Durable Module Materials (DuraMAT) Consortium Final Technical Report

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1 National Renewable Energy Laboratory
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3 Lawrence Berkeley National Laboratory

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Technical Report
NREL/TP-5K00-85569
March 2023

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NOTICE

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Final Technical Report (FTR)

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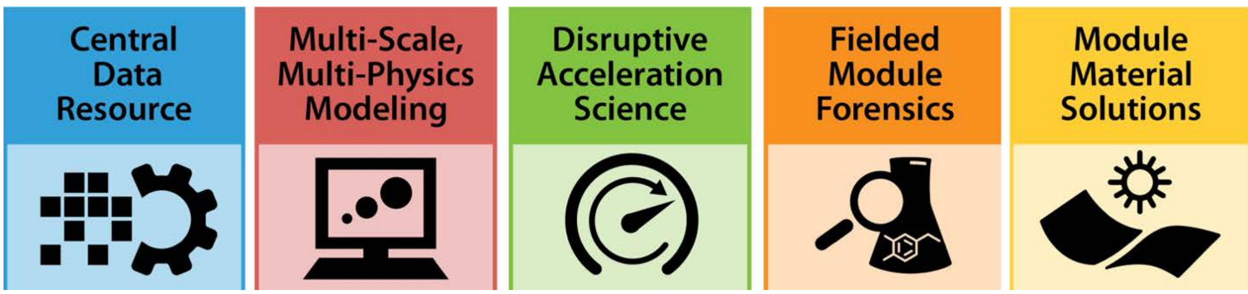
Executive Summary

The DuraMAT Consortium brings together DOE national lab and university research capabilities with the photovoltaic (PV) and supply-chain industries to accelerate a sustainable, just, and equitable transition to zero carbon electricity generation by 2035 through our five core objectives:

- development of a central data resource for PV modules
- multi-scale and multi-physics modeling
- disruptive acceleration science
- forensic tools for fielded modules
- materials solutions for more durable, reliable, and resilient modules.



DuraMAT leverages the decades of experience, expertise, and world-class facilities at the national laboratories to create a "one-stop-shop" for timely solutions to critical barriers limiting module reliability and durability. ***In its first five years, DuraMAT has become a trusted partner for the US industry.***

The core objectives have been defined in partnership with DuraMAT's Industry Advisory Board (IAB) and are long term research objectives that are expected to continue throughout the duration of the DuraMAT program. Selection and funding of specific projects however are dynamic, allowing the consortium the flexibility to address the most current and pressing industry concerns. DuraMAT funding supports research projects through a number of different competitive processes.

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Background:

Solar photovoltaic (PV) technology is central to global decarbonization efforts, requiring deployments of at least 630 GW/year by 2030.[1] Reliable PV modules and systems are key to meeting these ambitious deployment targets.[2] Reliable modules last longer, produce more energy, are more cost-competitive, and have less environmental impact.[3] Moreover, reliability builds confidence in PV technology among potential end users and financiers, enabling faster and more widespread deployment.

However, the PV industry has always faced downward price pressure and demands for higher efficiency cells and module designs. These trends are ongoing and lead to the introduction of new materials, designs, and manufacturing processes to lower costs and improve efficiency—resulting in a continually changing technological landscape.[4,5] On top of that, PV module lifetime expectations are increasing. Current research efforts aim for up to 50-years of service life while keeping performance degradation at a minimum for decades—putting additional pressure on improving the accuracy of long-term reliability assessments.

Fast-moving technological evolution, shortened product development cycles, and new players moving into the rapidly growing market present challenges in accurately assessing the reliability of new products.[6,7] New materials, designs, and manufacturing processes have the potential to introduce new, unknown degradation mechanisms and failure modes that are difficult to diagnose, analyze, test, and model.

To ensure that PV can continue driving global decarbonization, the PV community must get ahead of the curve on module reliability.[8] In their review of module degradation and failure phenomena, Aghaei et al.[9] call for research on new materials and module designs as they are

[1] International Energy Agency. Net Zero by 2050: A Roadmap for the Global Energy Sector. Paris: International Energy Agency; 2021.
[2] Mirletz H, Ovaitt S, Sridhar S, Barnes TM. Circular economy priorities for photovoltaics in the energy transition. PLoS ONE 2022;17:e0274351. https://doi.org/10.1371/journal.pone.0274351.
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[4] Wilson GM, Al-Jassim M, Metzger WK, et al. The 2020 photovoltaic technologies roadmap. J Phys D: Appl Phys. 2020;53(49):493001.
[5] Oreski G, Stein J, Eder G, et al. Designing New Materials for Photovoltaics: Opportunities for Lowering Cost and Increasing Performance through Advanced Material Innovations. SAND-2021-4837R, IEA Photovoltaic Power Systems Programme; 2021.
[6] Zhang P, Li W, Li S, Wang Y, Xiao W. Reliability assessment of photovoltaic power systems: review of current status and future perspectives. Appl Energy. 2013; 104:822-833.
7 Yang HE, French R, Bruckman L. Durability and Reliability of Polymers and Other Materials in Photovoltaic Modules, Plastics Design Library: William Andrew; 2019.
[8] Zuboy, Jarett and Springer, Martin and Palmiotti, Elizabeth and Karas, Joseph and Smith, Brittany and Woodhouse, Michael and Barnes, Teresa, Getting Ahead of the Curve: Assessment of New Photovoltaic Module Reliability Risks Associated with Projected Technological Changes (November 3, 2022). http://dx.doi.org/10.2139/ssrn.4273054
[9] Aghaei M, Fairbrother A, Gok A, Ahmad S, Kazim S, Lobato K, et al. Review of degradation and failure phenomena in photovoltaic modules. Renewable and Sustainable Energy Reviews 2022; 159:112160. https://doi.org/10.1016/j.rser.2022.112160.

introduced, considering reliability along with performance, cost, and sustainability. They also stress the importance of developing tests that can predict long-term reliability in the context of multiple materials and multiple stresses that vary over time.[10] Reliability researchers have started to make progress on this effort, but it is difficult to keep up with product development and deployment cycles.[11,12]

The Consortium Approach

The Durable Module Materials Consortium (DuraMAT) was established in recognition of the need to accelerate PV reliability research for a rapidly growing industry. DuraMAT operates on a core principle of strong collaboration such that expertise from a broad range of scientific fields can address the multidisciplinary challenges associated with PV reliability. An advisory board made up of industry leaders helps to identify critical mid- to- long-term research problems which benefit from broader expertise, extensive national lab resources and more time commitment than would be available at individual companies or research institutions. This close relationship with industry allows DuraMAT to remain ahead of the technology curve and investigate emerging designs and materials prior to widespread deployment. DuraMATs organizational structure is such that there are more frequent funding cycles and more opportunities for collaboration compared to typical three-year programs. This allows for greater flexibility and enables rapid pivoting to address new challenges as they arise. Focus areas are evaluated annually through cross-project working groups that allow collaboration across projects to apply results to these emerging questions.

[10] Owen-Bellini M, Hacke P, Miller DC, Kempe MD, Spataru S, Tanahashi T, et al. Advancing reliability assessments of photovoltaic modules and materials using combined-accelerated stress testing. Prog Photovolt Res Appl 2021;29:64–82. https://doi.org/10.1002/pip.3342

[11] Jordan DC, Haegel N, Barnes TM. Photovoltaics module reliability for the terawatt age. Prog Energy 2022;4:022002. https://doi.org/10.1088/2516-1083/ac6111

[12] Springer M, Jordan DC, Barnes TM. Future-proofing photovoltaics module reliability through a unifying predictive modeling framework. Progress in Photovoltaics: Research and Applications 2022

The primary leadership team at the end of the period of performance is listed below. Each project PI is listed above in the project table organized by Core Objectives. A full list of students and postdocs can be found in the attached RPPR2.

Name	***Role***	***Organization***	***Contributions***
Teresa Barnes	*Director*	National Renewable Energy Laboratory	*Leadership Team*
Laura Schelhas	*Executive Director*	National Renewable Energy Laboratory	*Leadership Team*
Cliff Hansen	*Lab Lead*	Sandia National Laboratories	*Leadership Team*
Lindsay Steinman	*Project Manager*	National Renewable Energy Laboratory	*Leadership Team*
Anubhav Jain	*Lab Lead*	Lawrence Berkeley National Laboratory	*Leadership Team*

Name	***Core Objective***	***Organization***	***Contributions***
Anubhav Jain	*Central Data Source*	Lawrence Berkeley National Laboratory	*Core Objectives Leader*
Michael Owen-Bellini	*Multi-Scale, Multi-Physics Model,*	National Renewable Energy Laboratory	*Core Objectives Leader*
David Miller	*Disruptive Acceleration Science*	National Renewable Energy Laboratory	*Core Objectives Leader*
Laura Schelhas	*Fielded Module Forensics*	National Renewable Energy Laboratory	*Core Objectives Leader*
Bruce King	*Module Materials Solutions*	Lawrence Berkeley National Laboratory	*Core Objectives Leader*

Project Objectives:

The overarching goal of DuraMat was to discover, develop, de-risk, and enable the rapid commercialization of new materials and designs for photovoltaic (PV) modules with the potential to improve performance and lifetime while achieving a levelized cost of electricity (LCOE) < \$0.03/kWh. As part of the Energy Materials Network, DuraMat brings together the best of the national lab and university research infrastructure in collaboration with the PV and supply-chain industries to achieve this goal.

The project impacts are described in detail below. DuraMAT established a central DataHUB that is used for multiple SETO funded reliability projects and leveraged for extensive multi-institutional and industrial collaborations. DuraMAT established a predictive materials and modeling framework and validated models for multiple applications, including improved accelerated testing. The Combined Accelerated Stress Testing approach to environmentally driven combinations of stresses provided key insights into many degradation mechanisms and weaknesses. Materials Forensics is key to validating accelerated tests and models, and for failure analysis. DuraMAT also advanced new module materials including flexible packaging, recyclable materials, design innovations, and coatings.

A copy of the SOPO and all project milestones are attached as an appendix to this report.

Project Results and Discussion:

As the DuraMAT consortium has evolved, we have adjusted several goals within DuraMAT. We reorganized from a six-node capability network with demonstration projects to a simpler structure with five core objectives. The purpose of doing this is to ensure we remain relevant to the PV industry and research community by clearly communicating the problems we will solve. This structure has broad objectives with SMART key results that can be updated yearly with our achievements and emerging challenges.

