rounsaville, Vijaykumar Upadhyaya, and Ajeet Rohatgi. 2021. "Silver-Carbon-Nanotube Composite Metallization for Increased Durability of Silicon Solar Cells Against Cell Cracks." Solar Energy Materials and Solar Cells 225: 111017. *10.1016/j.solmat.2021.111017*.

33. Sinha, Archana, Stephanie L. Moffitt, Katherine Hurst, Michael Kempe, Katherine Han, Yu-Chen Shen, David C. Miller, Peter Hacke, and Laura T. Schelhas. 2021. "Understanding Interfacial Chemistry of Positive Bias High-Voltage Degradation in Photovoltaic Modules." Solar Energy Materials and Solar Cells 223 (May): 110959. *10.1016/j.solmat.2021.110959*.

34. Jeffries, April M., Tara Nietzold, Laura T. Schelhas, and Mariana I. Bertoni. 2021. "Corrosion of Novel Reactive Silver Ink and Commercial Silver-Based Metallizations in Diluted Acetic Acid." Solar Energy Materials and Solar Cells 223 (May): 110900. *10.1016/j.solmat.2020.110900*.

35. Karin, Todd, David Miller, and Anubhav Jain. 2021. "Nondestructive Characterization of Antireflective Coatings on PV Modules." IEEE Journal of Photovoltaics 11 (3): 760–69. *10.1109/JPHOTOV.2021.3053482*.

36. Owen-Bellini, Michael, Stephanie L. Moffitt, Archana Sinha, Ashley M. Maes, Joseph J. Meert, Todd Karin, Chris Takacs, et al. 2021. "Towards Validation of Combined-Accelerated Stress Testing through Failure Analysis of Polyamide-Based Photovoltaic Backsheets." Scientific Reports 11 (1): 2019. *10.1038/s41598-021-81381-7*.

37. Springer, Martin and Nick Bosco. 2021. "Environmental Influence on Cracking and Debonding of Electrically Conductive Adhesives." Engineering Fracture Mechanics 241 (January): 107398. *10.1016/j.engfracmech.2020.107398*.

Publication and Research Output

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

38. Newkirk, Jimmy M., Illya Nayshevsky, Archana Sinha, Adam M. Law, QianFeng Xu, Bobby To, Paul F. Ndione, et al. 2021. "Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First-Surfaces." Solar Energy Materials and Solar Cells 219 (January): 110757. *10.1016/j.solmat.2020.110757*.

39. White, Robert R., Kristin Munch, Nicholas Wunder, Nalinrat Guba, Chitra Sivaraman, Kurt M. Van Allsburg, Huyen Dinh, and Courtney Pailing. 2021. "Energy Material Network Data Hubs." International Journal of Advanced Computer Science and Applications (IJACSA) 12 (6). *10.14569/IJACSA.2021.0120677*.

40. Nietzold, Tara, Nicholas Valdes, Michael E. Stuckelberger, Michelle Chiu, Trumann Walker, April M. Jeffries, Archana Sinha, Laura T. Schelhas, Barry Lai, William N. Shafarman, and Mariana I. Bertoni. 2021. "Role of Cation Ordering on Device Performance in (Ag,Cu) InSe2 Solar Cells with KF Post-Deposition Treatment." ACS Applied Energy Materials 4 (1): 233–41. *10.1021/acsaem.0c02197*.

41. Hah, Jinho, Michael Sulkis, Minsoo Kang, Zhijian Sun, Jihoon Kim, Kyoung-Sik Moon, Matthew O. Reese, and Ching Ping Wong. 2021. "Surface Modification of Backsheets Using Coupling Agents for Roll-To-Roll Processed Thin-Film Solar Photovoltaic (PV) Module Packaging Application." ACS Applied Materials Interfaces 13 (1): 1682–92. *10.1021/acsami.0c13805*.

42. Gunda, Thushara, Sean Hackett, Laura Kraus, Christopher Downs, Ryan Jones, Christopher McNalley, Michael Bolen, and Andy Walker. 2020. "A Machine Learning Evaluation of Maintenance Records for Common Failure Modes in PV Inverters." IEEE Access 8 (November): 211610–20. *10.1109/ACCESS.2020.3039182*.

43. Young, Ethan, Xin He, Ryan King, and David Corbus. 2020. "A Fluid-Structure Interaction Solver for Investigating Torsional Galloping in Solar-Tracking Photovoltaic Panel Arrays." Journal of Renewable and Sustainable Energy 12 (6): 063503. *10.1063/5.0023757*.

