



FY 2022

ANNUAL REPORT

Towards Predicting Lifetime



Durable Module Materials Consortium



BERKELEY LAB

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About DuraMAT

The Durable Module Materials Consortium (DuraMAT) launched in November 2016 with five years of funding from the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO). The program renewed in 2022 for an additional 6 years. DuraMAT is a multi-lab consortium led by the National Renewable Energy Laboratory, with Sandia National Laboratories (Sandia) and Lawrence Berkeley National Laboratory (LBNL) as core research labs. 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 and the technical management team at SETO.

DuraMAT Director's Letter

DuraMAT transitioned from our first 5-year program (D1) into a new 6-year program (D2) in 2022. It was a very busy year; we wrapped up projects from DuraMAT 1 and kicked off new laboratory-led projects for DuraMAT 2. This transition brings new goals and a renewed focus on accelerating the energy transition by improving photovoltaic (PV) module reliability. 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?

Our work will focus on improving our ability to predict and extend PV module lifetimes by continuing to reduce early failure and developing a deeper understanding of wear-out. Both are essential for long lifetimes and were identified as critical needs by our industry advisory board (IAB). Our IAB, SETO partners, and DuraMAT researchers agreed that success requires further build-out of our predictive modeling capabilities. DuraMAT published a *gap analysis* and research strategy for predictive modeling in 2022 that prioritizes building experimentally validated models of individual degradation mechanisms that can be combined into model chains to describe module failure modes.

DuraMAT also published its first annual *Technology Scouting Report* in 2022. This report identifies the biggest changes in new PV module technologies—larger sizes, new interconnect materials and designs, bifacial technologies, and high-efficiency cell technologies—and their impacts on module performance and reliability.

DuraMAT Director's Letter (continued)

In FY22, DuraMAT kicked off nine projects focused on understanding early failures, routine degradation, and wear-out in modern module technologies using data analytics, predictive modeling, accelerated testing, module forensics, and new material development. We solicited additional proposals and awarded six projects focused on predictive modeling that will kick off in FY23.

Outreach and communications efforts are ongoing, with invited and contributed talks at the NREL PV Reliability Workshop (PVRW), IEEE Photovoltaic Specialists Conference (PVSC), Terawatt Workshop, International Photovoltaic Science and Engineering Conference (PVSEC), ModuleTech, RE+, and many others. At the end of FY22, DuraMAT had 52 published journal articles and over 130 presentations since 2017. We will continue our hybrid webinars, presentations, and other events so we can remain accessible, inclusive, and open.

DuraMAT's goals are ambitious, and we remain focused on building predictive reliability capabilities that will accelerate PV deployment for the energy transition. 2022 was an exciting year for solar in the United States—the Inflation Reduction Act is bringing manufacturing back to the United States and scaling the industry at an unprecedented rate. DuraMAT remains a trusted resource for the PV industry as it deals with growing pains as well as the tremendous opportunity to decarbonize electricity generation.

Here are some key results from FY22:

• Predictive Modeling Strategy

- Predictive models should be a hybrid of fundamental physics and empirical observations to quickly bridge knowledge gaps.
- Lifetime predictions require a holistic modeling framework that can link individual models together in model chains to represent multiple mechanisms and failure modes. Complex co-modeling and co-simulation frameworks are not necessary yet.
- Combining modeling with accelerated testing will allow for faster model validation and test development. Field validation will remain the gold standard, but laboratory-based accelerated stress testing is required for timely results.

• Mechanics and Cell Cracking

- Crack propagation is more critical for predicting future damage and failure than crack initiation, because many modules have preexisting cracks.
- The dynamic mechanical loading (DMX) tool enables highly accelerated testing to quantify the effects of repeated vibration and cyclic loading, which are the primary drivers of propagation.
- Detailed studies of hail impact and damage propagation enable us to establish correlations between measurable parameters like module displacement and the likelihood of damage propagation as a function of module design.
- PLatypus is a new high-resolution nighttime photoluminescence tool that can scan a PV power plant for small cracks without electrical disconnection.
- Methods have been developed for direct imaging of cell stress in glass/glass packages using X-ray topography and water reflectometry detection.

• Effects on High-Efficiency Cells and Modules

- Two different DuraMAT projects observed potential-induced degradation of the polarization type (PID-p) in glass/glass modules, indicating that PID-p is a field-relevant mechanism.
- UV exposure leads to a significant power decrease in modern cell types (-3.6% on average; -11.8% maximum), compared with conventional aluminum back surface field cells (<-1% on average).
- The rear sides of bifacial cells appeared to be more susceptible to UV damage compared to the front sides.
- These results are important, as 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.

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

DuraMAT Predictive Modeling Working Group

Photovoltaic module technologies are constantly changing, making it challenging to evaluate the lifetime and reliability of new module designs. Improved predictive modeling frameworks are necessary to keep up with the rapid pace of technological change. Currently, predictive modeling efforts are often based on very specific heterogeneous models that focus on a single failure mode rather than the underlying physical degradation mechanisms. Shifting the focus toward a mechanistic understanding allows for the rapid application of existing models to new technologies, which, in turn, reduces the time needed to assess the reliability and lifetime of new designs. A summary of the Predictive Modeling Working Group's motivation and progress was presented at this year's DuraMAT Workshop. The working group hosted regular meetings to facilitate discussions among subject matter experts focused on the organization and development of new

predictive capabilities. Meeting topics included detailed examples of effectively building modeling chains and linking models, as well as hosting and publishing modeling tools in an open-source format. These meetings and discussions have demonstrated that continued collaboration is critical to developing advanced modeling frameworks that effectively predict module performance and reliability.

Topic: Predictive Modeling

CONTACT

Martin Springer, National Renewable Energy Laboratory,
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DuraMAT Fiscal Year 2022 Financial Report

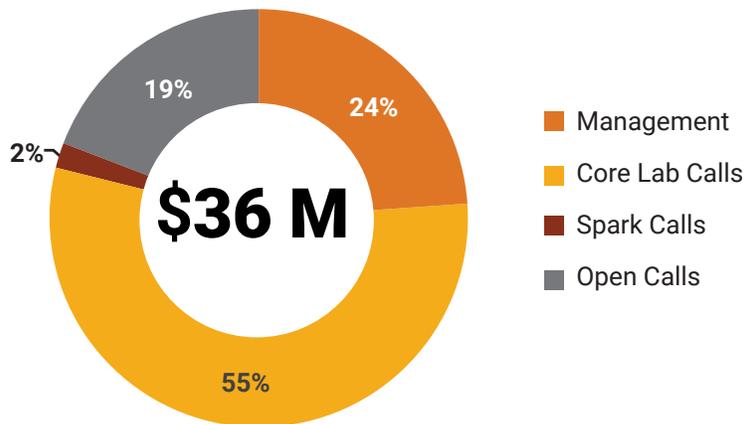
The DuraMAT program was awarded a \$36-million, 6-year extension at the end of FY21. We launched this new phase of DuraMAT at the beginning of FY22 with a plan to award over \$27 million in new research projects. The remaining funds will cover necessary program management activities, including financial management, developing requests for proposals (RFPs), and reporting.

New research projects will be awarded through the same three RFP categories we had in DuraMAT 1: core lab calls and spark calls, which are open to national laboratory researchers only; and open calls, which are open to university and industry partners. Our open call awards are subject to cost sharing.

Due to the existing infrastructure in place from the past 5 years, the program was able to move quickly with the release of two core lab calls and a spark call. Fifteen projects were awarded and started work in FY22. Another spark call and our first open call RFP were also released in FY22, bringing several new projects that will be announced and start work in FY23.

DuraMAT 1 concluded with 49 projects and partnerships with over 20 different organizations. A full list of DuraMAT publications and our project portfolio can be found on our website: <https://www.duramat.org/publications.html>, <https://www.duramat.org/projects.html>.

DURAMAT 2 FUNDS DISTRIBUTION PLAN





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 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



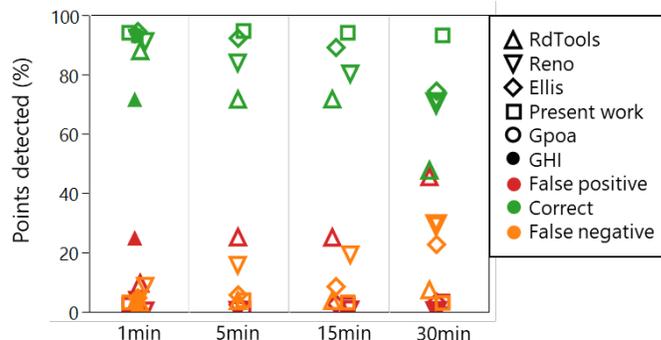
KEY RESULT

Ensuring Reliable Analytics Through Dependable Data Quality Tools

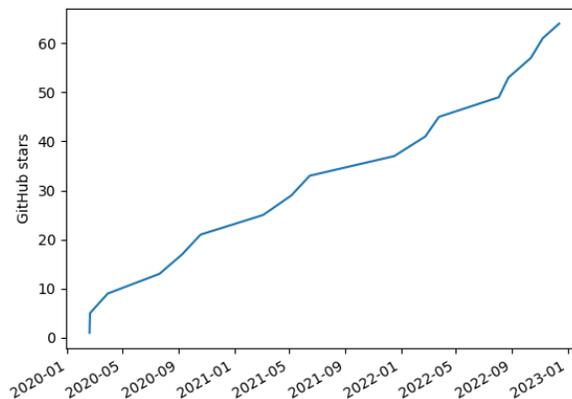
PI: Clifford Hansen (Sandia)

Team Members: Thushara Gunda (Sandia); Dirk Jordan, Michael Deceglie, Matt Muller (NREL); Will Vining, Michael Hopwood, Hector Mendoza (Sandia)

Summary of Result: We significantly advanced capabilities to prepare data to quantify degradation rates of PV systems. We launched the pvlb/PVAnalytics open-source library to collect and publish code for data quality control, filtering, and feature recognition. We demonstrated a new capability that automatically translates textual maintenance records to a time series of system state indicators. We extended an available clear sky labeling algorithm that had been validated only for one-minute global horizontal irradiance (GHI) to apply it to time-averaged and tilted-plane irradiance data.



Detection accuracy using different clear sky detection methods at different data frequencies. Current work improves detection at longer frequencies. Tilted plane (Gpoa) is indicated by open symbols.



Increase in GitHub stars over time for the PVAnalytics repository indicates broad interest outside the developers' projects.

LEARN MORE

PVAnalytics: <https://github.com/pvlb/pvanalytics>

Text to time series: <https://github.com/sandialabs/pvOps>

Jordan, D. and C. Hansen. 2022. "Clear-Sky Detection for PV Degradation Analysis." In review.