Core Objective 1 - Central Data Resource: Collect and disseminate module reliability related data, and apply data science to derive new insights and evolve the DuraMAT DataHub into the central data resource for PV

Project Title	PI	Institution	Project Dates
Data Analytics and Management	Jain	LBNL	04/01/2017-03/31/2019
Technoeconomic Analysis	Woodhouse	NREL	04/01/2017-9/30/2021
DataHUB Design and Deployment	White	NREL	04/01/2017-09/30/2022
Climate Classifications Targeted to Photovoltaic Degradation Through Data Analytics	Jones/Jain	SNL/LBNL	04/01/2019-12/31/2019
IV-TOOLS: Methods for Determining Photovoltaic Degradation from Maximum Power Production Data	Jain	LBNL	10/01/2019-7/31/2022
Data Cleaning for Degradation Analyses	Hansen	SNL	10/01/2019-9/30/2022

Key Results:

- Demonstration of a central data resource, the DuraMAT Data Hub, that securely hosts a mix of private and public data of multiple data types (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.
- Demonstration of applications of the data and software tools to address short-term commercial challenges that are beyond current industry capabilities and long-term research challenges. For example, the "Vocmax" tool is used by independent engineers to help design rational string sizes and was the subject of a short article in *Solar Power World*. (https://pvtools.lbl.gov/string-length-calculator)
- Techno-economic analysis of the effects of more predictive accelerated testing, lower degradation, and resilient module designs and materials. In particular, the simplified PV levelized cost of energy (LCOE) calculator allows for interactive modeling of installed system cost and LCOE in response to changing variables such as location, tracker system, and cell technology. (https://www.nrel.gov/pv/lcoe-calculator/)

Core Objective 2 - Multi-Scale, Multi-Physics Modeling: Develop modeling tools to rapidly scale accelerated testing results and quantitatively assess the impacts and degradation modes of new materials and designs.

Project Title	PI	Institution	Project Dates
Measurement of PV cell crack characteristics in PV modules using digital image correlation	Stein	SNL	03/01/2020-2/28/2021
Predictive Simulation - thermomechanical modeling	Hartley	SNL	04/01/2017-03/31/2020
Cohesive Zone Model to Simulate PV Encapsulant Delamination	Bosco	NREL	04/01/2018-12/31/2018
Highly instrumented modules for environmental characterization and simulation model validation	Hartley	SNL	04/01/2019-03/31/2020
Advanced Lab and Field Testing for PV Systems	Corbus	NREL	07/01/2018-03/31/2020
A Unified Constitutive Model for ECA Degradation	Bosco	NREL	07/01/2018-9/30/2021
An integrated, multi-physics, multi-scale modeling capability for PV stressors and failures	Hartley	SNL	10/01/2019-3/31/2022

Key Results:

- A multi-scale model of a full-sized shingled module was developed to quantify and predict degradation of ECA interconnects.
- The primary driving force behind ECA degradation was determined to be shear stresses, which promote adhesive and cohesive fracture.
- Setting a common baseline for thermomechanical modeling: DuraMAT demonstrated that 80°C is the most representative reference temperature for determining the stress-free temperature of the module in models. This is relevant for all module designs and encapsulant types.
- Quantified the differences between stresses in full size modules and smaller test articles (mini-modules) used in accelerated testing to enable more realistic stresses in accelerated testing.
- Models of full-sized modules were also used to assess the impact of mounting configuration on mechanical stress. Interconnect stress and cell crack probability were found to be heavily affected by module mounting.

Core Objective 3 - Disruptive Accelerated Testing: Data driven accelerated testing of PV-material, -component, -module, & -system specimens that enables degradation rate models and screening of design or material weaknesses without a-priori knowledge of failure modes.

Project Title	PI	Institution	Project Dates
Module Prototyping and Testing	Hacke	NREL	04/01/2017-03/31/2020
Module Level Solutions for Degradation by Ionization Damage	Hacke	NREL	07/01/2018-11/30/2021
Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics	Owen-Bellini	NREL	07/01/2018-9/30/2022
Application of Acceleration Science and Validation for Combined-Accelerated Stress Test Development	Hacke	NREL	10/01/2019-09/30/2022
High-Throughput Optical Mapping for Accelerated Stress Testing of PV Module Materials	Miller	NREL	10/01/2019-9/30/2022

Key Results:

- Demonstration of an accelerated testing method capable of identifying materials and design field failures that are not captured by existing standard steady-state or sequential tests.
    - C-AST, an application-based test method, based on environmental and climatic conditions rather than previously observed failures, was demonstrated to identify failure modes observed in PV installations, including backsheet cracking, interconnect corrosion, LeTID and LID (now distinguished from other modes), and thermal runaway of balance of system components (connectors and fuses).
- Compared a set of commercial and experimental encapsulation formulations containing EVA, POE, TPO, and PVB, in glass/encapsulant/glass coupons after ultraviolet (UV), damp heat, and sequential (UV followed by damp heat) accelerated testing. We found that competing chain-scission and cross-linking reactions are influenced by material type, test temperature, and oxygen presence. The importance of the cumulative effects of aging was shown through sequential testing, which resulted in greater—but likely more realistic—degradation than the DH or UV tests alone.
- Post-examination of specimens (DECS, optical mapping, voltage ionization, and UV-ID DuraMAT projects) confirmed degradation modes resulting from accelerated testing and revealed mechanism-specific insights, improving understanding and corresponding degradation rate models.
- Identification and quantification of the effects of UV weathering, damp heat testing, and potential-induced degradation testing to known degradation modes.

Core Objective 4 - Module Forensics: Apply module and material characterization techniques to understand degradation modes, mechanisms, weaknesses, the impacts of design changes, to ultimately identify opportunities for improved reliability.

Project Title	PI	Institution	Project Dates
Degradation Mechanisms in Fielded Modules w/ Luminescence and Thermal Imaging	Sulas	NREL	02/01/2019-10/31/2019
Anti-reflection coatings for photovoltaic module glass: how long do they last in the field?	Karin	LBNL	02/01/2020-7/31/2021
Materials Forensics	Schelhas	SLAC	04/01/2017-03/31/2019
Non-Destructive Testing of Fielded Modules	King	SNL	04/01/2017-09/30/2019
A novel method to evaluate the crack propensity of PV backsheets	Kempe	NREL	04/01/2018-11/30/2019
DuraMAT Fielded Module Study	King	SNL	04/01/2019-03/31/2020
Effect of Cell Cracks on Module Power Loss and Degradation	Libby	EPRI	04/01/2019-9/30/2022
Outdoor Accelerated Testing of PV Modules	Stein	SNL	04/01/2019-12/31/2019
In-situ Mapping of Deformation in Crystalline Silicon Modules: Understanding the Effects of Viscoelasticity	Bertoni	ASU	10/1/2020-9/30/2022
Direct Imaging of Stress in Crystalline Silicon Modules	Bertoni	QESST	10/01/2017-04/25/2020
Investigation of Interfacial Degradation in Glass/Glass PV Modules	Schelhas	SLAC	10/01/2019-12/31/2021
Fielded Module Library	King	SNL	10/01/2020-9/30/2022
Back side defect imaging in crystalline silicon photovoltaic modules	Bora	LLNL	10/17/2018-07/15/2019
In-the-field rebound-indent tester for photovoltaic backsheets	Mate	Stanford	11/05/2018-12/31/2019
Brookfield Energy CRADA (BOM Squad)	Barnes	NREL	8/01/2017-9/30/2022

Key Results:

- New tool development, including a novel apparatus for dynamic mechanical accelerated testing, called DMX, that uses subwoofers to apply low-pressure (<200 Pa), realistic-frequency (~10 Hz) sinusoidal pressure cycles to modules, and two new field-compatible tools to measure ARC thickness and porosity.

- Direct imaging of cell stress using X-ray topography and water reflectometry detection. These nondestructive and reliable methods monitor the presence and evolution of deflection and moisture in modules ex situ as well as in situ to quantify the impact of module 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 glass/glass modules.
- Continued efforts to validate accelerated test protocols against field failures using a combination of structural, chemical, and mechanical characterization.
- Lab analysis and characterization to provide feedback on PV materials and components, including backsheet, cell, encapsulant, glass, gridlines, interconnects, solder bonds, etc.

Core Objective 5 - Materials Solutions: Design, develop, de-risk innovative materials and module architectures to address PV reliability issues using DuraMAT Capabilities.

Project Title	PI	Institution	Project Dates
Establishing Structural Changes with Backsheet Degradation and Cracking	Colli	BNL	02/01/2018-07/31/2018
Development of a Spray Deposition Method for a Polysilsequioxane Coating for PV Modules	Staiger	SNL	02/08/2018-03/15/2019
Low-Cost Advanced Metallization to Reduce Cell-Crack-Induced Degradation for Increased Module Reliability	Han	Osazda	02/08/2019-9/30/2021
Advancing Bifacial Solar Module Reliability and Manufacturability with New Module Materials and Light-Weight Transparent Back Lamination	Dauskardt	Stanford	04/01/2020-8/31/2022
Development of Flexible Panel Front Sheet with Twenty-Five (25) Year Rated Lifetime	Okawa	SunPower	05/17/2018-10/30/2019
Advanced material development to support low-LCOE 25-year flexible photovoltaic modules	Ng	SunPower	06/03/2019-9/2/2022
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	Durme-van	Endurans Solar (formerly DSM)	06/12/2019-07/1/2022
Low cost, crack tolerant metallization	Han	Osazda	10/01/2017-02/12/2019
Discovering New Materials for PV Encapsulation	Barth	NGPV	10/01/2017-02/28/2019
A Hybrid Hydrophobic-Hydrophilic Coating with combined AR/AS properties	Lyons	BAPVC	10/01/2017-02/29/2020
Scalable Packaging Materials for R2R thin film solar cells	Graham	BAPVC	10/01/2017-03/31/2020
Reliability of modules with high efficiency solar cells with copper contacts	Bowden	QESST	10/01/2017-04/25/2020
Failure mechanisms in electrically conductive adhesive interconnects	Holman	QESST	10/01/2017-04/25/2020
Advanced multifunctional coatings for PV glass to reduce soiling and PID losses	Fleming	Wattglass	10/01/2017-09/30/2018
Highly-conductive, Low-cost Polymer Adhesive Composites with Complex Dimensional Fillers	Zhu	BAPVC	10/01/2017-09/30/2019
New Concepts for Reliable Low-Cost Module Encapsulation and Barrier Technologies	Dauskardt	BAPVC	10/01/2017-12/31/2019

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.
    - Quantified differences in adhesion for modules with Smartwire interconnects. The SmartWire film inclusion results in a significantly reduced initial adhesion, with nearly 80% adhesion lost after 5000 hours of exposure.
    - 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 backsheet 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.

Significant Accomplishments and Conclusions:

DuraMAT has completed 36 projects spanning our five core object areas and completed over a hundred project and management milestones. Here will we highlight key results from our five core outcome areas:

Core Objective 1 - Central Data Resource Highlights

Six central data resources projects were completed during DuraMAT 1.