44. Owen-Bellini, Michael, Peter Hacke, David C. Miller, Michael D. Kempe, Sergiu Spataru, Tadanori Tanahashi, Stefan Mitterhofer, Marko Jankovec, and Marko Topič. 2020. "Advancing Reliability Assessments of Photovoltaic Modules and Materials Using Combined-Accelerated Stress Testing." Progress in Photovoltaics: Research and Applications 29 (1): 64–82. *10.1002/pip.3342*.

45. 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): 1254–61. *10.1109/JPHOTOV.2020.3001723*.

46. 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): 1424–40. *10.1109/JPHOTOV.2020.3005086*.

47. 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 & Interfaces 12 (23): 26405–12. *10.1021/acsami.0c01493*.

48. Moffitt, Stephanie L., Conor Riley, Benjamin H. Ellis, Robert A. Fleming, Corey S. Thompson, Patrick D. Burton, Margaret E. Gordon, Andriy Zakutayev, and Laura T. Schelhas. 2020. "Combined Spatially Resolved Characterization of Antireflection and Antisoiling Coatings for PV Module Glass." ACS Combinatorial Science 22 (4): 197–203. *10.1021/acscombsci.9b00213*.

49. Karin, Todd and Anubhav Jain. 2020. "Photovoltaic String Sizing Using Site-Specific Modeling." IEEE Journal of Photovoltaics 10 (3): 888–97. *10.1109/JPHOTOV.2020.2969788*.

50. 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): 838–43. *10.1109/JPHOTOV.2020.2971139*.

51. 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 (March): 110281. *10.1016/j.solmat.2019.110281*.

52. Nayshevsky, Illya, QianFeng Xu, Jimmy M. Newkirk, Daniel Furhang, David C. Miller, and Alan M. Lyons. 2020. "Self-Cleaning Hybrid Hydrophobic–Hydrophilic Surfaces: Durability and Effect of Artificial Soilant Particle Type." IEEE Journal of Photovoltaics 10 (2): 577–84. *10.1109/JPHOTOV.2019.2955559*.

53. Karas, Joseph, Archana Sinha, Viswa Sai Pavan Buddha, Fang Li, Farhad Moghadam, Govindasamy TamizhMani, Stuart Bowden, and André Augusto. 2020. "Damp Heat Induced Degradation of Silicon Heterojunction Solar Cells With Cu-Plated Contacts." IEEE Journal of Photovoltaics 10 (1): 153–58. *10.1109/JPHOTOV.2019.2941693*.

54. Springer, Martin and Nick Bosco. 2020. "Linear Viscoelastic Characterization of Electrically Conductive Adhesives Used as Interconnect in Photovoltaic Modules." Progress in Photovoltaics: Research and Applications 28 (7): 659–81. *10.1002/pip.3257*.

55. 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): 7870–78. *10.1021/acsaem.9b01316*.

56. Jean, Joel, Michael Woodhouse, and Vladimir Bulović. 2019. "Accelerating Photovoltaic Market Entry with Module Replacement." Joule 3 (11): 2824–41. *10.1016/j.joule.2019.08.012*.

Publication and Research Output

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

57. 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): 1748–53. *10.1109/JPHOTOV.2019.2938108*.

58. 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 (October): 110082. *10.1016/j.solmat.2019.110082*.

59. 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 (October): 110072. *10.1016/j.solmat.2019.110072*.

60. Shimpi, Tushar M., Christina Moffett, Walajabad S. Sampath, and Kurt L. Barth. 2019. "Materials Selection Investigation for Thin Film Photovoltaic Module Encapsulation." Solar Energy 187 (15): 226–32. *10.1016/j.solener.2019.04.095*.

61. 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*.

62. 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: Research and Applications 27 (8): 693–705. *10.1002/pip.3144*.

63. Bosco, Nick, Stephanie 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): 340–45. *10.1002/pip.3106*.

64. Hovish, Michael Q., Florian Hilt, Nicholas Rolston, Qiran Xiao, and Reinhold H. Dauskardt. 2019. "Open Air Plasma Deposition of Superhydrophilic Titania Coatings." Advanced Functional Materials 29 (19). *10.1002/adfm.201806421*.