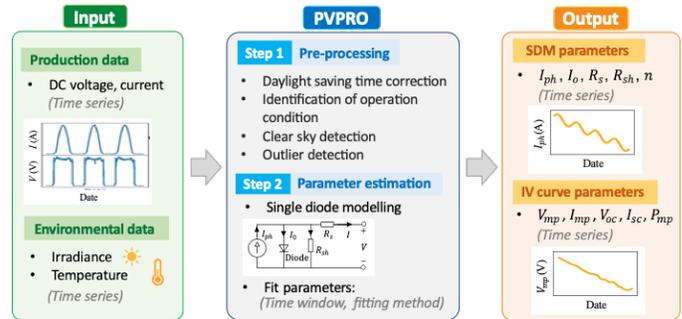
KEY RESULT

PV Production Data Can Tell Us More About Degradation

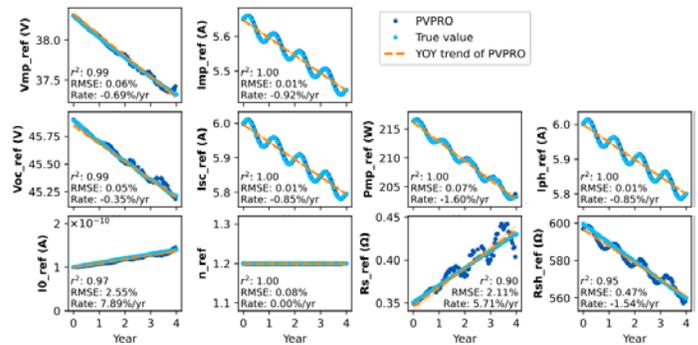
PI: Anubhav Jain (LBNL)

Team Members: Baojie Li, Xin Chen (LBNL); Todd Karin (PV Evolution Labs); Michael Deceglie, Dirk Jordan, Laura Schelhas (NREL); Bennet Meyers (SLAC); Clifford Hansen, Bruce King (Sandia)

Summary of Result: Understanding PV degradation is essential to the operation and maintenance of PV systems. To this end, the time evolution of key PV module parameters like series and shunt resistance need to be analyzed. However, obtaining these parameters typically requires a full current-voltage characteristic (I-V curve), the acquisition of which involves specific measurement devices and costly methods. Here, we propose a methodology (PVPRO) to estimate these I-V curve parameters using only production data (string-level direct current (DC) voltage and current) and weather data (irradiance and temperature). PVPRO first performs multi-stage data preprocessing to remove noisy data. Next, the time-series DC data are used to fit an equivalent circuit single-diode model (SDM) to estimate the circuit parameters by minimizing the differences between the measured and estimated values. In this way, the time evolutions of the SDM parameters are obtained. We evaluate PVPRO on synthetic data sets and find an excellent estimation of both SDM and the key I-V parameters. The performance, especially the extracted degradation rate of parameters, is robust to various types of measurement noise and the presence of faults. PVPRO represents a promising open-source tool to extract the time-series degradation trends of key PV parameters from routine production data.



Flow chart illustrating PVPRO analysis. The overall goal of PVPRO is to estimate SDM parameters and I-V curve parameters using only typical production and environmental data as inputs.



Degradation trend of I-V and SDM parameters estimated by PVPRO using a synthetic data set modeling an 11-kW PV array. Overall, PVPRO achieves good estimation of the parameters with a coefficient of determination ≥ 0.9 . Year-over-year trends are shown in orange.

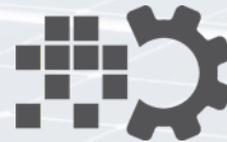
LEARN MORE

Online software repository of PVPRO: <https://github.com/duramat/pvpro>

Li, B., X. Chen, T. Karin, and A. Jain. 2022. "Estimation and Degradation Analysis of Physics-Based Circuit Parameters for PV Systems Using Only DC Operation and Weather Data." 2022 IEEE 49th Photovoltaics Specialists Conference. 1236–1236.

Central Data Resource

Core Objective



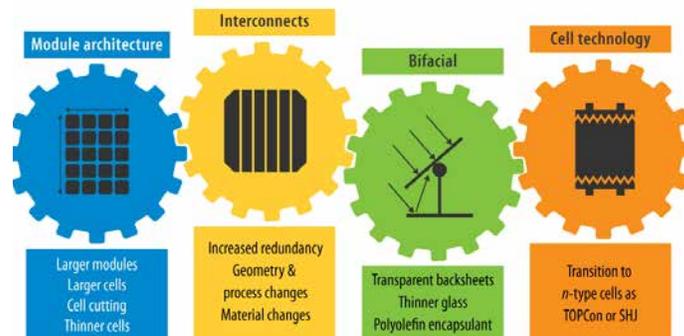
KEY RESULT

Techno-Economic Analysis Puts DuraMAT Work in Context

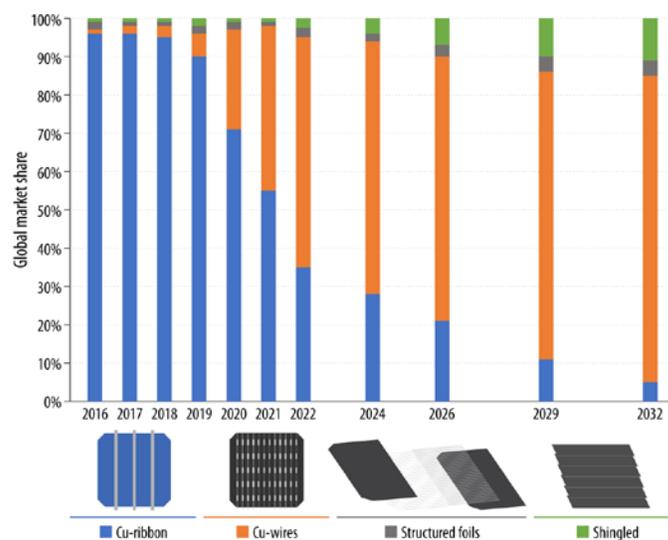
PIs: Michael Woodhouse and Brittany Smith (NREL)

Team Members: Jarett Zuboy (NREL)

Summary of Result: Techno-economic analysis (TEA) identifies promising research directions for improved PV module and system reliability, durability, and sustainability. TEA is needed to quantify the value of these improvements in financial and environmental terms, and it is used for synthesizing qualitative information about technology and reliability trends from industry stakeholders. For example, we synthesize a range of sources (PV market reports, stakeholder interviews, peer-reviewed literature) to identify likely and impactful near-term module and system technology trends and assess the reliability implications of those trends. To calculate the cost trade-offs between technology approaches, we deploy our bottom-up manufacturing and module testing cost modeling capabilities, as well as our capital cost models that cover utility and distributed generation systems. 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 substituting materials, 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.



The 11 technology trends analyzed in this effort grouped into four categories. The interlocking gear motif indicates our analysis of reliability-related interactions among multiple trends.



Historical (2016–2021) and projected (2022–2032) International Technology Roadmap for Photovoltaic Data on shares of interconnect technologies.

LEARN MORE

For more information, see: <https://www.nrel.gov/solar/market-research-analysis/solar-cost-analysis.html>

Zuboy, Jarett, Martin Springer, Elizabeth Palmiotti, Joseph Karas, Brittany Smith, Michael Woodhouse, and Teresa Barnes. 2022. "Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated With Projected Technological Changes." Renewable and Sustainable Energy Reviews, submitted. Preprint available here: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4273054.

Woodhouse, Michael, Brittany Smith, Vignesh Ramasamy, and David Feldman. "Solar and Storage Techno-Economic Analysis Tutorial." Presented at the IEEE Photovoltaic Specialist Conference. NREL/PR-7A40-82956. <https://www.nrel.gov/docs/fy22osti/82956.pdf>.

Technology Scouting Report Webinar: <https://www.nrel.gov/docs/fy22osti/82871.pdf>

DuraMAT online LCOE calculator: <https://datahub.duramat.org/dataset/lcoe-calculator-tool>

Central Data Resource

Core Objective



KEY RESULT

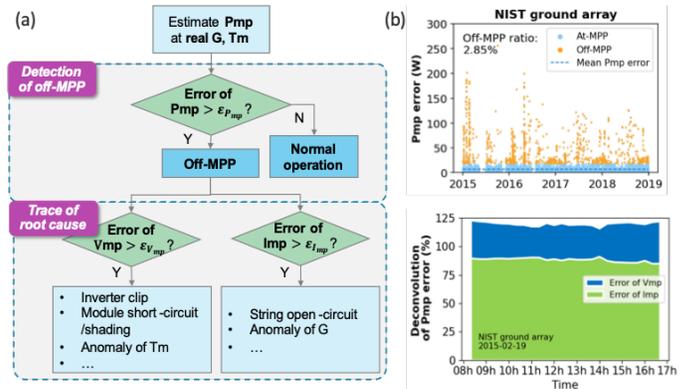
Data Reveal the Critical Factors of PV Degradation

PI: Anubhav Jain (LBNL)

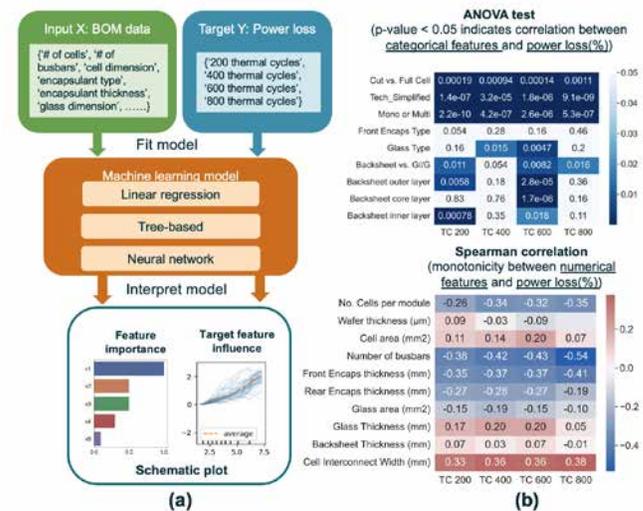
Team Members: Baojie Li, Xin Chen (LBNL); Todd Karin (PV Evolution Labs); Michael Deceglie, Dirk Jordan, Laura Schelhas (NREL); Bennet Meyers (SLAC); Clifford Hansen, Bruce King (Sandia)

Summary of Result: PV systems can operate off-maximum power point (MPP) for a variety of reasons. Existing methods detect off-MPP based on only direct current (DC) or alternating current (AC) power (via thresholding or shape of power data), which provides limited information regarding the trace of root causes. Seen in this light, we develop an algorithm to determine off-MPP points based on modeling of expected I-V parameters using irradiation and temperature. This allows us to quantify the contribution of voltage and current error to the power error, which then allows us to understand the causes. This algorithm will be integrated with the final data filter of PVPRO (a tool to extract the degradation trends of essential PV parameters using operation data) and other open-source degradation analysis tools such as RdTools and solardatools.

Another focus of the project is on the bill of materials (BOM) of PV modules, which influences the overall durability of PV modules. Based on the collected BOM data of approximately 500 PV modules, we leverage data-driven methods to determine the most influential factors in the current module design that can cause module degradation. Using thermomechanical durability as a start, we have begun correlating the BOM data with power loss data and interpreting the models to determine the dominant factors in the module design that influence module durability. This work could provide insights and directions for future research on module optimization.



(a) The off-MPP analysis flow chart. Off-MPP points are detected based on the P_{mp} error and then separated into errors from V_{mp} and I_{mp} . (b) A demonstration using the National Institute of Standards and Technology (NIST) ground array data set. This tool can detect and trace the main source of error to off-MPP.



Demonstration of BOM analysis. (a) Schematic diagram of process in BOM analysis. Fitting a regression model and interpreting the model are the two essential parts. (b) Correlation between BOM features and power loss. Certain features show high correlation with power loss and may require further investigation via the simulation, forensics, or field testing objectives of DuraMAT.