DuraMAT Data Hub - Supporting Collaborative Research for 202 Scientists

One of the main efforts in this core objective is the development, deployment and maintenance of a central data repository where DuraMAT researchers can share information and experimental data to support the Energy Materials Network concept. Within DuraMAT this is referred to as the DuraMAT datahub. This is a central repository for heterogeneous module/material/test data and the integration of time series data. The entire system is deployed in a FedRamp approved cloud infrastructure. A summary of the current usage statistics are shown in Figure 1. *(White, NREL)*

Now in its fifth year, the DuraMAT Data Hub (*https://datahub.duramat.org*) continues to archive and provide secure access to data for users within the consortium as well as the public. Along with the data sets themselves, a variety of user resource documentation is available. Much of this year's work focused on developing automated tools to help researchers consolidate and deploy their data to the data hub. Two main data upload tools were developed this year to support the combined-accelerated stress testing (C-AST) and the High-Throughput Optical Mapping teams.

At the end of FY 2021, the data hub had 5,104 users with 47,150 page views, as well as 76 projects and 191 datasets.

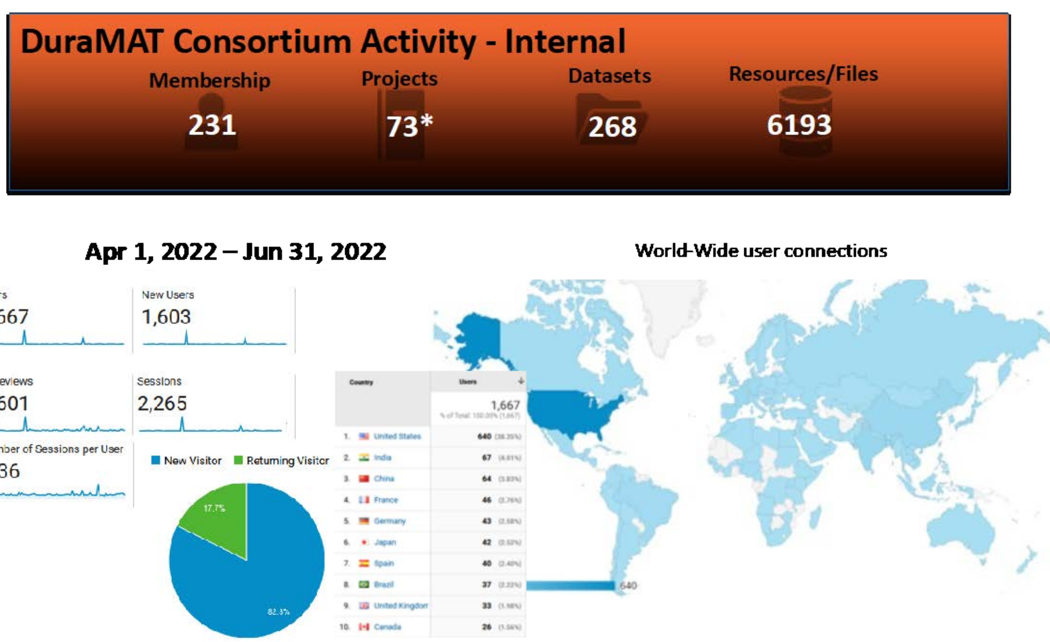


Figure 1: DataHub overview and statistics as of July 2022.

PVPRO: Extracting Module Parameters From Operating Data

Understanding the nature of PV performance degradation can aid in technology development and predictive maintenance, but commercial PV systems' production and operating data typically do not provide detailed insight into module performance. The goal of PVPRO is to begin with the parameters that are already available from operating PV power plants (e.g., DC voltage, DC current, module temperature, and plane-of-array irradiance measurements) and extract time series information on detailed module parameters, such as series and shunt resistance, that would typically only be obtainable with costly in situ string I-V tracers. The methodology is based on the recently developed Suns-Vmp method, which is being expanded upon and formalized for this project.

Initial results show that, on synthetic data sets with noise applied, the PVPRO methodology can extract the time dependence of module parameters without the need for dedicated online string I-V curve tracing equipment, Figure 2.

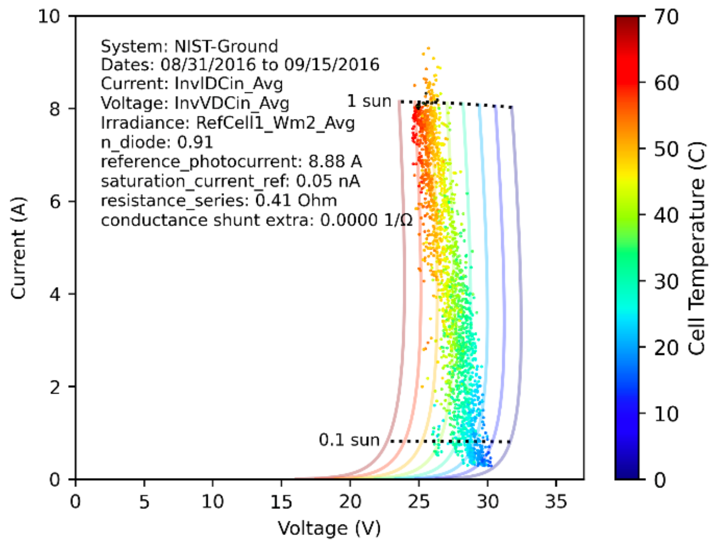


Figure 2: The PVPRO method analyzes snapshots encompassing several days of operating data on an I-V-style plot. The data is fit to a single diode model to extract module parameters from the operating data.

<u>Select Publications:</u>

"Energy Material Network Data Hubs: Software Platforms for Advancing Collaborative Energy Materials Research" in the *International Journal of Advanced Computer Science and Applications*. http://dx.doi.org/10.14569/IJACSA.2021.0120677.

PVPRO has an online software repository located at: https://github.com/DuraMAT/pvpro.

Core Objective 2 - Multi-Scale, Multiphysics Model Highlights

Seven multi-scale, multi-physics modeling projects were completed during DuraMAT 1.

Quantitative Prediction of Module Mechanical Damage Using Computational Models: An Integrated, Multi-Physics, Multi-Scale Modeling Capability for PV Stressors and Failures

Computational models are useful for understanding how external environments propagate into a module, enabling parametric studies of how material or design choices can increase or decrease internal stresses. However, extending results to discrete lifespan predictions rather than relative comparisons requires that models are both quantitatively accurate and able to produce outputs that are compatible with material-level failure metrics.

In this research, failure models for cell fracture and interconnect metal fatigue were integrated into a detailed module model to explicitly quantify cell cracking likelihood and interconnect fatigue damage accumulated during a mechanical pressure load cycle, Figure 3. Because material-level stresses were derived from module simulation results, damage predictions are directly informed by all module inputs, including design, materials, mounting configuration, and load application methodology. We applied this modeling capability to better understand the degree to which accelerated test setups may underestimate or overestimate module damage due to mounting artifacts. Additional applications could include operating models using site-specific, field-representative mechanical load cycles; directly predicting the cell and interconnect damage expected over a periodic environmental exposure; and analyzing what modifications would help achieve a 50-year lifetime.

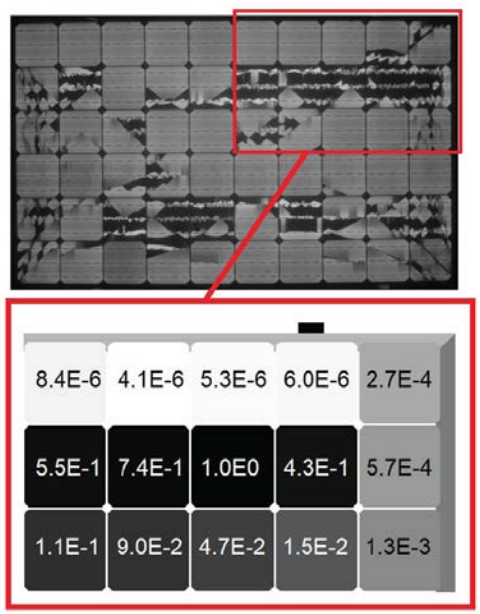


Figure 3: Normalized probability of cell fracture predicted by simulation (bottom) mirrors the typical cell crack distribution observed during uniform pressure load testing (top).

Moisture Can Lower the Fracture Resistance of Epoxy-Based ECAs

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

Our overall technical goal was to develop the framework for a unified constitutive model for ECA to provide an assessment of the new interconnect's durability and reliability. To achieve this goal, we utilize a three-layered approach: (i) materials characterization, (ii) numerical modeling, and (iii) validation, Figure 4. We found that fracture resistance of the candidate ECA decreases with increasing moisture level and that in humid environments, Figure 5. We utilized a multi-scale modeling approach to create a numerical damage model and investigated different loading conditions. When compared with the fracture properties obtained from our materials characterization, we found that interconnect failure is only expected for poor quality or otherwise damaged joints. We designed a test vehicle that causes ECA interface failure under thermal cycling and validated our numerical model against the experimental results.