65. Moffitt, Stephanie L., Laura T. Schelhas, Sunjay Melkote, and Michael F. Toney. 2019. "7 - Multifunctional Optical Coatings and Light Management for Photovoltaics." In Advanced Micro- and Nanomaterials for Photovoltaics. Edited by David Ginley and Thomas Fix, 153–73. Micro and Nano Technologies. Elsevier. *10.1016/B978-0-12-814501-2.00007-4*.

66. Nayshevsky, Illya, QianFeng Xu, and Alan M. Lyons. 2019. "Hydrophobic–Hydrophilic Surfaces Exhibiting Dropwise Condensation for Anti-Soiling Applications." IEEE Journal of Photovoltaics 9 (1): 302–7. *10.1109/JPHOTOV.2018.2882636*.

67. 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): 189–95. *10.1109/JPHOTOV.2017.2768959*.

68. 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 5 (44): 22975–83. *10.1039/C7TA09178H*.

PATENT APPLICATIONS AND PATENTS AWARDED

1. 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.

2. 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.

3. 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.

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

Data, Tools, and Capabilities

Industry-Relevant Data, Tools, and Capabilities From DuraMAT Research

The DuraMAT Data Hub

The DuraMAT Data Hub has now been operational for six years. It is deployed on an Amazon Web Services federal government cloud hosted at NREL, and can be found at *https://datahub.duramat.org/*. It currently has 267 registered users working on 96 projects that encompass 12,107 files (an 11.5% increase from last year). Public data sets cover areas from soiling maps to PV orientation machine learning training sets. The Data Hub provides 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 research team from Sandia and NREL has launched the first collaborative public software library for organizing and distributing reusable code for data preparation, called PVAnalytics: *https://github.com/pvlib/pvanalytics*. This resource provides functions for quality control, filtering, feature labeling, and other tools, supporting 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. This modeling tool can compare the behavior of different module designs, encapsulants, edge sealants, adhesives, and other materials in terms of stiffness and mechanical response to external loads and temperature changes, aiding in optimization and failure analysis. The tool has applications in predicting module deflection and cell cracking in deployment conditions.

Contact: *jkyuan@sandia.gov*.

Combined-Accelerated Stress Testing (C-AST)

C-AST is a novel accelerated testing approach that uses a combination of field-PV-specific stress levels 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 been shown to elucidate a variety of degradation modes in materials and components used in modules and PV systems.

Contact: *peter.hacke@nrel.gov*.

PV-Vision: Automated Analysis of Electroluminescence Images

PV-Vision uses machine learning to analyze electroluminescence images and detect module features such as cells and busbars, find defects such as cracks and solder failures, and extrapolate the maximum power loss area. Hundreds of thousands of images can be analyzed very rapidly and without human input. A code repository is available at *https://github.com/hackingmaterials/pv-vision*.

Contact: *ajain@lbl.gov*.

PVTOOLS: Interactive Website for DuraMAT Tools

PVTOOLS contains interactive web visualizations and exploratory tools for two DuraMAT projects: the PV String Sizing Tool (used by various independent engineers to determine string sizing) and the PV Climate Zones Map (which may provide more degradation-relevant climate zones than the Köppen-Geiger classification). The web site is at *https://pvtools.lbl.gov*.

Contact: *ajain@lbl.gov*.

Data, Tools, and Capabilities

Industry-Relevant Data, Tools, and Capabilities From DuraMAT Research

PVPro: Extracting Module Characteristics and Power Prediction

PVPro is a tool that analyzes production power and irradiance data to determine single diode parameters (applied to a string) as a function of time. One can then deconstruct power degradation trends into individual degradation parameters such as series resistance increase or shunt resistance decrease. The power prediction module maps the forecasted irradiance to output power based on dynamic physical models without additional I-V characterization. A code repository is available at *https://github.com/DuraMAT/pvpro*.

Contact: *ajain@lbl.gov*.

Simplified Online Levelized Cost of Energy (LCOE) Calculator

The online PV LCOE calculator allows researchers to perform quick estimates of how various PV module and system performance and cost parameters affect the final LCOE. The online tool is at *https://pvlcoe.nrel.gov*.

Contact: *brittany.smith@nrel.gov*.

Multimodal Electro-Optical Imaging

Photoluminescence (PL), electroluminescence (EL), UV fluorescence (UVF), and dark lock-in thermography (DLIT) are camera-based characterization tools available to DuraMAT collaborators upon request. PL imaging provides details on absorber quality and the defects causing carrier recombination. EL imaging provides different information about electrical contact quality. DLIT imaging shows power dissipation as heat, either in forward or reverse bias. UVF imaging captures the high-energy emission profiles of degraded polymer materials such as encapsulants and backsheets.