LEARN MORE

DuraMAT webinar: <https://www.duramat.org/assets/pdfs/duramat-webinar-november-2022.pdf>

Online software repository of PVPRO: <https://github.com/duramat/pvpro>

Central Data Resource

Core Objective



KEY RESULT

DuraMAT Data Hub

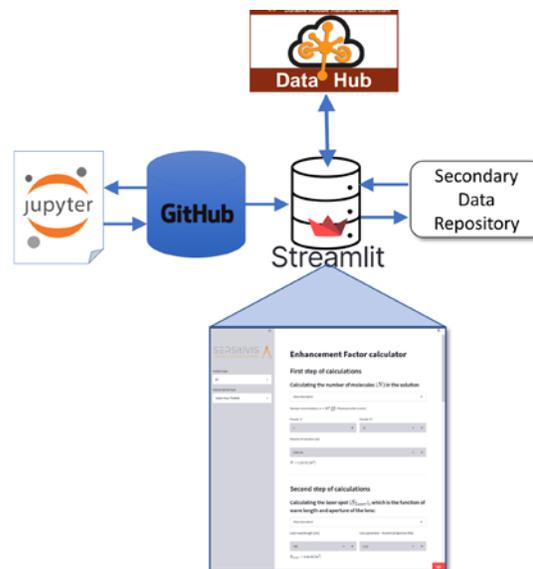
PI: Robert White (NREL)

Team Members: Anubhav Jain (LBNL); Emily Harrell, Rachel Hurst, Nalinrat Guba, Chris Webber (NREL)

Summary of Result: By utilizing expertise and capabilities from across the national laboratory complex, the U.S. Department of Energy (DOE) has created a set of virtual laboratories focused on specific research topics to push the frontiers of energy research. The DuraMAT consortium is part of these Energy Material Networks and focuses on PV reliability and durability research. Making such a virtual laboratory possible requires constructing a system that can securely and efficiently facilitate the sharing and interactive exploration of data and ideas. The DuraMAT Data Hub continues to archive and provide secure access to data for users and the public from a variety of scientific thrusts. Much of the work this year was focused on greater researcher engagement and studying better methods to facilitate data tool development and deployment.



The Data Hub shows continuous, steady growth—both in internal activity and worldwide engagement with other researchers and the public.



We have identified and tested new software (Streamlit) for the development of data tools that will help alleviate web development costs by removing the need for full-stack programming.

LEARN MORE

Information about the Data Hub can be found at: <https://datahub.duramat.org/project/duramat-help>

How the Data Hub was designed, how it operates, and examples of the research can be found in the following article:

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: Software Platforms for Advancing Collaborative Energy Materials Research." IJACA 12 (6). <http://dx.doi.org/10.14569/IJACSA.2021.0120677>.



Multi-Scale Multi-Physics Model

Core Objective Lead: Michael Owen-Bellini,
Michael.OwenBellini@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:

- Use of high-speed video and digital image correlation to characterize instantaneous glass displacement during hail impact.
- Frame-by-frame analyses showing that surface displacements of the module can be captured to ± 0.1 millimeters at 0.1-millisecond temporal resolution.
- Implementation of silicon cell electrical simulation capabilities into an existing mini-module simulation test bed.
- Use of scanning electron microscopy and electrical characterization methods to quantify silicon cell gridline wear-out under mechanical loads. These methods will be used to identify the physical drivers for long-term gridline wear-out, the first step in developing a probabilistic failure model for gridlines over cracked cells.

Multi-Scale Multi-Physics Model



Core Objective

KEY RESULT

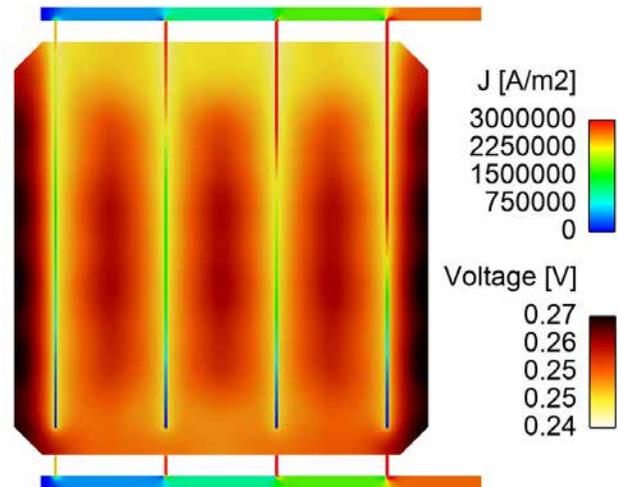
Adding Electrical Physics to PV Simulation Models

PI: James Hartley (Sandia)

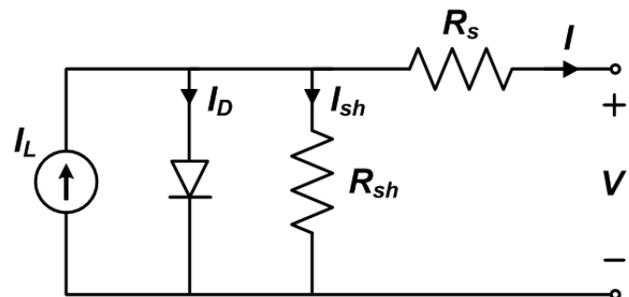
Team Members: Scott Roberts, Farhan Rahman (Sandia); Michael Owen-Bellini, Peter Hacke (NREL)

Summary of Result: Computational analyses of PV module and component degradation have predominantly focused on thermal-mechanical modes, such as stressors induced by environmental temperature changes or mechanical loading. However, predicting power loss from simulated mechanical damage cannot be completed without also modeling electrical physics. Likewise, the accuracy of some predicted degradation modes could be improved by incorporating coupled electrical effects such as temperature changes induced by Joule heating. This work adds simulation of electrical current flow through modeled PV geometries to enable coupling of electrical operation to thermal and mechanical states. Ultimately, these coupled models will enable simulations of phenomena such as power loss from a cracked cell or hot spot temperatures and their subsequent mechanical effects.

A previously developed mini-module model was used as a test bed for implementing electrical simulation capabilities. The modeled cell volume used the single-diode equivalent circuit model to generate current as a function of assumed illumination, interconnect resistivities, and external load, such that the simulated mini-module outputs matched analytical expectations. Because this electrical capability uses the same geometry as simulations with other physics, simulated current density distribution results can be directly coupled to subsequent thermal or thermal-mechanical analyses.



Finite element model of an illuminated mini-module in operation under load, showing simulated current density and voltage distributions.



The single-diode equivalent circuit model is the basis for the finite element implementation.

LEARN MORE

Hartley, James Y. 2022. "An integrated, multi-physics, multi-scale modeling capability for PV stressors and failures." 2022 Photovoltaics Reliability Workshop. Poster E.1.11. February 25, 2022. SAND2022-1398C. <https://www.nrel.gov/docs/fy22osti/82935.pdf>.

Hartley, James Y. 2022. "Finite element modeling and PV lifetime prediction: Applications, limitations, and perspectives on future approaches." DuraMAT Service Life Predictive Modeling Working Group Presentation. March 28, 2022. SAND2022-3573 PE.

Boyd, M. and Hansen, C. "Single Diode Equivalent Circuit Models." PV Performance Modeling Collaborative. <https://pvpmc.sandia.gov/modeling-steps/2-dc-module-iv/diode-equivalent-circuit-models/>.

Multi-Scale Multi-Physics Model

Core Objective



KEY RESULT

Mechanical Models for 50-Year Lifetime PV Modules: Gridline Wear-Out

PIs: Michael Owen-Bellini, Nick Bosco (NREL)

Team Members: Junki Joe, Timothy Silverman (NREL)

Summary of Result: To extend PV module lifetimes to and beyond 50 years, loss of power due to silicon cell cracking and subsequent cell fragment electrical isolation must be mitigated. Electrical isolation of cracked cell fragments occurs when the cell's conductive metal gridlines also fail electrically across the cell's cracked surfaces—also known as gridline wear-out. Although gridline wear-out has been repeatably demonstrated through accelerated testing sequences, little evidence has been presented that it also manifests in fielded modules in the first 10 years following a cell cracking event. Therefore, this mechanism is likely a trigger for end-of-life wear-out and thus requires a validated accelerated testing protocol to properly assess a module's 50-year reliability.

This project seeks to identify and understand the drivers for gridline wear-out and develop a probabilistic model that will enable long-term prediction of gridline wear-out in cracked solar cells. Using electrical characterization and scanning electron microscopy (SEM), we are able to quantify the wear-out of gridlines under dynamic mechanical loading conditions to then determine physical drivers.

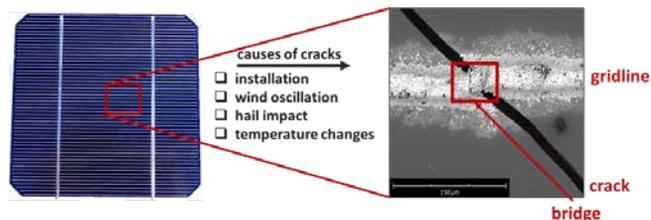
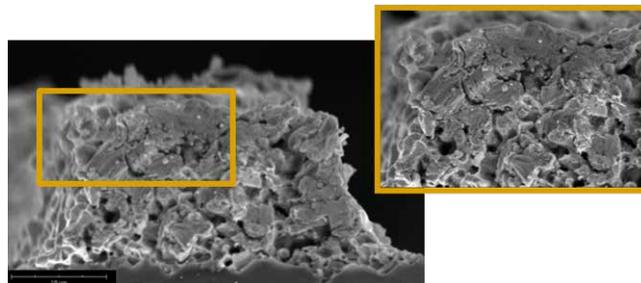


Illustration of the drivers behind cell cracking and gridline bridging, which maintains electrical conductivity across the crack. Subsequent wear-out of the gridline bridge can eventually lead to electrical isolation, thereby affecting cell performance.



Cross-sectional SEM image of a gridline after 10 mechanical loading cycles showing plastic deformation.

LEARN MORE

Joe, Junki, Michael Owen-Bellini, Timothy J. Silverman, and Nick Bosco. 2022. "Mechanical Models for 50-Year Lifetime PV Modules: Gridline Wear-Out." DuraMAT Fall Workshop. Breckenridge, CO. August 30, 2022.

Multi-Scale Multi-Physics Model



Core Objective

KEY RESULT

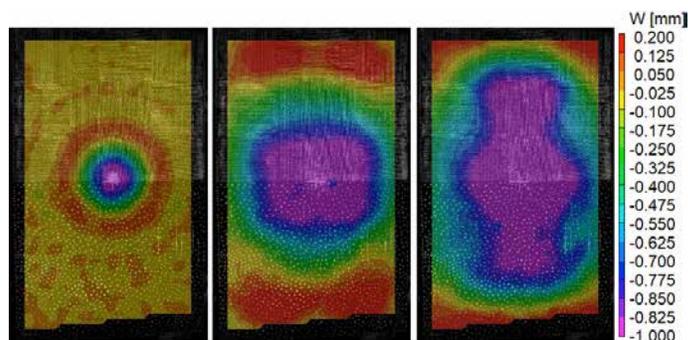
Measurement of Module Displacements During a Hail Impact Event

PI: James Hartley (Sandia)

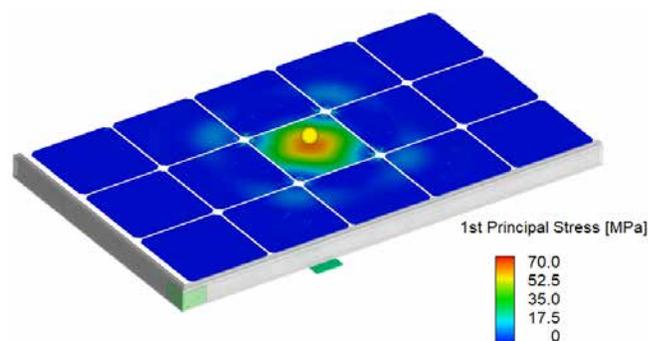
Team Members: Colin Sillerud (CFV Labs),
Jennifer Braid (Sandia)

Summary of Result: Large hail events are a significant threat to PV deployments in many geographical regions. However, quantifying module robustness against hail is difficult to achieve beyond a simplistic damaged versus undamaged criteria. This project seeks to further characterize the hail vs. module impact event using a combination of computational simulation and experimental diagnostics. A continuous understanding of damage probability based on module design features and incoming hail size enables efficient, cost-effective decision-making for at-risk deployment sites.

In this research, high-speed video of experimental hail strikes against a PV module were analyzed using digital image correlation to calculate instantaneous glass displacements during impact. Frame-by-frame analyses showed that surface displacements of the module could be captured to ± 0.1 millimeters at 0.1-millisecond temporal resolution. These quantitative maps provide validation data sets for impact simulations and allow damage statistics to be correlated to physical module response characteristics. With validated simulations of module displacement during impact and an experimental understanding of how displacement correlates to damage, computational predictions of damage likelihood become possible, along with the ability to rank robustness across module designs.