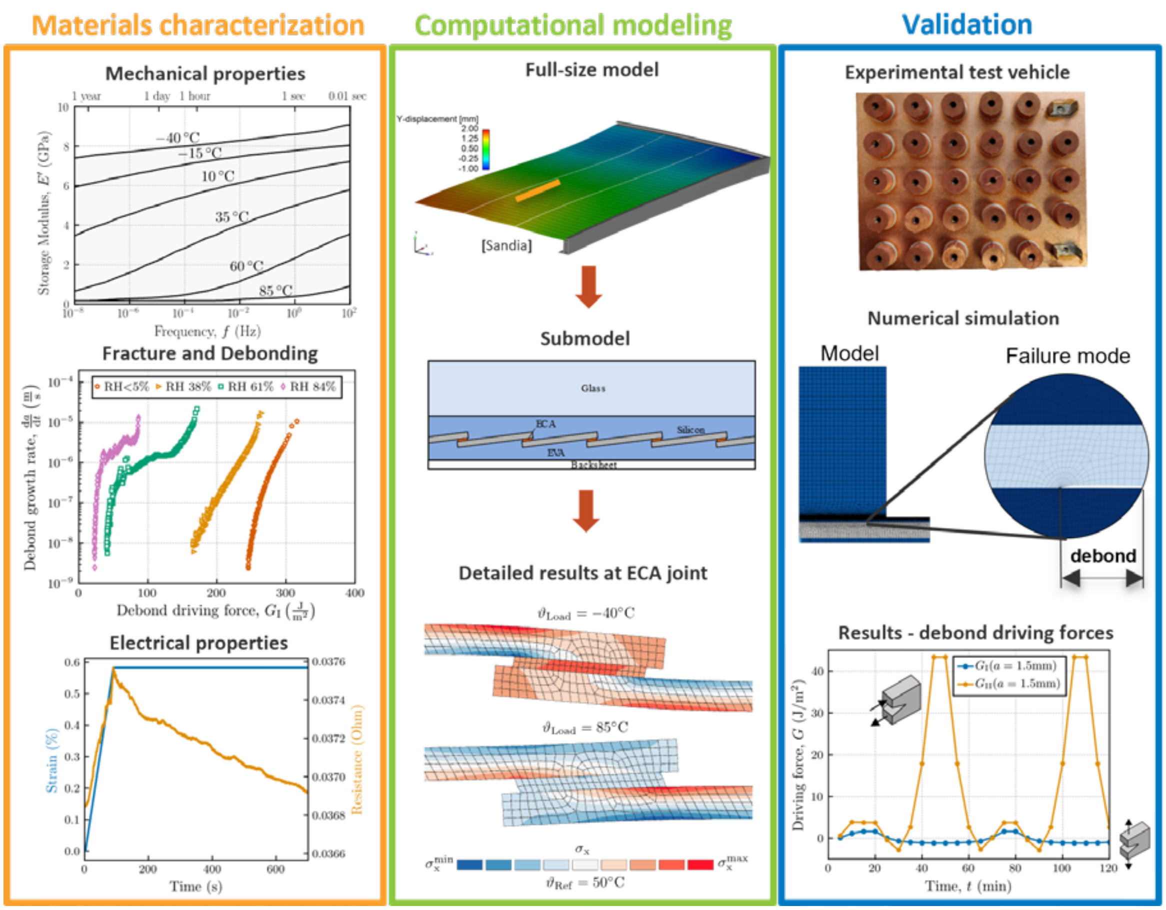


Figure 4: Illustration of the development approach to establish a unified constitutive modeling framework for electrically conductive adhesives.

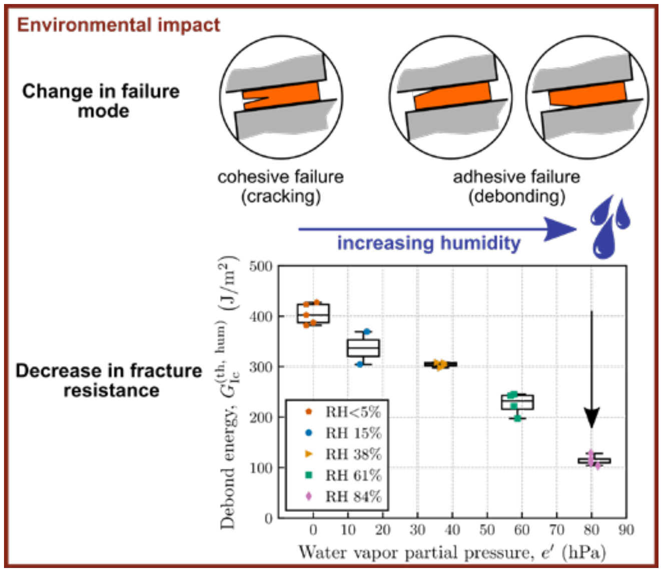


Figure 5: Illustration of the shingled cell technology using ECA as interconnect. Humid environments can weaken the ECA joint by lowering the fracture resistance and changing the failure mode.

<u>Select Publications:</u>

Hartley, J. 2021. "Effects of Frame Constraints on Internal Module Damage During Mechanical Load Testing." 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). 1359-1362. https://doi.org/10.1109/PVSC43889.2021.9519057.

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

Springer, M., J. Hartley, and N. Bosco. 2021. "Multiscale Modeling of Shingled Cell Photovoltaic Modules for Reliability Assessment of Electrically Conductive Adhesive Cell Interconnects." *IEEE Journal of Photovoltaics*. https://ieeexplore.ieee.org/document/9399493/.

Core Objective 3 - Disruptive Acceleration Science Highlights

Five disruptive acceleration science projects were completed during DuraMAT 1.

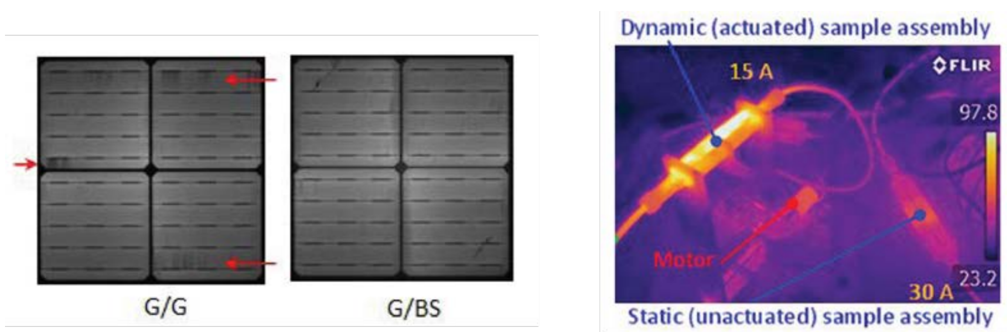
Application of Acceleration Science and Validation for Combined- Accelerated Stress Test (C-AST) Development

Combined-accelerated stress testing (C-AST) simultaneously combines stress factors found in the natural environment (including ultraviolet radiation, temperature, humidity, electrical current, and external mechanical force) into a single test that requires fewer modules and fewer chambers and makes it possible to discover weaknesses in new designs that are not known before testing. C-AST reduces risk, accelerates time to market, and improves bankability by reducing costly overdesign using test levels not exceeding those seen in the natural environment.

Glass/glass modules examined with C-AST show a propensity for grid finger breakage relative to glass/backsheet modules, Figure 6 (a). These results are consistent with DuraMAT X-ray tomography results showing higher stress in the cells encapsulated with glass compared to those encapsulated with a polymeric backsheet substrate. Neither module type exhibited delamination after four complete C-AST runs.

Balance of systems component test capability has recently been developed for C-AST, including cable connector, branch connector, and discrete fuse specimen assemblies. As shown in Figure 6 (b), the benchtop fixture protype reveals drastically elevated sample temperature occurring at a different location within the dynamic (actuated) sample assembly relative to the static (unactuated) sample assembly, despite twice greater current. The benchtop result substantiates the value of simultaneously applying stressors during accelerated testing and is presently being implemented in a C-AST chamber fixture.

Figure 6: Modules under test inside the C-AST chamber.



(a) (b)

Figure 7: Example of broken grid fingers (red arrows) in cells in a glass/glass module after C-AST relative to a glass/backsheet module exhibiting minimal broken fingers. The encapsulant is a polyolefin. (b) In infrared imaging, we observe a drastically elevated sample temperature occurring at a different location within a branch connector and fuse assembly under both applied current and external mechanical load relative to an assembly at greater current with no external mechanical load.

Performance-Affecting Changes in Crystalline Content Confirmed in Popular Encapsulant Materials for Glass/Glass PV Modules

In recent years, glass/glass (G/G) module designs have become an increasingly popular alternative to traditional glass/backsheet (G/B) modules, promising greater lifetimes and the possibility of higher power output when used with bifacial PV cells. However, greater degradation rates are observed in field-deployed G/G modules compared to G/B modules, with degradation modes including loss of optical performance of the encapsulants.

To avoid the potentially detrimental byproducts of EVA encapsulants, we are studying alternative noncrosslinked encapsulants. Polyvinyl butyral (PVB), polyolefin elastomer (POE), and thermoplastic polyolefin (TPO) encapsulants have the advantages of greater volume resistivity and lesser moisture permeability, and they do not contain vinyl acetate side-groups (which may contain acetic acid). These encapsulants are already on the market and are used in G/G PV modules; however, detailed studies—including comparison of their material properties (enabling optical performance) through accelerated stress testing—remain to be performed.

In this work, we compare a set of commercial and experimental encapsulation formulations containing EVA, POE, TPO, and PVB, after ultraviolet (UV), damp heat, and sequential (UV followed by damp heat) accelerated testing. Material properties of samples (unaged and after accelerated testing) are examined to gain insight into the durability of these PV materials when used in G/G configurations, Figure 6.

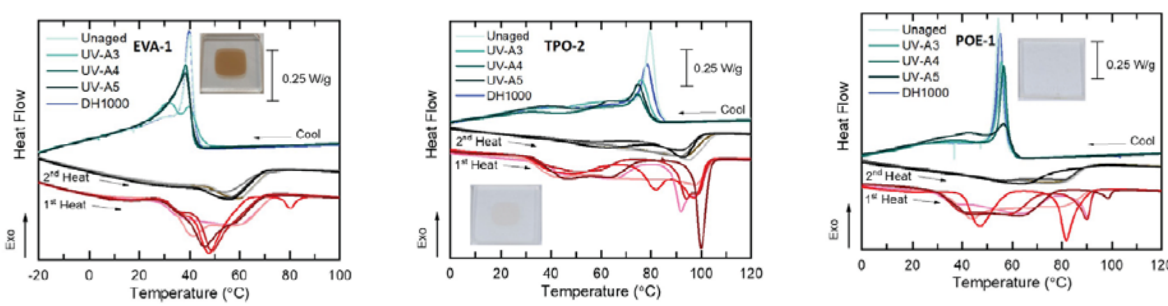


Figure 8: DSC thermograms from the center of the coupon of the "known bad" UV absorber containing EVA-1, high-crystallinity TPO-2 (no UV absorber), and UV absorber containing POE-1. EVA-1 was severely discolored after UV weathering; TPO-2 was less discolored; and POE-1 did not show signs of discoloration. The most significant changes in crystalline content upon aging are seen in for EVA (following IEC TS 62788-7-2 method A3 UV weathering) and for TPO and POE (following A5). The chamber temperatures in A3 (65°C) and A5 (85°C) are near their melting temperature. Irreversible changes from polymer chain scission or cross-linking are evidenced from the reduced melting temperature (2nd heating) and extended crystallization, occurring through lower temperatures on cooling. The changes in the crystalline structure were previously found to affect optical performance through optical scattering, independent of discoloration from chromophore formation.

<u>Select Publications:</u>

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

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

Uličná, S. et al. 2021. "Understanding Aging Mechanisms of Different Encapsulant Materials for Glass/Glass Photovoltaic Modules." In Proceedings of the European Photovoltaic Solar Energy Conference and Exhibition, September 2021, 4CO.2.3.

Core Objective 4 - Fielded Module Forensics Highlights

Fifteen fielded module forensics projects were completed during DuraMAT 1.

How Moisture and Temperature Affect the Deflection of Encapsulated Half-Cut Cells: In Situ Mapping of Deformation in Crystalline Silicon Modules

The impact of cell cracking on module performance remains a hot topic for the PV and DuraMAT community. Characterization of strain, module deformation, and cracks are therefore critical in understanding cracking and crack propagation.