Contact: *dana.kern@nrel.gov*.

Laser-Based Cutting and Module Deconstruction

The University of Virginia's high-power laser processing laboratory facility allows for laser ablation of thin films, laser cutting, laser annealing, laser patterning, and selective removal of thin-film layers for applications such as recycling of solar modules, repair of solar cells, fabrication of high-efficiency solar cells, and manufacturing of solar cells.

Contact: *mgupta@virginia.edu*.

PLatypus: Field Photoluminescence Measurements

PLatypus is a tool for detecting cracks and other flaws in PV modules using PL imaging. It can get a high-resolution image of an entire module in a few seconds, without unmounting the module or operating any connectors. A DuraMAT-funded proof-of-concept prototype was completed in 2023, and further prototypes may be available. An overview video can be found at *https://www.youtube.com/watch?v=MeUKo83Lo-c*. Mechanical files for the proof of concept are at *https://datahub.duramat.org/en/dataset/platypus-mechanical*, and results from a field trial are at *https://datahub.duramat.org/en/dataset/pl-imagery-on-100-fielded-modules*.

Contact: *timothy.silverman@nrel.gov*.

Sierra-COMSOL Interconversion

A research team from Sandia has developed a software tool, ExoToComsol, to convert finite element analysis (FEA) data between the Sierra code suite used at Sandia and the commercial FEA program COMSOL. ExoToComsol facilitates modeling capability sharing between Sandia and other DuraMAT partners to realize a multiphysics modeling chain approach to predict overall degradation mechanisms of PV modules. ExoToComsol will be available on GitHub after ongoing DOE review.

Contact: *frahman@sandia.gov*.

Data, Tools, and Capabilities

Industry-Relevant Data, Tools, and Capabilities From DuraMAT Research

PVade: Aerodynamic Design Engineering

PVade (PV aerodynamic design engineering) is a scalable fluid-structure interaction software designed to simulate the dynamic wind loads and interactions that occur within solar-tracking arrays. This tool is enabling researchers to test hardware, layout, and tracker control changes to increase system stability and decrease wind-driven damage. For more information, see *https://github.com/NREL/PVade*.

Contact: *ethan.young@nrel.gov*.

High-Throughput Surface Topology Screening System

The Laser Technology Group at LBNL has developed a high-throughput characterization system to identify promising topologies for multifunctional surfaces, which can make and analyze hundreds of unique surfaces per hour on various materials. All tools are custom-made, and they include a laser patterning system, an automated goniometry system to screen self-cleaning ability, and an automated optical characterization system. An accelerated aging chamber is also in development to screen for long-term durability.

Contact: *vzorba@lbl.gov*.

PV Degradation Tools

PV Degradation Tools is an open-source library of functions and values to calculate degradation responses and degradation-related parameters for PV. It aims to be the go-to location for peer-reviewed degradation algorithms, functions, and literature values, as well as providing users with an easy way to apply degradation calculations geospatially and temporally by leveraging NREL's NSRDB database and parallel cloud computing. GitHub: *https://github.com/NREL/PVDegradationTools*. Try the online training now: *https://nrel.github.io/PVDegradationTools/intro.html*.

Contact: *Michael.Kempe@nrel.gov*.

WhatsCracking: The PV Module Cell Fracture Prediction App

WhatsCracking provides manufacturers, developers, users, and testing laboratories easy access to an accurate, mechanistic tool to assess how PV module design impacts the propensity for cell fracture. Website: *https://datahub.duramat.org/dataset/whatscracking-application*.

Contact: *nick.bosco@nrel.gov*.

DuraMAT
Durable Module Materials Consortium

FY 2023

ANNUAL REPORT

DuraMAT leverages decades of experience, expertise, and world-class facilities to create a "one-stop shop" for timely solutions to critical barriers limiting PV module reliability and durability. It offers university and industry researchers the opportunity to work with national lab partners: the National Renewable Energy Laboratory (NREL), Sandia National Laboratories (Sandia), and Lawrence Berkeley National Laboratory (LBNL). Our work is guided by a 22-member Industry Advisory Board, which helped to develop DuraMAT's five core objectives and reviews all project calls.

duramat.org

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office. The views expressed in the report do not necessarily represent the views of the DOE or the U.S. Government.

NREL/BR-5K00-88805
February 2024