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



Simulated cell stresses during a 35-millimeter hail ice impact.

LEARN MORE

Hartley, James Y., J. Braid, F. Rahman, C. Sillerud, and J. Richards. 2022. "Analyzing Hail Impacts on PV Modules Using Computational Simulation." DuraMAT Fall Workshop. Breckenridge, CO. August 30, 2022. SAND2022-11500C.

Hartley, James Y. "Analyzing Hail Impacts on PV Modules Using Computational Simulation." 2022 Photovoltaics Reliability Workshop. Poster B.2.5. February 22, 2022. SAND2022-11393C. <https://www.nrel.gov/docs/fy22osti/82935.pdf>.



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 without *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 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), and thermal runaway of connectors and fuses.
- Confirmation of degradation modes through correlation to field data and laboratory characterization, optical mapping instruments (OMIs), voltage ionization, and ultraviolet light-induced degradation (UV-ID)—enabled use to quantify degradation mechanisms and degradation rate model(s).
- Quantification of the effects of UV weathering and damp heat testing—individually or in series—to better understand the degradation of modern encapsulants.
- Contemporary cell interconnects identified in industry survey will be examined using accelerated stress tests, C-AST, and outdoor aging (Mesa, Arizona, and Fairbanks, Alaska).

Disruptive Acceleration Science



Core Objective

KEY RESULT

Acceleration Factor Estimated for C-AST, the Test Method Recently Demonstrated for Balance of System Components

PI: Peter Hacke (NREL)

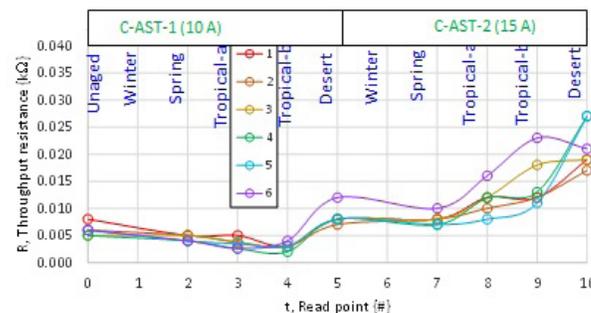
Team Members: Michael Owen-Bellini, David Miller (NREL); James Hartley, Bruce King, Joseph Meert, Joshua Stein (Sandia)

Summary of Result: Combined-accelerated stress testing (C-AST) combines stress factors for PV in the natural environment (including UV radiation, temperature, humidity, electrical current, and external mechanical force) into a single test that requires fewer modules and fewer chambers. C-AST makes it possible to discover weaknesses in new designs that are not known *a priori*. C-AST reduces risk, accelerates time to market, and improves bankability by avoiding costly overdesign using test levels that do not exceed those seen in the natural environment.

We determined acceleration factors for C-AST using Florida locations as a basis for (1) degradation of the outer layer of the backsheet as a function of temperature and light, (2) degradation of the inner polyethylene terephthalate (PET) layer in the backsheet as a function of temperature and humidity, (3) electrochemical degradation using leakage current as an indicator, and (4) thermomechanical fatigue. For the polymeric degradation modes, we validated the results with three backsheet types (PA, PVDF, and a stabilized PET).

A balance of system component test capability has recently been developed for C-AST, including for cable connectors, branch connectors, and discrete fuse specimen assemblies. Branch connectors known to have failed in the field, now examined in C-AST, show a dependency on the use of mechanical perturbation and electrical current applied through the sample assembly.

Degradation	Acceleration Factor	
	High Desert	Tropical
Temperature/irradiance of outer layer polymeric	10.5	17.3
Temperature/humidity degradation of inner layer PET	*	426
Electrochemical degradation	*	14.1
Thermomechanical fatigue (PbSn solder)	28.6	23.5



(Top) Acceleration factors for four degradation modes in the high-temperature climate sequences of C-AST relative to outdoor locations in Florida (*judged insignificant due to negligible humidity). (Bottom) Comparison of the resistance data through two rounds of C-AST (10 A then 15 A) for six branch connector assemblies. The resistance was affected for both sample sets (static and dynamic, particularly after the second Tropical-a sequence). In the static run, Sample 6 failed (open circuit, burnt fuse cartridge) in the second Tropical-a sequence. In addition to mechanical perturbation ("dynamic," this figure), degradation and failure were observed during the static branch connector assembly experiment at elevated (15 A) current. Environmental effects (corrosion from elevated humidity and water spray) as well as specimen assembly (torque used on end nuts) are also suspected.

LEARN MORE

Hacke, Peter, Akash Kumar, Kent Terwilliger, et al. 2022. "Evaluation of Bifacial Module Technologies With Combined-Accelerated Stress Testing." *Progress in Photovoltaics: Research and Applications*. <https://doi.org/10.1002/pip.3636>.

Hacke, Peter, Michael Owen-Bellini, David C. Miller, et al. 2020. "Establishing Module Durability With Combined-Accelerated Stress Testing." 10th International Conference of Crystalline Silicon Photovoltaics (Silicon PV), virtual. <https://cms2020.siliconpv.com/video/list>.

Miller, David C., Greg Perrin, Kent Terwilliger, et al. 2022. "Development of fixtures and methods to assess the durability of balance of systems components." *IEEE Journal of Photovoltaics*. <https://doi.org/10.1109/jphotov.2022.3205154>.

Disruptive Acceleration Science

Core Objective



KEY RESULT

Spatial Reflectance Mapping Demonstrated for MiMo Samples

PI: David Miller (NREL)

Team Members: Rachael Arnold, Imran Khan, Naila Al Hasan, Joshua Morse, Robert White (NREL)

Summary of Result: Spatial quantification can reveal insights about degraded PV materials and modules that cannot be understood from bulk or single point measurements. To enable spatial characterization, we have created a custom optical mapping instrument that can be used to quantify the transmittance and reflectance of a variety of material, coupon, and mini-module (MiMo) specimens. We demonstrate the mapping capability here—most recently developed for optical reflectance measurements. The instrument uses optical fibers and has a millimeter-scale diameter spot size (rather than a test region greater than 1 cm^2 , as in commercial spectrophotometer instruments) to allow spatial mapping (Figure 1). To fit the instrument, (a) an artificially aged MiMo was diced so that (b) a quadrant could be fitted in the optical mapping instrument for reflectance mapping. Details of the MiMo can be seen in maps (c) and (d), including the cell, ribbon interconnects, and sun-facing backsheet. In Figure 1(e) and (f), details of the gridlines and corrosion of the gridlines could not be resolved in profiles from the maps, in part because of the measurement step size used. A localized delamination (pink ellipse) is confirmed from the 7% rise in reflectance in (d) and (f).

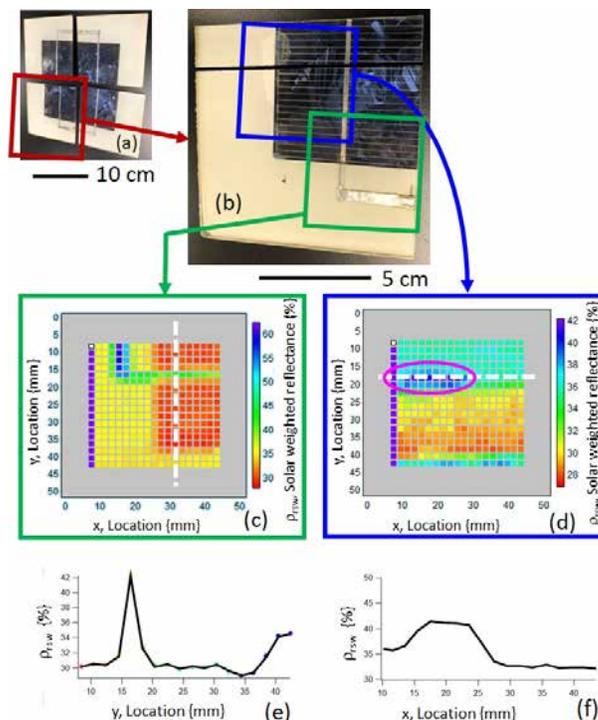


Figure 1. Reflectance maps (representative solar-weighted reflectance, with a step size of 3 millimeters to give a total of 342 pixels) were obtained using the optimal 2,000-millisecond integration time for the average of three separate measurements: photos of the diced specimens are given in (a) and (b), relative to maps of separate regions in (c) and (d), with profiles from the maps in (e) and (f).

LEARN MORE

Khan et. al. 2021. "A Custom High-Throughput Optical Mapping Instrument for Accelerated Stress Testing of PV Module Materials." IEEE J PV 12 (1): 73–80. <https://doi.org/10.1109/JPHOTOV.2021.3122925>.

Khan, Imran S., Joshua Morse, Robert R. White, and David C. Miller. 2021. "A Custom High-Throughput Optical Mapping Instrument (OMI) for Accelerated Stress Testing of PV Module Materials." IEEE PVSC (virtual/Florida). <https://www.nrel.gov/docs/fy21osti/80365.pdf>.

Disruptive Acceleration Science



Core Objective

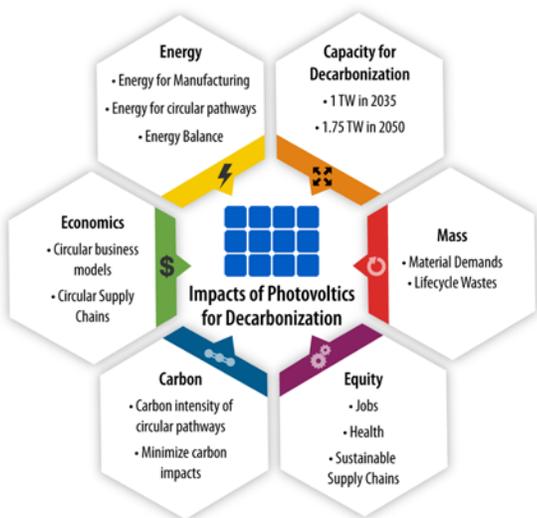
KEY RESULT

Terawatt-Scale Sustainability With PV

PI: Silvana Ovaitt (NREL)

Team Members: Heather Mirletz, Teresa Barnes (NREL)

Summary of Result: As we plan for fast PV deployment to attain decarbonization goals, this study provides a method to gauge sustainability in material and manufacturing choices as well as through the lifetime of PV systems. The “PV in the Circular Economy” (PV ICE) tool was improved through this DuraMAT study to facilitate better understanding of materials choices toward circularity in energy. After evaluating the different decision steps and yields through the lifetime of a PV module, we have found that the best lever for sustainability is to ensure module quality and longevity.



Holistic dimensions to evaluate circular PV for decarbonization.



Metrics of success and quantitative estimates for improvement for the circular economy. The percent improvement (i.e., decrease) in life cycle waste comes from varying the most impactful parameters affecting waste in the PV ICE tool. A decrease (larger bars to the left) in life cycle waste is considered beneficial. The 10% columns indicate in what direction and magnitude the parameter (listed at the left) was varied.

LEARN MORE

For more information, see: <https://www.nrel.gov/pv/pv-ice-tool.html>

Ovaitt et al. 2022. "Terawatt Scale Sustainability with Silicon PV." Proc. Fall MRS Work., invited speaker. <https://www.nrel.gov/docs/fy23osti/84714.pdf>.

PV ICE contributed to the circular economy analysis of PV virgin material needs and wastes in the Solar Futures Study: Jones-Albertus et. al. 2021. "Solar Futures Study." <https://www.energy.gov/sites/default/files/2021-09/Solar%20Futures%20Study.pdf>.

Mirletz et al. 2022. "Circular economy priorities for PV in the energy transition." PLOS ONE. <https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0274351>.