The "In-situ Mapping of Deformation in Crystalline Si Modules: Understanding the Effects of Viscoelasticity" project combines novel XRT, and WARD characterization methods with FEA modeling to understand role of moisture on cell deformation. This work explores both glass/backsheet and glass/glass module architectures. Deflection maps shown in Figure 7 show a narrowing of the distribution with moisture and the largest difference in deflection at the modules edges. It is also noted that the EVA softens slightly with moisture incorporation. Additional characterization has shown the dominant role of interconnects and bus bars. Ultimately the distribution is a complex combination of stressors (T and RH). *(Bertoni, ASU).*

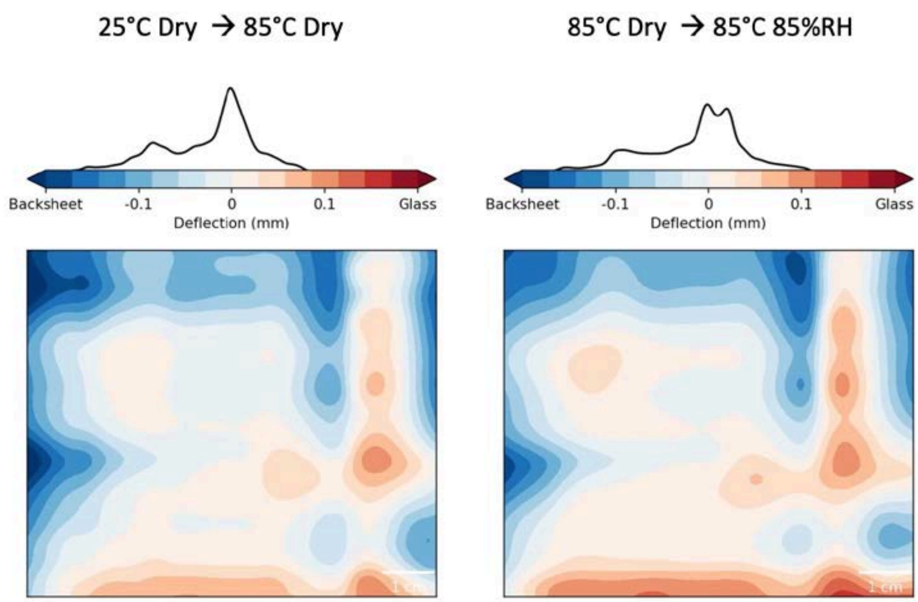


Figure 9: Deflection maps of glass/glass Si modules at 85 C dry (left) and at 85% RH (right)

Subwoofers Aren't Just for Heavy Metal Concerts: A Unique Method for Testing How Wind Pressure Affects PV Panels: Effect of Cell Cracks on Module Power Loss and Degradation

While initial cell cracks are not always detrimental to performance, long-term exposure to external stressors like wind and snow can cause an accumulation of damage. It is not known how the long-term damage accumulation affects module performance, especially in newer module designs and architectures. One reason for the lack of understanding is due to the difficulty of testing. Wind is a major source of the mechanical loading a fielded module will experience, and the amplitude and frequency of loading is extremely variable. During its lifetime, a PV module can experience millions of small amplitude wind loads. Until now, it has been difficult to evaluate the effect these loads have due the time-limitations of accelerated dynamic mechanical loading methods which could apply loads at a maximum of ~0.1 Hz. We developed a new technique, called "DMX", for applying small-amplitude mechanical loads to full-sized PV modules at up to 20 Hz. Meaning that 1 million pressure cycles could be applied in ~1 day instead of 100 days. This enables the study of cell crack damage accumulation and metallization wear-out at different amplitudes over the lifetime of a PV module mounted at NRELs wind test site in Golden, CO. These studies will begin to elucidate the long-term effects of cell propagation and metallization wear-out. *(Libby, EPRI)*

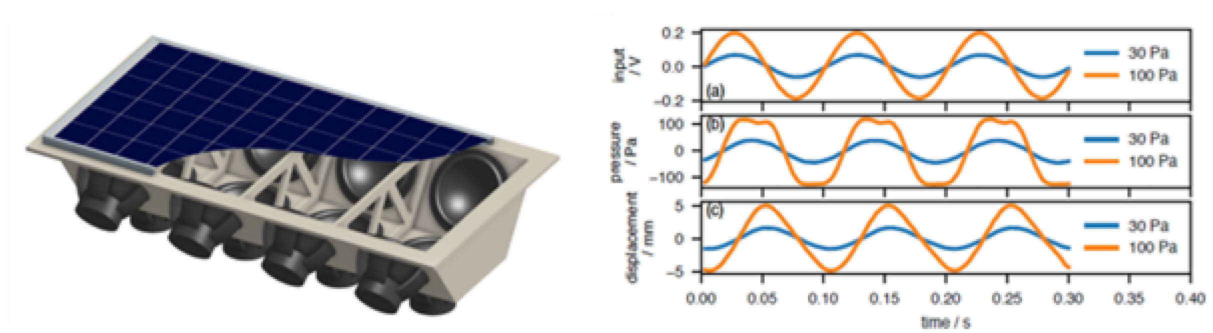


Figure 10: A diagram of the dynamic mechanical acceleration (DMX) apparatus, which uses 12 loudspeakers to apply a time-varying pressure to a PV module. The time series show an example of input voltage (a), enclosure pressure (b), and module displacement at its c center (c) during a 10 Hz DMX test.

Select Publications:

T. J. Silverman, N. Bosco, M. Owen-Bellini, C. Libby and M. G. Deceglie, "Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells," in *IEEE Journal of Photovoltaics*, vol. 12, no. 4, pp. 1090-1093, July 2022, doi: 10.1109/JPHOTOV.2022.3177139.

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

Slauch, I., S. Vishwakarma, J. Tracy, W. Gambogi, R. Meier, F. Rahman, J. Hartley, and M. Bertoni. 2021. "Manufacturing Induced Bending Stresses: Glass-Glass vs. Glass-Backsheet." In Proceedings of the 48th IEEE Photovoltaic Specialists Conference Volume 1. https://doi. org/10.1109/PVSC43889.2021.9518938.

Core Objective 5 - Material Solutions Highlights

Sixteen materials solutions projects were completed during DuraMAT 1.

Comprehensive Quantification of POE/ SmartWire Adhesion and Plasma Deposition of Low WVTR Moisture Barrier in Open Air: Advancing Bifacial Solar Module Reliability and Manufacturability With New Module Materials and Lightweight Transparent Back Lamination

Characterization of adhesive degradation in modules with and without SmartWire is characterized and shown in Figure 9. The mini-modules are exposed to accelerated test conditions on the front and rear of the modules (UV, UV+heat , damp heat). The adhesion is quantified with tapered single cantilever beam tests. The POE encapsulants exhibit high stability in adhesion through 5000 hours of accelerated exposure (>78% retained). The rear POE interfaces are unlikely to delaminate during normal module lifetimes due to high stability and indirect exposures. The SmartWire film inclusion results in a significantly reduced initial adhesion, with nearly 80% adhesion lost after 5000 hours of exposure. Therefore it is concluded that the SmartWire construction introduces a potentially weak adhesive interface that needs to be accounted for in material selection. *(Dauskardt, Stanford).*

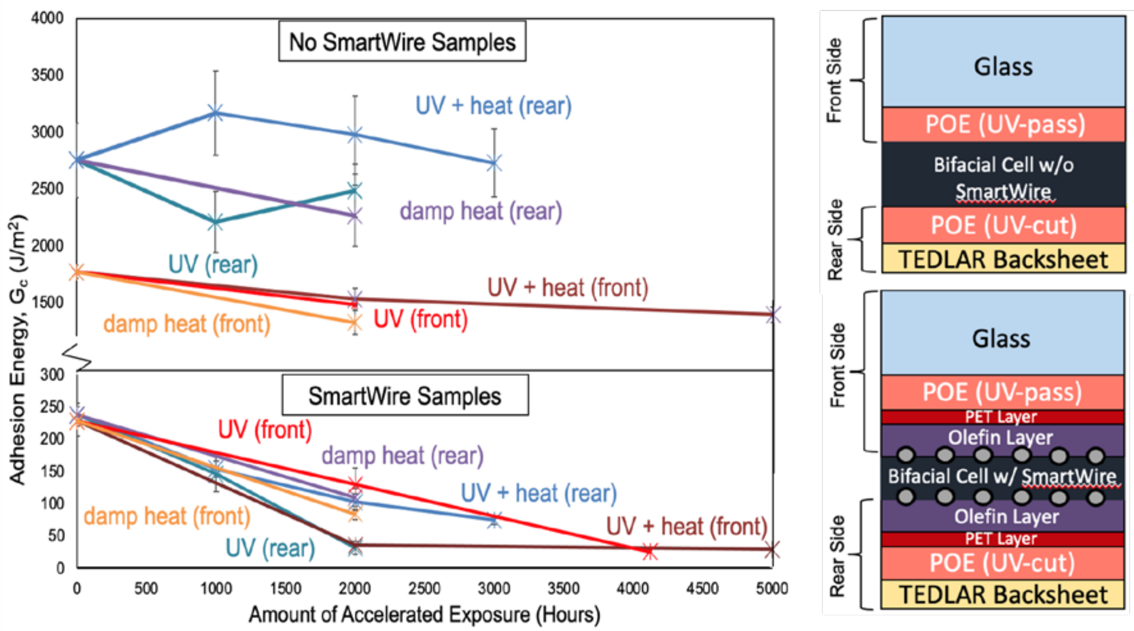


Figure 11: Adhesion energies for both sides of mini-modules aged in accelerated conditions. SmartWire specimens exhibit lower initial adhesion and see greater relative losses (~80%) compared with those without SmartWire (~25%) after 5000 hours.

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

Osazda's metal matrix composites (MetZilla) directly address cell cracks as a plug-in solution that electrically bridges fractured cells. Resistance Across Cleaves and cracKs (RACK) testing can measure the conductance through grid fingers, as they are tensilely strained at micrometer increments to failure (Figure 12). Composite metallization with short carbon nanotubes (**MMC A**) can electrically bridge gaps ≥65 μm upon initial crack and ~30 μm after repeated open- and closed-gap cycles, mimicking wear-out failure. Composite metallization with long carbon nanotubes (**MMC B**) can bridge large gaps ~60 μm upon initial cracking, but the bridging distance rapidly levels off to ~20 μm after repeated open- and closed-gap cycles. In contrast, the standard metallization (**Baseline**) can bridge only ~35-μm gaps upon initial crack and levels off at ~20 μm after repeated open-and closed-gap cycles. The three-point bend method developed at NREL (Figure 13), where resistance along two parallel grid fingers is measured as they are cracked by flexural strain, has been replicated at the University of New Mexico to quickly optimize various paste formulations. We observe that the formulation with long carbon nanotubes (**MMC D**) shows greater critical open displacement than the formulation with short carbon nanotubes (**MMC A**) and the standard metallization. The results from RACK and three-point-bending tests point to a different formulation for improved crack tolerance. However, performing these two different tests (RACK and three-point bending) to measure the metallization's resistance to cell fracture gives us insight into which materials-level characterization technique translates well to the observed module-level degradation caused by cell cracks. This work is a step toward finding the most appropriate materials characterization technique that correlates with the fielded module results.

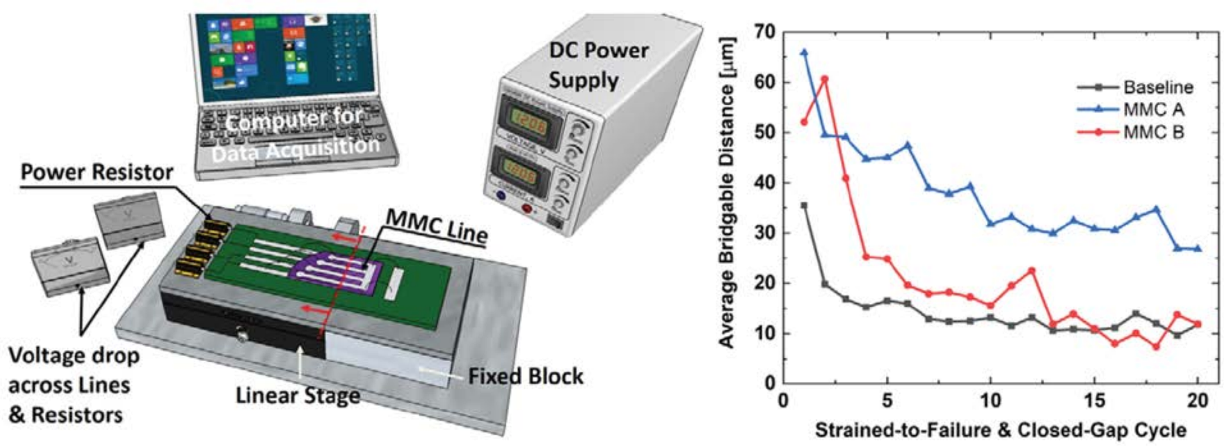


Figure 12: (Left) RACK testing setup to measure the conductance through grid fingers as they are tensilely strained at micrometer increments to failure. (Right) The summary of two different metal matrix composite (MMC) formulations compared to the baseline.

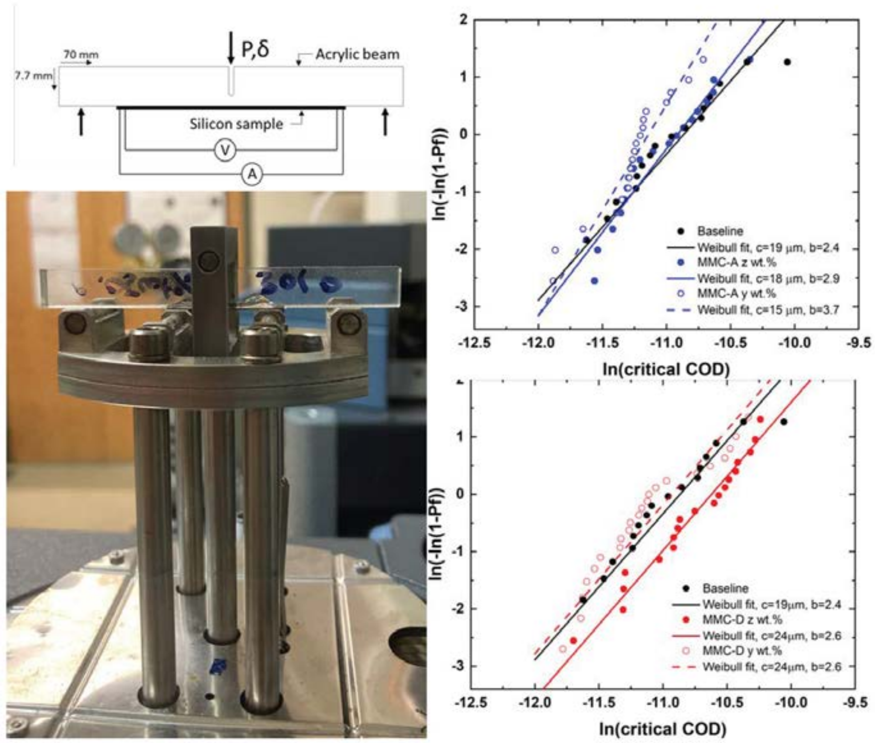


Figure 13: (Left) Three-point bend test setup to measure the conductance through grid fingers as they are flexurally strained at sub-micrometer increments to failure. (Right) The Weibull plots of two different MMC formulations at various CNT concentrations.

Select Publications:

Zhao, O.; Ding, Y.; Pan, Z.; Rolston, N.; Zhang, J.; Dauskardt, R. H. 2020. "Open-Air Plasma-Deposited Multilayer Thin Film Moisture Barriers." ACS Applied Materials and Interfaces. doi.org/10.1021/acsami.0c01493.

Thornton, P., J. Tracy, P. Roraff, K. Roy Choudhury and R. H. Dauskardt. 2021. "Durability of Polyolefin Encapsulation in Photovoltaic Modules with SmartWire Technology." 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC), pp. 1170–1172. https://doi.org/10.1109/PVSC43889.2021.9518610.

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 Cell*s 225, 111017: 1–7. https://doi.org/10.1016/j.solmat.2021.111017

Public Dissemination and outreach:

DuraMAT communicates through academic journals, conference and industry event presentations, free webinars, workshops, newsletters, bimonthly IAB calls, frequent website updates, training students/postdocs for the industry, and other modes. We have found that our IAB meetings, workshops, webinars, open source data/software, and video outreach engage industry members effectively. Journal publications and conference presentations facilitate collaboration and engagement with other researchers.

Statistics for DuraMAT webinars are reported in the table below, webinar recording are available at www.DuraMAT.org :

Month	Year	Title	Presenter(s)	Attendance
September	2022	A retrospective of DuraMATs first 5 years	Michael Owen-Bellini	41
July	2022	Performance and soiling losses from the PV Fleet Performance Data Initiative	Chris Deline & Matt Muller, NREL	67
May	2022	“Reliability Implications of Recent PV Module Trends”	Jarett Zuboy and Martin Springer, NREL; Elizabeth Palmiotti, Sandia; Teresa Barnes, Joe Karas, Brittany Smith, and Michael Woodhouse, NREL	50
April	2022	Data analytics for solar PV: case studies in EL imaging and re-analysis of field data	Anubhav Jain, Xin Chen, Baojie Li Lawrence Berkeley Lab	42
February	2022	Multi-scale Multi-physics modelling of photovoltaic systems: a co-development approach	Philippe Nivelle, Universiteit Hasselt	36
January	2022	Updates from: “Advanced material development to support low-LCOE 25-year flexible photovoltaic modules” & "A Comparison of Emerging Non-Fluoropolymer-Based Co-Extruded PV Backsheets to Industry-Benchmark Technologies"	Mike Kempe (NREL), Hoi Ng (Sunpower) - David Miller (NREL)	63
November	2021	Combined accelerated stress testing: PV modules and BOS components	Peter Hacke and David Miller, NREL	51

Month	Year	Title	Presenter(s)	Attendance
October	2021	Effect of Moisture and Temperature on the Deflection of Encapsulated Cells	Mariana Bertoni, ASU	33
September	2021	Glass/Glass Focus Group: Modules Technology and Durability Roadmap	Dana Kern-Sulas, NREL & Archana Sinha, SLAC	74
August	2021	Updates to the LCOE Calculator Tool in the DuraMAT Data Hub and LCOE Analysis of Latest PV Fleets Results	Brittany Smith, NREL	59
July	2021	Cell Cracking Focus Group	Martin Springer, NREL, Jenn Braid, Sandia & Oliver Zhao, Stanford	55
May	2021	Understanding polymer materials properties for PV module reliability	Michael Owen-Bellini, NREL & Soňa Uličná SLAC	
April	2021	The impacts of Module Reliability and Lifetime on PV in the Circular Economy	Teresa/Silvana/Heather Mirletz	
March	2021	"Characterization of Silicon Photovoltaic Module Durability Guided by Luminescence and Thermal Imaging" (Glass/Glass Interface Characterization)	Dana Kern-Sulas	
January	2021	"Degradation Analysis with Real-World PV Power Plant Data"	Todd Karin, LBL, and Cliff Hansen, Sandia	
December	2020	"Boron-Oxygen and Ultraviolet Light Induced Degradation (BO LID and UV LID) and Light and Elevated Temperature Induced Degradation (LeTID) Impacts to Photovoltaic Module Performance and System Economics"	Michael Woodhouse, Ingrid Repins, David Miller, and Peter Hacke, NREL	
November	2020	"Detailed Investigations into PV Cell Cracks—Why Some Cracks Can Lead to Power Loss"	Josh Stein, Sandia, and Cara Libby, EPRI	
October	2020	"A Fluid Solver for Studying Torsional Galloping in Solar-Tracking PV Panel Arrays"	Ethan Young, NREL	
September	2020	"Adding Climate Effects to the Online LCOE Calculator in DataHub"	Brittany Smith, NREL	

Month	Year	Title	Presenter(s)	Attendance
August	2020	"A Researcher's Guide to the DuraMAT Data Hub: How To Make It Work for Your Project and Research"	Robert White, NREL	
July	2020	"Multi-Scale Modeling of Photovoltaic Module Electrically Conductive Adhesive Interconnects for Reliability Testing"	Nick Bosco, NREL	
June	2020	"A Pathway To Reduce Operations and Maintenance Expenses by Mitigating Cracked Solar Cells and Hot Spot Formation"	Sang Han, Osazda and University of New Mexico; Mike Woodhouse, NREL	
May	2020	"An Overview of Backsheet Materials for Photovoltaic Modules"	Michael Owen-Bellini, NREL	
April	2020	"Measuring and Understanding Moisture Ingress for Photovoltaics"	Matt Reese, NREL	
March	2020	"On the Costs and Benefits of Combined Accelerated Stress Testing (C-AST) for PV Project Economics"	Mike Woodhouse & Peter Hacke, NREL; Tristan Erion-Lorico, PVEL	
February	2020	"Data Driven Approaches for Analyzing PV System Performance and Reliability"	Bennet Meyers, Standford University	
January	2020	"How Might Machine Learning Help To Advance Solar PV Research?"	Anubhav Jain, Lawrence Berkeley Lab	
December	2019	"Demonstrating New Concepts for Reliable Low-Cost Module Encapsulation and Moisture Barrier Technologies"	Reinhold Dauskardt, Stanford	
November	2019	"Low-Cost, Crack-Tolerant Metallization: A Materials Engineering Solution to Module Reliability"	Sang Han, Osazda and University of New Mexico	
October	2019	"Multi-Scale, Multi-Physics Modeling Capabilities towards Predicting PV Reliability"	James Hartley, Sandia	