Ovaitt et al. 2022. "PV in the circular economy, a dynamic framework analyzing technology evolution and reliability impacts." iScience. [https://www.cell.com/iscience/pdf/S2589-0042\(21\)01459-0.pdf](https://www.cell.com/iscience/pdf/S2589-0042(21)01459-0.pdf).

Disruptive Acceleration Science

Core Objective



KEY RESULT

A Survey of Emerging Interconnects

PI: Peter Hacke (NREL)

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

Summary of Result: Combined-accelerated stress testing (C-AST) combines stress factors for PV in the natural environment (including UV radiation, temperature, humidity, electrical current, and external mechanical force) into a single test that requires fewer modules and fewer chambers. C-AST makes it possible to discover weaknesses in new designs that are not known *a priori*. C-AST reduces risk, accelerates time to market, and improves bankability by avoiding costly overdesign using test levels that do not exceed those seen in the natural environment.

This project seeks to evaluate the strengths and weaknesses of modern cell interconnect designs using C-AST to screen multiple climates. The project will also use finite element and failure analysis to assess the possibility of a 50-year lifetime. Figure 1 illustrates some of the new interconnect technologies. Toward these, we seek to develop methods of characterization to assess the degradation of interconnects, enable predictive rate models with material forensics and finite element analysis, and show C-AST's ability to find interconnect failures and benchmark durability relative to other accelerated stress test methods, including temperature cycling and cyclic dynamic mechanical loading.

We performed advanced forensics to quantify the geometry and identify the materials used in finite element analysis (see Figure 2). The results for unaged samples will also be compared to accelerated testing, C-AST, and outdoor weathering.

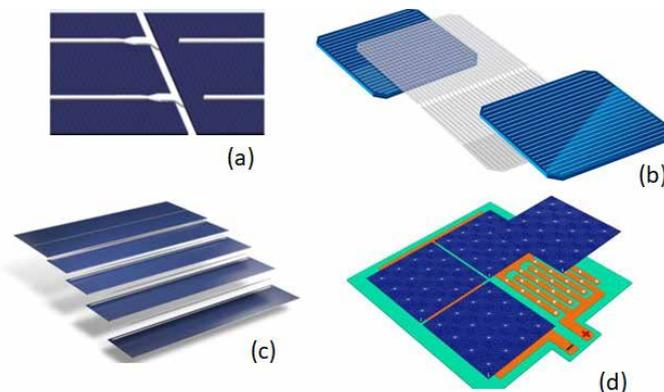
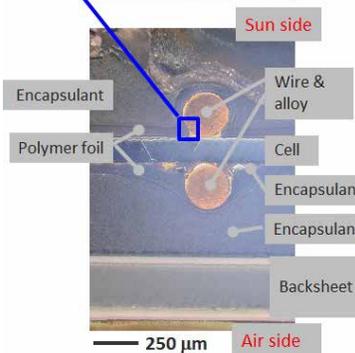


Figure 1. Examples from this project's initial guiding survey of modern interconnect designs, including (a) Canadian Solar Hetero Technology ribbon enabling closer cell interconnections, (b) SmartWire (e.g., Meyer-Burger technology), (c) shingled cells, and (d) interconnects integrated into the backsheet.



Figure 2. Cross-sectional geometry (optical microscope) and composition (electron dispersive spectroscopy (EDS)) of a potted and polished SmartWire-type specimen.



LEARN MORE

Publications will be forthcoming as the project develops.



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 in order to identify opportunities for improved reliability.

Key Results:

- Establishment of a collection of modern PV modules—selected for technological interest and commercial relevancy—to study material degradation and to develop and validate nondestructive field forensics methodologies.
- Pre-cracked modules generally showed greater outdoor power loss than the mean power loss observed in uncracked modules of the same type; however, in a separate set of modules, the opposite was observed, suggesting that further study is needed.
- PLatypus, a newly developed, low-cost, high-resolution nighttime photoluminescence system that can scan a PV power plant for cracks without manipulating any electrical connections in the plant, spending only a few seconds on each module.
- Direct imaging of cell stress using X-ray topography and water reflectometry detection. These nondestructive methods monitor the presence and evolution of deflection and moisture in modules *ex situ* and *in situ* to quantify the impact of loading on cell reliability.
- Quantification of the potential increase in reliability for glass/glass module construction through chemical, structural, and mechanical insights to enable cutting-edge understanding of the degradation processes at the material interfaces in these modules.
- Continued efforts to validate accelerated test protocols against field failures using a combination of characterization methods.
- Lab analysis and characterization to provide feedback on PV materials and components, including backsheets, cells, encapsulants, glass, gridlines, interconnects, and solder bonds.

Fielded Module Forensics

Core Objective



KEY RESULT

Fielded Module Library Completes Final Year

PI: Bruce King (Sandia)

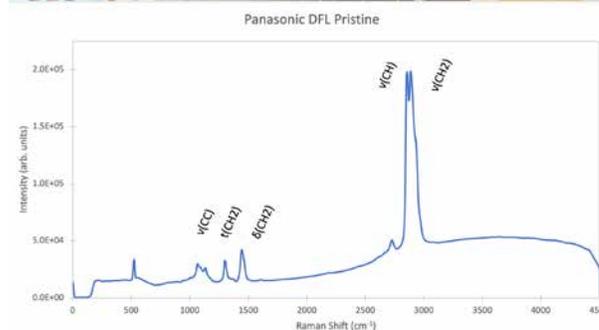
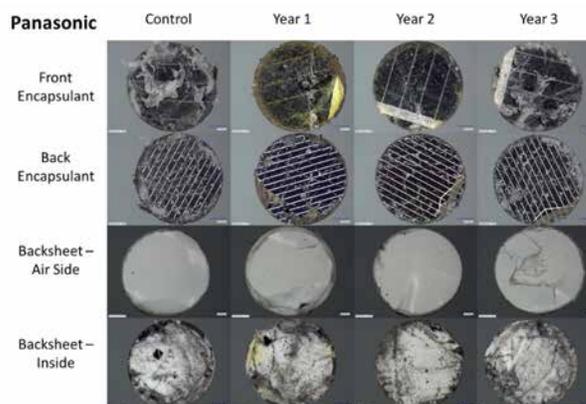
Team Members: Elizabeth Palmiotti and William Snyder (Sandia)

Past Contributors: Ashley Maes, Joshua Stein, Karen Yang (Sandia); Laura Schelhas (SLAC); Todd Karin (LBNL)

Summary of Result: The DuraMAT Fielded Module Library established a collection of modern PV modules—selected for technological interest and commercial relevancy—to study material degradation and to develop and validate nondestructive field forensics methodologies. At the beginning of the project, modules from seven different manufacturers were installed in the field alongside larger, grid-tied arrays of the same type. All modules were characterized annually using nondestructive methods, while one module of each type was removed for destructive characterization. One unaged module of each type was characterized to establish a baseline, while a pristine spare was retained as a future reference.

At the end of FY22, six arrays had been fielded for 42 months and a seventh had been fielded for 30 months. Year-over-year characterization data include nondestructive electrical performance, electroluminescence imaging, backsheet yellowing, and gloss measurements. Differential scanning calorimetry (DSC) and Fourier transform infrared spectroscopy (FTIR) inspection were completed on encapsulant and backsheet samples extracted from core samples. These arrays were also used to develop or validate multiple field forensics methods, including field Raman inspection of front encapsulants, anti-reflective coating imaging, near-IR inspection of backsheets, and FTIR spectrum classification. Seven modules of each type remain actively installed in the field and available for future study.

Manufacturer	Model	Cell Type	Backsheet
Canadian Solar	CS6K-300MS Quintech	Mono-Si	PVDF
Hanwha Q Cells	Q.Peak-G4.1 300	Mono-Si	PET
Itek	360 SE	Mono P-type	PET
JinkoSolar	JKM270PP-60	Multi-Si	TPT
LG	LG320N1K-A5	Mono (N)	PET
Mission Solar	MSE300SQ5T	Mono PERC	PET
Panasonic	VBHN330SA17 HIT	HIT N-type	PET



(Top) Core samples are extracted as a complete material stack using a modified CNC table and a diamond core drill. Samples are carefully split by hand to expose individual material layers and perform further benchtop characterization, such as DSC and FTIR.

(Middle and bottom) A fieldable Raman system has been developed using modules from this project. The system is designed to probe through the module cover glass to characterize polymer encapsulant in the field without damaging the module.

LEARN MORE

To learn more, contact Bruce King (bhking@sandia.gov).

Fielded Module Forensics

Core Objective



KEY RESULT

Cracking the Code: Modules With Cracked Cells Show More Power Loss When Aged Outdoors

PI: Cara Libby (Electric Power Research Institute)

Team Members: Michael Deceglie, Timothy Silverman, Nick Bosco, Michael Owen-Bellini, Ethan Young, Xin He, Elizabeth Bernhardt, Peter Hacke, Bill Sekulic, Greg Perrin, Byron McDanold (NREL); Anubhav Jain, Xin Chen (LBNL); Will Hobbs (Southern Company); Daniel Fregosi, Vathsavi Venkat (Electric Power Research Institute)

Summary of Result: Wind and other routine environmental stressors can turn benign PV cell cracks into harmful cracks linked to degradation and safety issues. Today, it is not possible to predict crack aging, and subsequent power loss, based on crack characteristics. Through physical testing, modeling, and computer vision, we are developing methods to predict long-term power loss from nascent cracks.

Four sets of four multi-crystalline silicon modules of different types were deployed outdoors for ~2 years (Figure 1). Two modules from each set were subjected to an “installer drop” designed to crack approximately one-third of the cells. Modules were characterized using current-voltage measurements (Figure 2) and temperature-dependent electroluminescence (EL) imaging (one full thermal cycle: -15°C to 65°C to -15°C) upon arrival and at interim steps. EL images before and after outdoor exposure (Figure 3) show increased electrical isolation of cell fragments in cracked cells, likely due to weathering of grid lines. For three module types, the cracked modules had greater outdoor power loss than the mean power loss observed in uncracked modules of the same type (positive red numbers). The opposite was observed in the fourth set of cracked modules (negative red numbers). Next, crack features will be quantified and correlated with module in-field performance and accelerated test results.



Figure 1. NREL outdoor test bed in Golden, Colorado, where cracked and uncracked PV modules from four manufacturers were aged outdoors.

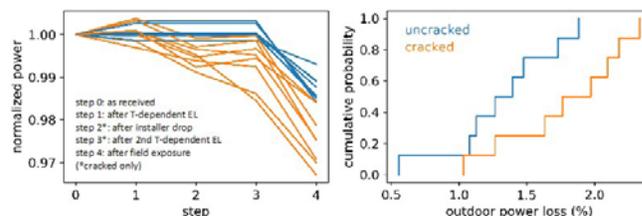


Figure 2. (Left) Difference in uncracked vs. cracked module power loss at different steps in the experiment; (right) cumulative distribution function of power loss during ~2 years of outdoor exposure..

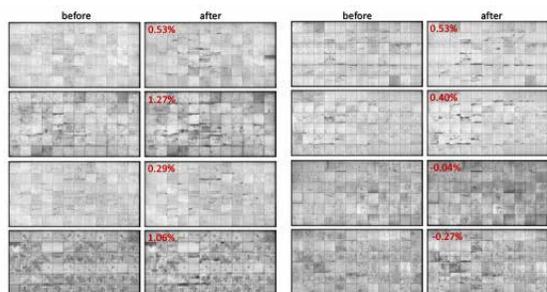


Figure 3. Composite EL images of cracked modules before and after outdoor exposure, calculated using the minimum relative intensity for each pixel observed over a temperature-dependent EL cycle from -15°C to 60°C .