Month	Year	Title	Presenter(s)	Attendance
September	2019	"Testing at Scale: Methods and Challenges Associated with Curated, Grid-Tied PV System Research"	Bruce King, Sandia	
August	2019	"Materials Forensics for Understanding PV Module Material Durability"	Laura Schelhas, SLAC	
July	2019	"Overview of Encapsulant Materials and Other Sealing Polymers in Photovoltaic Modules"	Ashley Maes, Sandia	
May	2019	"Development of Combined and Sequential Accelerated Stress Testing for Derisking Photovoltaic Modules"	Peter Hacke, NREL	
April	2019	"An Introduction to the DuraMAT DataHub"	Robert White, NREL	
February	2019	"The Role of Reliability and Durability in Photovoltaic System Economics"	Michael Woodhouse, NREL	
January	2019	"Si PV: Present and Future Challenges"	Paul Stradins and David Young, NREL	

Budget and Schedule:

DuraMAT requested to carryover approximately $2.9M in FY22 adding one fiscal year to the initial period of performance. In addition to some COVID delays, the majority of these expenditures were related to technical work that allowed for a continuity of research into DuraMAT 2. The management funds requested permitted the labs to close out existing projects and are due, in part, by hiring delays for the Sandia postdoc. At the end of FY22 all projects described in the tables above were completed.

All projects were completed by Sept. 30, 2022, and closeout was completed 12/31/22.

Original POP	10/1/2016-9/30/2021
Actual POP	10/1/2016-9/30/2022
Federal Share	$30,000,000
Cost Share	$3,496,429
Amount Spent	$29,976,231
Unspent Funds	$23,787

Path Forward:

A follow-on DuraMAT program (DuraMAT2 or D2) was awarded for six years in 2021 as part of the NREL AOP negotiations for FY22-27. This program continues the core objectives, industry engagement, and core partners from DuraMAT. D2 shifts focus towards enabling 50 year module lifetimes and predictive modeling.

All of the core objectives are focused on the DuraMAT goal of accelerating a sustainable, just and equitable transition to zero carbon electricity generation by 2035 by addressing these two questions:

- 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?

DuraMAT's core objectives encompass data science, multi-scale modeling, accelerated testing, module forensics/characterization, and materials solutions. Defining the state of art in this area spans many lengths scales and research areas. From atomic layers and interfaces to full modules, economics to chemistry, and data structures to degradation rate modeling, there are many. We briefly discuss a few key aspects of this field in brief here, understanding this is topic is extensive enough to warrant a dedicated textbook.[13]

DuraMAT has started to focus our modeling core objective on the development of predictive models for PV module degradation based on the fundamental physical mechanisms that cause degradation. In FY 22 we funded five new projects in this focus area and more details on these specific projects can be found here: https://www.duramat.org/projects.html. Work on these projects is planned to start in FY23 so we describe here the larger consortium goal of this work rather than individual project objectives.

Many existing models attempt to predict degradation using empirical fits that aggregate degradation processes in order to reach answers quickly. DuraMAT would like to shift our approach (many lab researchers strive to do this already) to focus on the "physics of failure" by means of well-validated models of individual degradation mechanisms, material property models, interfacial models, stressor models, mass transport, and chemical reactions that can be used to build predictive model chains describing overall degradation. Stated differently, DuraMAT is aiming to build mechanistic rather than phenomenological models of degradation.

DuraMAT's ultimate goal is to develop a mechanistic model for service life prediction. However, we understand the challenge this poses. Instead, we are focused now on models that can be integrated into model chains to leverage work done by multiple groups and institutions to collaboratively build degradation, failure, and/or service-life prediction capabilities. We define a model chain as a series of interconnected models that interact to yield an overall prediction. The individual models will focus on one particular physical, chemical, or degradation mechanism. The interconnection of the models will allow for the prediction of failure modes and their implication on module performance and/or lifetime. For example, a modeling chain focused on metallization corrosion will consist of models that are capable of modeling moisture ingress, acetic acid formation, and corrosion reactions. The interconnection of these "bottom-up" models will result in an increase in series resistance which will decrease the fill factor and cause performance loss. The model chain can then be validated with "top-down" approaches by

[13] Photovoltaic Module Reliability 1st Edition by John H. Wohlgemuth, ISBN-13: 978-1119458999

comparing the prediction results with field observations. DuraMAT expects a mixture of "top-down" probabilistic models and "bottom-up" deterministic models in the portfolio. Each model can focus on either a specific stressor, material or interface property, mechanism, or failure mode, but when incorporated into a larger modeling chain needs to contribute to a more complete understanding of premature failure events or long-term degradation effects.

Developing mechanistic models can be difficult and time-consuming, therefore it is of the essence to develop such models in parallel and include methods to effectively collaborate and share results between models so that they can be interconnected in the future. To address this challenge, models developed in DuraMAT must demonstrate that they can contribute to a multi-physics modeling chain with sub-models from multiple groups. More specifically, projects here should describe how their work either accept inputs from or provide outputs to other projects, provides simplified sets of equations or mathematical descriptions for phenomena, or contributes to material, stress, or mechanistic property libraries. This does not mean that projects must use the same modeling software packages, but it does encourage researchers to develop linkers or connectors between models where logical and human readable input/output and data files that can be shared between packages. Modeling packages that enable the creation of publicly accessible and free to use calculation tools (e.g. Ansys or COMSOL Java widgets) are strongly encouraged within DuraMAT.

We aim to focus on the development and demonstration of computational models, with supporting experimental validation or characterization as needed. Supporting experimental work may include experimental material, interface, or package/module characterization, accelerated stress and/or field testing, and performance/degradation characterization to validate model inputs and outputs.

A complex system can have multiple failure modes that can be independent or may interact in ways that may be difficult to predict. A failure mode describes a deviant function or behavior of a component or part. Failure modes are caused by failure mechanisms. A failure mode can be the direct result of a single or a combination of degradation mechanisms. Degradation mechanisms are described by physical, chemical, thermodynamic or other processes that ultimately result in a failure mode, e.g., creep, fracture, corrosion and so forth. New work in DuraMAT focuses on degradation mechanisms rather than observed failure modes. Projects are required to include a simplified Failure Mode and Effects Analysis (FMEA) approach to identify relevant mechanisms. The right side of Figure 8 shows an example of an FMEA, and the left side of Figure 1 shows how that can be extended to the desired modeling approach.

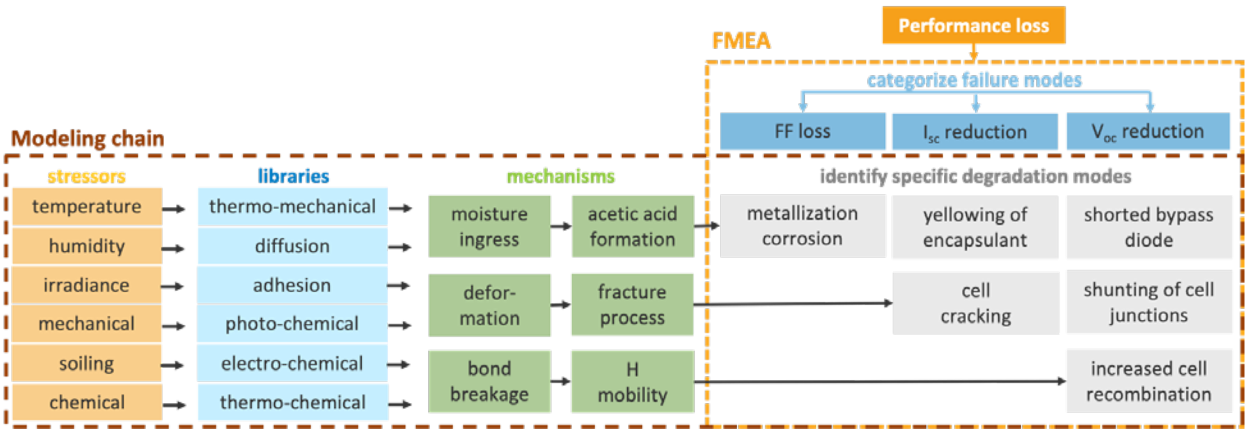


Figure 8 left: Material and Mechanism modeling approach's DuraMAT is most interested in. Figure 8 right: Simplified FMEA starting from a field observation (performance loss) and working towards a specific failure mode(s). The full figure demonstrates how modeling chains combine different stressors, libraries, mechanisms, describe complex field observable failure modes based on fundamental physics of failure.

To date, DuraMAT has not defined an overarching modeling framework. DuraMAT researchers have convened a working group to collaborate and define this framework. An illustration of a model chain is shown in Figure 9. One example of how a model chain could be used is to answer this type of question:

What happens when a module that has been slowly and predictably degrading in the field for 10-15 years is hit by a sudden hail or wind event?

Answering this will require a set of models describing the expected slow field degradation and the response after the sudden event. Modeling the slow field degradation will require incorporating, for example, photochemistry, thermo-mechanical stress, cyclic loading, moisture diffusion, chemical degradation of the encapsulant, mechanical degradation of the encapsulant, etc. A shock or stress model would then be applied to the degraded state to simulate the result. We hypothesize that this can be done in a sequential way that does not require complex co-modeling or co-simulation. Projects include individual or multiple stresses driving the slow degradation, and/or the shock or extreme event. However all work in DuraMAT modeling is not limited to this type of question. It is used here only as an example of sequential modeling.

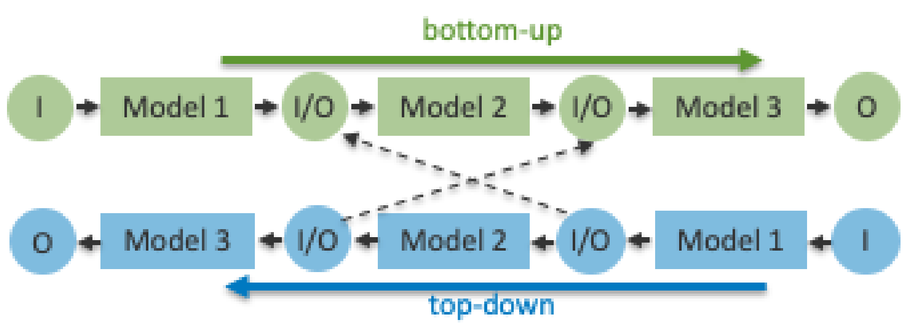


Figure 9: Model chain approach with inputs and outputs that can be used or combined in different mechanisms.