LEARN MORE

Silverman, T. J., N. Bosco, M. Owen-Bellini, C. Libby, and M. G. Deceglie. 2022. “Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells.” *IEEE Journal of Photovoltaics* 12 (4): 1090–1093. doi: 10.1109/JPHOTOV.2022.3177139.

2022. “Effect of Cell Cracks on Module Power Loss and Degradation.” Presented at the DuraMAT Fall Workshop, Aug. 29–31, 2022.

Project webpage: <https://www.duramat.org/cell-crack-power-loss.html>

Video: “NREL Breaks Solar Panels,” <https://www.youtube.com/watch?v=aK8Sw8iMGMI>

Fielded Module Forensics

Core Objective



KEY RESULT

Linking Polymer Properties to Outdoor/ Indoor Aging in Bifacial Module Designs

PI: Dana Kern (NREL)

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

Summary of Result: Two ways to increase PV power generation per area are: (1) bifacial PV, which can generate 10%–30% higher power compared to monofacial PV, and (2) half-cell modules, which decrease cell-to-module losses by lessening resistive power dissipation (i.e., less heating). Although deployment of both technologies is rapidly growing, there is a lag in fundamental understanding of the new module packaging requirements and degradation processes. Here, we combine accelerated stress testing, spatially resolved imaging analysis, outdoor characterization, and microscopy/chemical failure analysis to understand the module packaging materials' degradation mechanisms specific to these emerging module designs.

Figure 1 shows our experimental process, which compares the durability of mini-modules deployed outdoors to those that undergo accelerated stress testing. The stress test is modified from International Electrotechnical Commission (IEC) 63209-2 to target an understanding of package susceptibility to delamination. A test run of the procedure demonstrated the ability to expose processing concerns in a set of mini-modules comparing glass/glass to glass/backsheet designs. After nondestructive analysis via current-voltage curves and imaging, we assessed the material properties using destructive tests. Figure 1 highlights the Fourier-transform infrared spectroscopy (FTIR) and differential scanning calorimetry (DSC) polymer testing used to identify the functional groups and thermo-mechanical properties of the encapsulants. Baseline studies highlight the differences between the encapsulants (EVA, POE, and EPE), which will be further compared to post-stress modules.

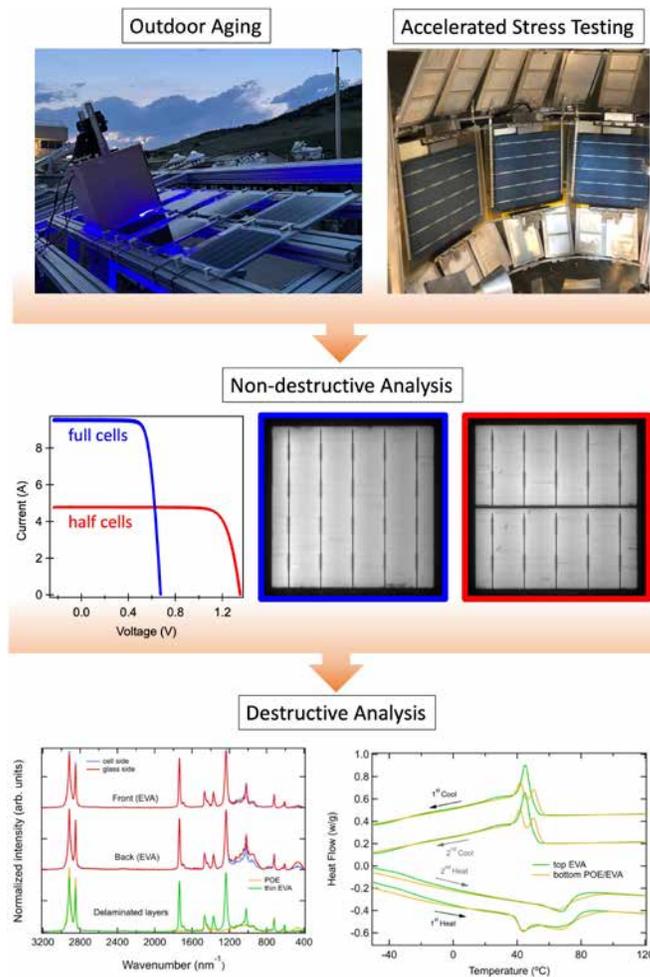


Figure 1. This project's experimental process to assess the delamination susceptibility of glass/glass module packaging with full-cell or half-cell designs, including outdoor aging and accelerated stress testing followed by nondestructive and destructive analysis.

LEARN MORE

For more information, please contact Dana Kern (dana.kern@nrel.gov).

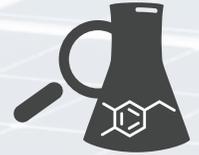
"Glass/Glass Photovoltaic Module Reliability and Degradation: A Review." Journal of Physics D. (2021).

"Electrochemical Degradation Modes in Bifacial Silicon Photovoltaic Modules." Progress in Photovoltaics: Research and Applications. (2022).

"Chemical and Mechanical Interfacial Degradation in Bifacial Glass/Glass and Glass/Transparent Backsheet Photovoltaic Modules." Progress in Photovoltaics: Research and Applications. (2022).

Fielded Module Forensics

Core Objective



KEY RESULT

PLatypus Detects Cracked Cells in Seconds Without an Electrical Connection

PI: Timothy Silverman (NREL)

Team Members: Nicole Luna (NREL); Will Hobbs (Southern Company); Kelsey Horowitz (Applied Energy Services)

Summary of Result: PV system cracks can start out benign—and invisible—and later lead to power loss or safety failures. Early detection would help PV system owners prepare for these changes. Detecting cracks usually requires cumbersome, expensive, or low-resolution electroluminescence (EL) technology. EL 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 are building a low-cost, very-high-resolution nighttime photoluminescence (PL) system called PLatypus that can detect cracked cells in a module without making any electrical connection to it. The system 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 (LEDs) to be mounted between cameras, exciting PL in the module without making any electrical connection to it.

PLatypus will be able to scan a PV power plant for cracks without manipulating any electrical connections in the plant and spending a only few seconds on each module. The project is still underway, but a field demonstration of the first prototype is coming soon.



PLatypus is a multi-camera PL imager with no electrical connections to the PV module. It has a planar array of cameras (~100 megapixels) and a powerful LED array. It requires no tripod, crane, or drone. It has a modular design that rolls along module frames.



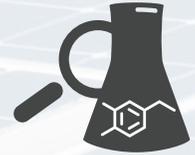
PL image results: A PL image from a two-camera subset of PLatypus clearly shows cracked cells in a module that has no external electrical connection.

LEARN MORE

PLatypus is a small DuraMAT Spark project. At its conclusion, you will find design documentation, videos, and test campaign results linked in the final report.

Fielded Module Forensics

Core Objective



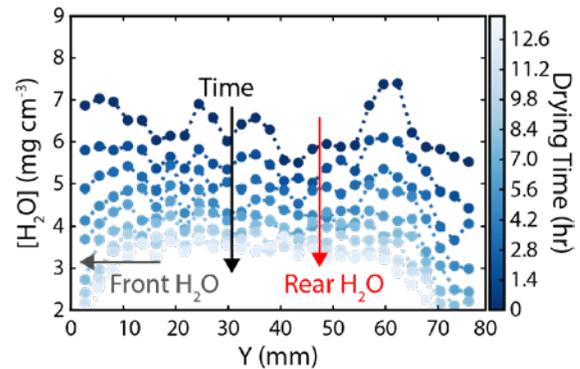
KEY RESULT

In Situ Monitoring of Moisture Diffusion and Deflection in Crystalline Silicon Modules

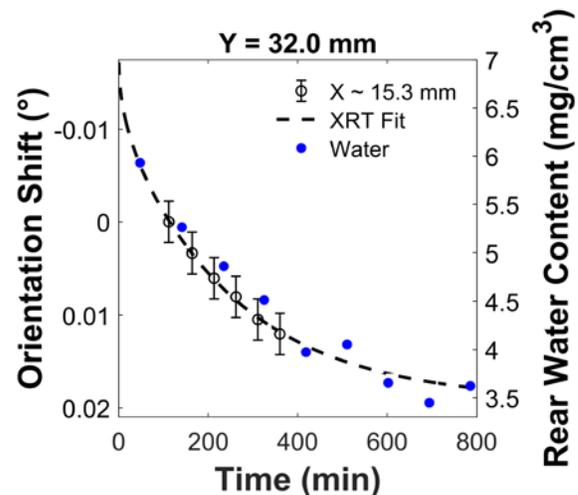
PI: Mariana Bertoni (Arizona State University)

Team Members: Ian Slauch, Hir Gandhi, Rico Meier (Arizona State University); Farhan Rahman, James Hartley (Sandia); Rishi Kumar, Tala Sidawi, David Fenning (University of California San Diego); Jared Tracy, Kaushik Roy Choudhury (DuPont)

Summary of Result: Module lamination imparts residual stresses onto the cell that persist during operation and contribute to power degradation. We aim to understand the impacts that module architecture, bill of materials, material properties, and conditioning have on these stresses in order to reduce degradation rates. We used X-ray topography (XRT) to image the cell deflection and stress *in situ* for modules with conventional four-busbar and nine-busbar multi-wire half-cell tabbing configurations while controlling temperature. Collaborators at the University of California San Diego measured encapsulant water concentration *in situ* with water reflectometric detection (WaRD), a noncontact optical technique, at conditions up to 85°C and 85% relative humidity. They have developed a model to predict the spatial distribution of water in module encapsulants depending on external conditions and can distinguish between water in front and rear layers. Collaborators at Sandia have worked to characterize the viscoelastic and hygroscopic properties of ethylene vinyl acetate (EVA) and incorporate them into finite element analyses of lamination conditions to further understand residual stresses. Through a combination of WaRD and XRT, we have shown that hygroscopic strain in module encapsulants exposed to water causes deflection of the cell, demonstrating a mechanical impact that can exacerbate existing stresses and accelerate degradation.



Time evolution of module water concentration across a half-cell during drying after saturation at 85°C and 85% relative humidity. Diffusion of front and rear water is indicated by arrows.



Comparison of cell orientation shift at one location determined via XRT and rear encapsulant water concentration determined via WaRD as the nine-busbar half-cell module dries from saturation at 85°C.

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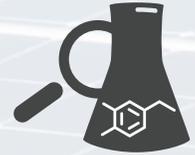
Sidawi, T. et al. "Moisture Ingress and Distribution in Bifacial Silicon Photovoltaics with Model Validation and Simulation." IEEE J. Photovolt. Forthcoming.

Slauch, M. et al. "In-Situ Determination of Moisture- and Temperature-Driven Deflection of an Encapsulated Si Photovoltaic Cell." Sol. Energy Mater. Sol. Cells. Forthcoming.

Kumar, R., G. von Gastrow, N. Theut, A. M. Jeffries, M. I. Bertoni, and D. P. Fenning. 2020. "Quantitative Moisture Mapping to Determine Local Impacts on Module Durability." 2020 47th IEEE Photovoltaic Specialists Conference (PVSC), pp. 1846–1849.

Fielded Module Forensics

Core Objective



KEY RESULT

Does Accelerated Testing Correlate With Solar Module Field Performance?

PI: Teresa Barnes (NREL)

Team Members: Joe Karas, Dirk Jordan, Mike Kempe (NREL); Jenya Meydbray, Max Macpherson (PV Evolution Labs); Mason Reed, Jim Rand (Core Energy Works); Robert Flottemesch (Luminance)

Summary of Result: A key question in solar PV module reliability is whether or not accelerated testing can predict or provide guidance for degradation that is later observed in the field. In this project, we undertook several investigations of field-observed degradation in different PV modules where we could compare the modules to accelerated testing results. In several of these investigations, we were able to identify where changes were made to the bill of materials (BOM) between the modules that were tested and those that were fielded. These changes, under the right climatic conditions, drove significant degradation.

An example is shown in Figure 1. Modules that passed accelerated testing were deployed for 10 years in the field in different climates. At one site, we observed corrosion-like degradation related to a change in the chemical composition of the metal paste; the other site did not exhibit the same degradation. After retrieving samples from both sites and subjecting them to damp heat testing, we determined that all the modules contained the BOM change that made them susceptible to the corrosion. This particular project emphasizes the need to retest any BOM changes, and highlights the way degradation modes can be climate-dependent as well as BOM-dependent.

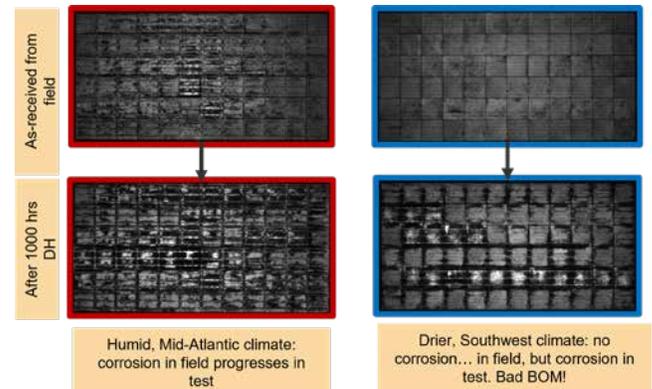


Figure 1. Electroluminescence images of modules from the same manufacturer and of the same vintage retrieved from the field (top row) from a site in the Mid-Atlantic (left) and the Southwest (right). Bottom row: Damp heat testing confirms that the Southwest modules were susceptible.

LEARN MORE

Karas, J., D. Jordan, T. Barnes, J. Meydbray, R. Flottemesch, J. Rand, M. McPherson, M. Reed, and M. Kempe. "Understanding Trends in Failure Modes of Photovoltaic Modules and Materials." DuraMAT Fall Workshop 2022, Breckenridge, CO. (Poster presentation).



Module Material Solutions

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

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

Key Results:

- De-risking of innovative materials using accelerated testing and materials forensics:
 - SLAC-led research has developed a scalable spray plasma process to deposit moisture barrier coatings with controlled organic content, adhesion, thickness, density, and antireflective properties, along with techniques for measuring their moisture vapor transmission rate, for low-cost, lightweight module encapsulation.
 - Osazda Energy achieved close to a 600% increase in fracture toughness against the “fatigue-like” failure mode for front surface metallization, along with electrical gap bridging for gridline cracks >60 um and “self-healing” to regain electrical continuity at a gap width of approximately 30 mm after repeated cycles of large open gap and gap closure.
- Enabling of new architectures:
 - Flexible modules: Accumulated 1000+ hours of photothermal, thermal, and water soak exposure for combinations of encapsulant and backsheets materials. Analysis is in progress, along with investigations of additional materials for layers to mitigate hail damage risk.
 - Artificial aging of backsheets to invoke field degradation modes has shown that surface and bulk degradation are not always clearly connected, indicating that more sophisticated aging procedures may be needed.



KEY RESULT

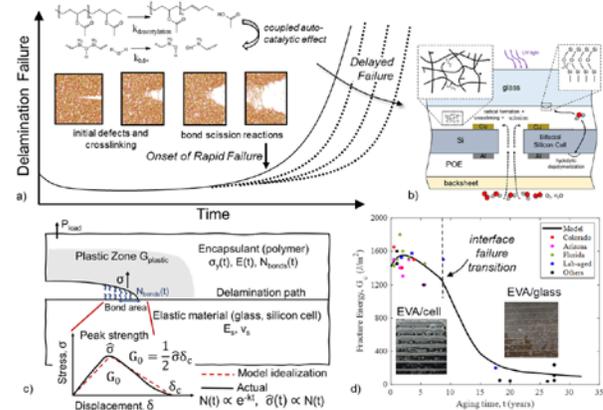
Predictive Model for Encapsulant Delamination and Plasma Deposition of Low Water Vapor Transmission Rate (WVTR) Moisture Barrier in Open Air Characterized With Calibrated Infrared Imaging

PI: Reinhold Dauskardt (Stanford University)

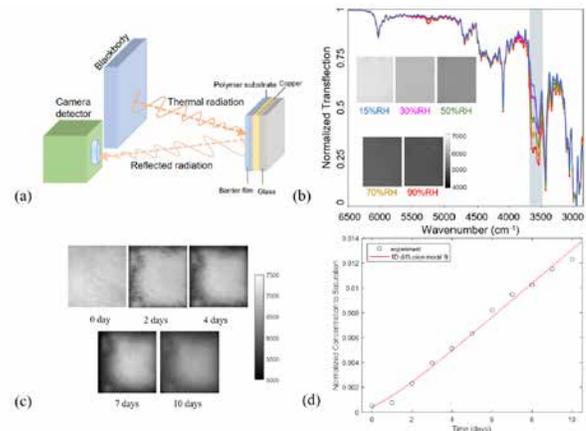
Team Members: Ziyi Pan, Alan Liu, Patrick Thornton (Stanford University); Laura Schelhas (SLAC National Laboratory); Mihail Bora (Lawrence Livermore National Laboratory); Jared Tracy, Kaushik Roy Choudhury (DuPont); Paul Roraff (SolarTech Universal)

Summary of Result: We addressed two major challenges for the long-term reliability of bifacial solar modules. In Thrust 1, we investigated the adhesive degradation mechanisms in bifacial modules using our advanced module materials and interface reliability characterization and modeling capabilities. In this thrust, we developed a new predictive model with added fundamental capabilities (degradation chemical kinetics, fracture mechanical methods) that showed marked improvement over the previous models. In Thrust 2, we developed and validated a highly transparent moisture protective coating system and evaluated it with a newly developed infrared imaging methodology. We developed multi-layer barrier films with our open-air spary-plasma system for improved moisture barrier properties; additionally, we developed an infrared imaging system to evaluate moisture barrier functionality.

We have developed a multi-scale predictive model that comprehensively quantifies adhesion after accelerated exposure to various field relevant conditions; we have also successfully demonstrated deposition of a multi-layer thin-film plasma-deposited barrier with a water vapor transmission rate of $8 \times 10^{-4} \text{ g/m}^2/\text{day}$ and confirmed the results measured by the infrared imaging system.



Wear-out failures in modules are determined by (a) the accumulation of damage and (b) degradation in different locations related to multiple stressors that are exacerbated in different locations. (c) Our reaction-rate-based reliability model incorporates detailed degradation kinetics, and fracture mechanics calculations accurately predict (d) the combined effects of multiple reactions on properties.



(a) Schematic of instrument setup. (b) Normalized FTIR transfection spectra from IR passage through the substrate. The highlighted wavelengths correspond to the water absorption band. The inset shows sample images indicating increased image intensity due to water absorption. (c) Infrared images of samples were acquired after exposure to the same aging condition. (d) The amount of water in the polymer substrate measured by the infrared imaging systems.

LEARN MORE

More information about this work can be found here:
<https://www.duramat.org/module-encapsulation-barrier.html>
<https://dauskardt.stanford.edu/research-overview/solar-reliability>
<https://dauskardt.stanford.edu/research/functional-and-transparent-coatings>

“Dependence of Adhesion on Degradation Mechanisms of Ethylene Co-Vinyl Acetate Encapsulants over the Lifetime of Photovoltaic Modules.” Solar Energy Materials and Solar Cells (2022).

“The Natural and Accelerated Evolution of EVA Adhesion Through Intermediate Exposures.” IEEE Journal of Photovoltaics. (2022).

Module Materials Solutions

Core Objective



KEY RESULT

BACKFLIP: Determination of Backsheet Material Properties: A Comparison of Market-Benchmark Technologies to Novel Non-Fluoro-Based Co-Extruded Backsheet Materials and Their Correlation and Impact on PV Module Degradation Rates

PIs: Peter Pasmans, Christopher Thellen (Endurans)

Team Members: Rachael Arnold, Soňa Uličná, Jimmy Newkirk, Kent Terwilliger, Naila Al Hasan, Emily Rago, Laura Schelhas, David Miller (NREL); Bruce King (Sandia)

Summary of Result: As the PV industry has rapidly expanded worldwide, there has been a growing interest in increasing the lifespan and reliability of PV modules. Recent concern has also emerged regarding module component materials and their recyclability, including fluoropolymer-based backsheets. This study examines seven backsheets, including traditional and emerging backsheets, subjecting them to accelerated or natural aging. Backsheets examined in the study include more recyclable thermoplastic materials. In Figure 1, the mechanical tensile performance (a proxy for KIC, the fracture toughness) is compared to the electrical insulation for all the backsheets subject to the seven steady-state accelerated test conditions. The BACKFLIP project compared the performance and durability of the backsheets through accelerated testing (including damp heat and IEC TS 62788-7-2) as well as natural weathering. Characterizations included discoloration (b*), gloss, macro- and micro-morphology, MiMo I-V performance, EL characteristics, mechanical tensile characteristics, DC breakdown voltage, differential scanning calorimetry (DSC), crystalline structure (wide angle X-ray scattering, or WAXS), and polymer chemical structure (FTIR). For some backsheets and characteristics,

the activation energy of degradation was determined to allow for future rate modeling. Recommendations regarding aging, characterization, and the backsheet material families are provided based on the study.

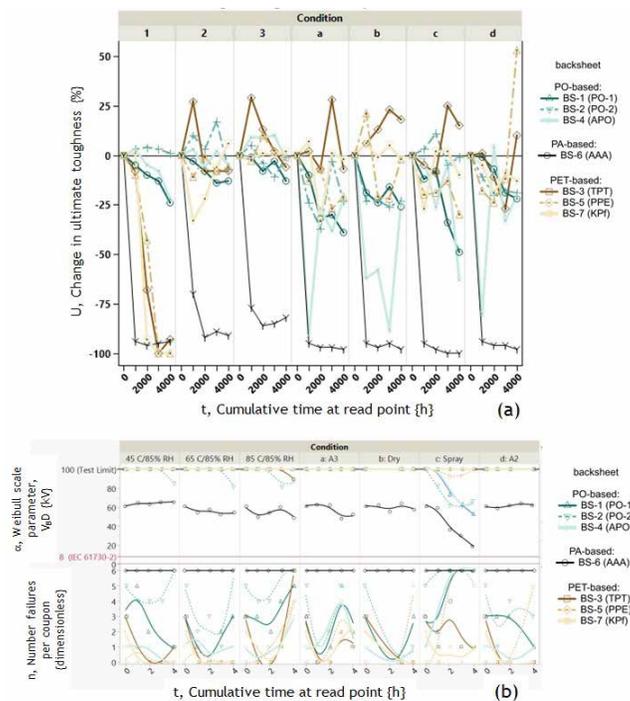


Figure 1. The (a) ultimate mechanical toughness is compared to the (b) direct current breakdown voltage, which could be measured up to 100 kV. Highlights include: the ubiquitous mechanical degradation of BS-6 (AAA) that did not affect electrical insulation (sequential aging is now recommended); the additional mechanical and electrical degradation from test c (water spray) of questionable validity (overaccelerated test); the spurious loss of toughness for PET-based backsheets in test 1 (damp heat, shown in BACKFLIP to be overaccelerated); and the electrical degradation of BS-2 in tests 1, 2, and 3 (hygrometric aging) that was also observed in outdoor aging (Cocoa, Florida; not shown).

LEARN MORE

Thuis et. al. 2021. "A Comparison of Emerging Nonfluoropolymer-Based Coextruded PV Backsheets to Industry-Benchmark Technologies." IEEE J PV 12(1): 88–96. <https://doi.org/10.1109/JPHOTOV.2021.3117915>.

Uličná et. al. 2021. "BACKFLIP: Identification of Materials and Changes Upon Aging of Emerging Fluoropolymer-Free and

Industry-Benchmark PV Backsheets." Proc. IEEE PVSC, 1842–1847. <https://doi.org/doi:10.1109/PVSC43889.2021.9518781>.

Al Hasan et. al. 2022. "BACKFLIP: A Comparison of Emerging Non-Fluoropolymer-Based, Co-Extruded PV Backsheets to Industry-Benchmark Technologies." DuraMAT webinar, 2022/1/10, NREL/PR-5K00-81880, 1–21. <https://www.nrel.gov/docs/fy22osti/81880.pdf>.

Module Materials Solutions

Core Objective



KEY RESULT

Advanced Material Development To Support Flexible, Low-LCOE, 25-Year PV Modules

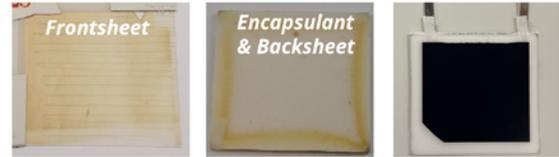
PI: Hoi Ng (SunPower Corporation/Maxeon Americas Inc.)

Team Members: Namrata Salunke (Maxeon Americas Inc.); Michael Kempe and Peter Hacke (NREL)

Summary of Result: Residential and commercial PV systems are challenged by relatively small job sizes and complicated balance of systems (BOS), which result in high overhead and labor costs. Lightweight, flexible modules that can be attached directly to a roof are advantageous for installation on buildings with weight limitations, curved surfaces, and mobile and portable applications. Traditional packaging designs used in PV are not developed toward this mission profile of lightweight, direct-attached PV modules that offer mechanical protection from hail/handling, water-ponding, etc., while remaining as low-cost and long-lived as possible. In this project, we worked to engineer, evaluate, and develop module material stacks to enable efficient, lightweight, low-cost, 25-year crystalline silicon modules. This was achieved by testing a wide variety of frontsheets, encapsulants, and backsheets that are both conventional and unconventional to PV; screening promising BOMs that underwent accelerated aging tests; and building their material lifetime models. Not only will the material recommendations coming out of this program be useful for the development of commercial flexible PV products, but also, the test methodology will serve as a guideline for PV module material testing and qualification for new applications or new mission profiles.

Accelerated aging: How do polymers degrade?

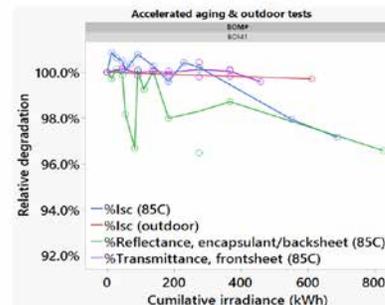
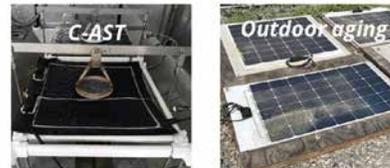
What is the BOM lifetime?



	BOM construction	Lifetime (years to 2% Pmp loss)	
		Phoenix	Denver
		BOM 1	ETFE cPOE wPOE FR epoxy
BOM 4	fPET cPOE wPOE FR polyester	18.32	43.35
BOM 9	fPET cPOE cPOE PET	19.21	43.08
BOM 8	fPET cPOE wEVA PC	15.09	36.22
BOM 6	fPET cPOE wEVA FR polyester	9.58	24.65
BOM 2	fPET cPOE cHM FR epoxy	3.96	8.68
BOM 5	fPET cPOE cPOE FR polyester	2.87	4.73

Frontsheets, material stacks, and mini-modules underwent photothermal aging. This was used to build material degradation models to predict their lifetimes (table).

What is the field performance?



Accelerated aging tests were compared to C-AST and outdoor aging tests (graph).

LEARN MORE

A detailed technical report published at the end of this program and various technical posters will be available through DuraMAT.

DuraMAT monthly webinar, January 2022: "Updates From 'Advanced Material Development To Support Low-LCOE 25-Year Flexible Photovoltaic Modules,'" presented by Hoi Ng, SunPower, <https://www.duramat.org/webinars.html>

Module Materials Solutions

Core Objective



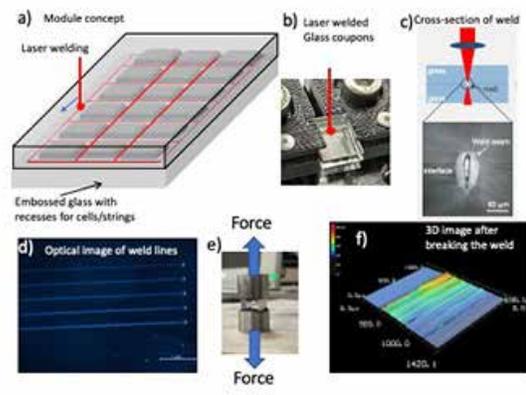
KEY RESULT

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

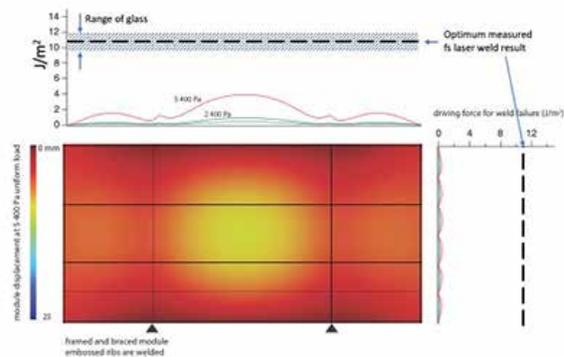
PI: David Young (NREL)

Team Members: Nick Bosco and 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, hermetic 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 that allowed a full area module (1 m x 2 m) simulation under static load (5,400 Pa). The tests showed that under optimum conditions, the laser welds were nearly as strong as 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 over two.



(a) 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 post 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. Simulated displacement heat map is of full area glass/glass module laser welded along thin black lines under uniform static load test of 5,400 Pa. The model shows that the module passes the IEC static load test.

LEARN MORE

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



DuraMAT Early-Career Scientists (DECS)

The DuraMAT Early-Career Scientists (DECS) program enables early-career scientists and postdoctoral researchers to engage in collaborative research and leadership among the DuraMAT member laboratories. Through DECS, members can develop skills that will prepare them for careers in the PV industry, academia, or national laboratories. DECS hosts meetings the third Monday of every month. Meeting topics range from discussions with established PV professionals and presentations about module technologies to developing proposal writing skills. DECS members are looking forward to practicing these skills and working across DuraMAT member laboratories to develop and propose novel work.

DECS participants have continued to represent DuraMAT at both domestic and international conferences, including the European Photovoltaic Solar Energy Conference and Exhibition, IEEE Photovoltaics Specialist Conference, NREL PV Reliability Workshop, and more. They also contribute to the organization and smooth operation of these conferences by chairing sessions, judging posters, and monitoring panels. Additionally, various members of DECS have published a number of journal papers in the last year.

DECS Leadership:

Soňa Uličná, Sona.Ulicna@nrel.gov

DuraMAT Workshop



We got the “band” back together again this year! We held our first in-person workshop Aug. 29–31, 2022, in Breckenridge, Colorado. Everyone agreed that the Colorado mountains are much more conducive to collaboration than calling in from our basements. We had about 55 people in person and 10 who called in for the hybrid meeting. As much as we love meeting in person, DuraMAT plans to keep this hybrid format for those times that people just can’t travel. Returning to mostly in-person attendance allowed us to return to our day-and-a-half workshop format with the afternoon of the second day reserved for extended discussions with our industry advisory board (IAB) members. We also went for some great hikes, bike rides, and meals.

Teresa Barnes, DuraMAT director, kicked off the workshop with a summary of our research results from DuraMAT 1 and our goals for DuraMAT 2. We spent the first day discussing highlights from each core objective area, including a summary from the core objective leaders and then a more detailed presentation from one or two projects in each core objective area. Every active project also presented a poster. As usual, the DuraMAT IAB and researchers provided detailed feedback on each project and contributed to the organic collaborations, sample exchanges, technical support, and data sharing that are essential to our work.

The second day of the workshop had a slightly different format, starting with two keynote presentations on predictive modeling and sustainability in PV manufacturing. A panel and several breakout sessions followed, where we discussed how we should move forward in an

environment that is changing so rapidly around us. The industry panel discussed what DuraMAT can do to accelerate manufacturing, deployment, and decarbonization. We then switched gears to talk about how we can move from field observations of degradation to predictive capabilities that can quantify the probability of failure. These themes continued in breakout sessions on sustainability, safety/performance risk, and predictive reliability in rapidly evolving technologies.

The in-person format allowed for much more detailed and thorough discussions between our researchers and IAB members. After lunch, DuraMAT leadership reconvened with the IAB for two hours to discuss the big takeaways, emerging gaps, and opportunities that came up during the workshop. We identified three research areas that will help us take field performance and laboratory testing data and combine it with computational models to move toward comparative and quantitative risk assessments. The first is developing scaling relationships to understand how our lab-scale results translate to rapidly changing (and growing) module designs. The second is building our understanding of multi-step and multi-stress degradation mechanisms, which can then be validated against field and accelerated testing data. The third is developing multi-modal data analytics techniques to extract the knowledge we need more quickly from field performance and laboratory data. Combining these with well-validated computational models will enable us to answer critical questions about damage propagation: *Will it get worse? Should I replace it?*

Publication and Research Output

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

JOURNAL ARTICLES

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Publication and Research Output

19. 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 (June): 111017. [10.1016/j.solmat.2021.111017](https://doi.org/10.1016/j.solmat.2021.111017).
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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 five 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 239 registered users working on 86 projects that encompass 9,684 files (a 59% increase from last year). Public data sets range from soiling maps to PV orientation machine learning training sets. The Data Hub provides a central place for researchers to archive, search, and obtain experimental and reference data, analysis tools, tutorials, and reports.

For more information, contact robert.white@nrel.gov.

PVAnalytics

A research team from Sandia and NREL has launched PVAnalytics, the first collaborative public software library for organizing and distributing reusable code for data preparation: <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.

For more information, 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 on 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.

For more information, contact jkyuan@sandia.gov.

High-Throughput Optical Mapping Tool

Spatial quantification can reveal insights about degraded PV materials and modules that are not apparent from bulk or single-point measurements. The team at NREL has created a custom optical mapping instrument that can be used to quantify the transmittance and reflectance of a variety of material, coupon, and miniature module specimens.

For more information, contact david.miller@nrel.gov.

Combined-Accelerated Stress Testing (C-AST)

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

For more information, contact peter.hacke@nrel.gov.

Fielded Module Study

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

For more information, contact: bhking@sandia.gov.

Data, Tools, and Capabilities

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

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; detect defects such as cracks and solder failures; and extrapolate the maximum power loss area. Hundreds of thousands of images can be analyzed rapidly and without human input. A code repository is available at <https://github.com/hackingmaterials/pv-vision>.

For more information, 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 website can be found at <https://pvtools.lbl.gov>.

For more information, contact: ajain@lbl.gov.

PVPRO: Extracting Module Characteristics From Performance Data

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. Power degradation trends can then be deconstructed into individual parameter degradation, such as series resistance increase or shunt resistance decrease. A code repository is available at <https://github.com/DuraMAT/pvpro>.

For more information, 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 levelized cost of energy. The online tool can be found at <https://pvlcoe.nrel.gov>.

For more information, contact: brittany.smith@nrel.gov.

WhatsCracking, the PV Module Cell Fracture Prediction App

A new app—WhatsCracking—can accurately predict cell fracture in crystalline silicon PV modules. The app is based on a structural mechanics model that calculates the probability of cell fracture using a Weibull distribution for cell strength and user inputs for module design and loading. It will be available on the DuraMAT datahub at <https://datahub.duramat.org/dataset/whatscracking-application>.

For more information, contact: nick.bosco@nrel.gov

FY 2022

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

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