Inventions, Patents, Publications, and Other Results: List all inventions developed or patents submitted under this award. Also list all publications, conference papers, or other public releases of results including any significant media reports/articles, awards received, or networks/collaborations fostered/formed as a result of this award.

The full accomplishments list is included as an appendix to this document. Given the size of this program we are omitting from the main text for space.

In summary, we have published 52 peer review journal articles (with approximately 20 more submitted for review), over 30 conference papers (e.g. IEEE PVSC, EUPVSEC), 142 conference presentations, and 3 patents.

In addition to our quarterly reporting which includes highlight slides from each active DuraMAT effort, RPPR-2 financials including cost share information, accomplishments, and milestones, DuraMAT puts out an Annual Report. Links to the previous five are below.

FY22 Annual Report

FY21 Annual Report

FY20 Annual Report

FY19 Annual Report

FY18 Annual Report

DuraMAT peer reviewed publications:

Title	Year	Author	Publication Title
Advanced X-Ray Scattering and Spectroscopy Characterization of an Antisoiling Coating for Solar Module Glass	2019	S. L. Moffitt, R. A. Fleming, C. S. Thompson, C. J. Titus, E. Kim, L. Leu, M. F. Toney and L. T. Schelhas	ACS Applied Energy Materials
Use of Indentation to Study the Degradation of Photovoltaic Backsheets	2019	D. C. Miller, M. Owen-Bellini and P. L. Hacke	Solar Energy Materials and Solar Cells
Optical Characterization of Curved Silicon Pv Modules With Dichroic Polymeric Films	2019	X. Meng, K. C. Fisher, L. O. Reinhart, W. S. Taylor, M. Stuckelberger, Z. C. Holman and M. I. Bertoni	Solar Energy Materials and Solar Cells
Quantitative Determination of Moisture Content in Solar Modules by Short-Wave Infrared Reflectometry	2019	R. E. Kumar, G. v. Gastrow, J. Leslie, R. Meier, M. I. Bertoni and D. P. Fenning	IEEE Journal of Photovoltaics
Automatic Detection of Clear-Sky Periods from Irradiance Data	2019	B. H. Ellis, M. Deceglie and A. Jain	IEEE Journal of Photovoltaics
Tearing and Reliability of Photovoltaic Module Backsheets	2019	P. Y. Yuen, S. L. Moffitt, F. D. Novoa, L. T.	Progress in Photovoltaics:

Title	Year	Author	Publication Title
		Schelhas and R. H. Dauskardt	Research and Applications
7 - Multifunctional Optical Coatings and Light Management for Photovoltaics	2019	S. L. Moffitt, L. T. Schelhas, S. Melkote and M. F. Toney	Advanced Micro- and Nanomaterials for Photovoltaics
Degradation Studies Including Light-Induced Degradation of C-Si Solar Cells With Nickel-Copper Plated Contacts	2018	J. Karas, L. Michaelson, K. Munoz, J. Rand and S. Bowden	7th World Conference on Photovoltaic Energy Conversion
Effects of Solar Cell Materials and Geometries on Thermally Induced Interfacial Stresses	2018	J. Hartley and S. Roberts	7th World Conference on Photovoltaic Energy Conversion
Automatic Detection of Clear-Sky Periods Using Ground and Satellite Based Solar Resource Data	2018	B. Ellis, M. Deceglie and A. Jain	7th World Conference on Photovoltaic Energy Conversion
Development of Low-Cost, Crack-Tolerant Metallization for Solar Cells	2018	O. K. Abudayyeh, C. Nelson, A. Chavez, J. Chavez, Y.-L. Shen, F. Zimbardi, B. Rounsaville, V. Upadhyaya, A. Rohatgi, B. McDanold, T. Silverman and S. M. Han	7th World Conference on Photovoltaic Energy Conversion
Improved Stability and Efficiency of Perovskite Solar Cells With Submicron Flexible Barrier Films Deposited in Air	2017	N. Rolston, A. D. Printz, F. Hilt, M. Q. Hovish, K. Brüning, C. J. Tassone and R. H. Dauskardt	Journal of Materials Chemistry A
Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load	2020	J. Y. Hartley , M. Owen-Bellini, T. Truman, A. Maes, E. Elce, A. Ward, T. Khraishi, and S. A. Roberts	IEEE Journal of Photovoltaics
Mechanisms of Adhesion Degradation at the Photovoltaic Module's Cell Metallization-Encapsulant Interface	2019	N. Bosco, S. L. Moffitt, and L. T. Schelhas	Progress in Photovoltaics: Research and Applications
Accelerating Photovoltaic Market Entry With Module Replacement	2019	J. Jean, M. Woodhouse, and V. Bulović	Joule
Damp Heat Induced Degradation of Silicon Heterojunction Solar Cells With Cu-plated Contacts	2019	J. Karas, A. Sinha, V. S. P. Buddha, F. Li, F. Moghadam, G. TamizhMani, S. Bowden, and A. Augusto	IEEE Journal of Photovoltaics

Title	Year	Author	Publication Title
Quantitative Mapping of Deflection and Stress on Encapsulated Silicon Solar Cells	2018	X. Meng, M. Stuckelberger, L. Ding, B. West, A. Jeffries, and M. Bertoni	IEEE Journal of Photovoltaics
Fluoropolymer Coatings for Solar Cover Glass: Anti-Soiling Mechanisms in the Presence of Dew	2019	I. Nayshevsky, Q. F. Xu, G. Barahman, and A. M. Lyons	Solar Energy Materials and Solar Cells
Hydrophobic-Hydrophilic Surfaces Exhibiting Dropwise Condensation for Anti-Soiling Applications	2019	I. Nayshevsky, Q. F. Xu, and A. M. Lyons	IEEE Journal of Photovoltaics
Self-Cleaning Hybrid Hydrophobic-Hydrophilic Surfaces; Durability and Effect of Artificial Soilant Particle Type	2019	I. Nayshevsky, Q. F. Xu, J. M. Newkirk, D. Furhang, D. C. Miller and A. M. Lyons	IEEE Journal of Photovoltaics
Development of Low-Cost, Crack-Tolerant Metallization for Solar Cells	2019	O. K. Abudayyeh, A. Chavez, J. Chavez, S. M. Han, F. Zimbardi, B. Rounsaville, V. Updhyaya, A. Rohatgi, B. McDanold, and T. Silverman	IEEE 46th PVSC
Effects of Photovoltaic Module Materials and Design on Module Deformation Under Load	2019	J. Y. Hartley, A. Maes, M. Owen-Bellini, T. Truman, E. Elce, A. Ward, T. Khraishi, and S. Roberts	IEEE 46th PVSC
Validation of Advanced Photovoltaic Module Materials and Processes by Combined-Accelerated Stress Testing (C-AST)	2019	K. Hartman, P. Hacke, M. Owen-Bellini, Y. Jin, M. Cummings, A. Taylor, J. Pretorius, and L. Fritzemeier	IEEE 46th PVSC
Geographic Assessment of Photovoltaic Module Environmental Degradation Stressors	2019	C. B. Jones, T. Karin, A. Jain, W. B. Hobbs, and C. Libby	IEEE 46th PVSC
Photovoltaic Degradation Climate Zones	2019	T. Karin, C. B. Jones, and A. Jain	IEEE 46th PVSC
Understanding PV Polymer Backsheet Degradation through X-ray Scattering	2019	S. L. Moffitt, P. Y. Yuen, M. Owen-Bellini, D. C. Miller, D. R. Jenket, A. M. Maes, J. Y. Hartley, T. Karin, P. Hacke, R. H. Dauskardt, and L. T. Schelhas	IEEE 46th PVSC

Title	Year	Author	Publication Title
Combined-Accelerated Stress Testing for Advanced Reliability Assessment of Photovoltaic Modules	2018	M. Owen-Bellini, P. Hacke, S. Spataru, D. C. Miller, and M. Kempe	35th EU PVSEC
Correlation of Advanced Accelerated Stress Testing With Polyamide-Based Photovoltaic Backsheet Field-Failures	2019	M. Owen-Bellini, D. C. Miller, L. T. Schelhas, S. L. Moffitt, D. R. Jenket, A. M. Maes, J Y. Hartley, T. Karin, and P. Hacke	IEEE 46th PVSC
Fill Factor Loss in Fielded Photovoltaic Modules from Metallization Failures, Characterized by Luminescence and Thermal Imaging	2019	D. B. Sulas-Kern, S. Johnston, and J. Meydbray	IEEE 46th PVSC
Acceptable Volume of Investment for Combined Stress Testing	2019	T. Tanahashi, M. Woodhouse, K. Sakurai, and P. Hacke	36th EU PVSEC
Linear Viscoelastic Characterization of Electrically Conductive Adhesives Used as Interconnect in Photovoltaic Modules	2020	M. Springer and N. Bosco	Progress in Photovoltaics
Photovoltaic String Sizing Using Site-Specific Modeling	2020	T. Karin and A. Jain	IEEE Journal of Photovoltaics
Artificial Linear Brush Abrasion of Coatings for Photovoltaic Module First Surfaces	2020	J. M. Newkirk, I. Nayshevsky, A. Sinha, A. Law, QF Xu,	Solar Energy Materials and Solar Cells
Advancing Reliability Assessments of Photovoltaic Modules and Materials Using Combined-Accelerated Stress Testing	2020	M. Owen-Bellini, P. Hacke, D. C. Miller, M. D. Kempe, S. Spataru, T. Tanahashi, S. Mitterhofer, M. Jankovec, and M. Topič	Progress in Photovoltaics
Methods for In Situ Electroluminescence Imaging of Photovoltaic Modules Under Varying Environmental Conditions	2020	M. Owen-Bellini; D. B. Sulas-Kern; G. Perrin; H. North; S. Spataru; and P. Hacke	IEEE Journal of Photovoltaics
Open-Air Plasma-Deposited Multilayer Thin Film Moisture Barriers	2020	O. Zhao, Y. Ding, Z. Pan, N. Rolston, J. Zhang, and R. H. Dauskardt	ACS Applied Materials & Interfaces
Viscoelastic Material Characterization and Modeling of Photovoltaic Module Packaging	2020	N. Bosco, M. Springer, and X. He	IEEE Journal of Photovoltaics

Title	Year	Author	Publication Title
Materials for Direct Finite-Element Method Input			
Combined-Accelerated Stress Testing System for Photovoltaic Modules	2018	S. Spataru, P. Hacke, and M. Owen-Bellini	7th World Conference on Photovoltaic Energy Conversion
Fundamental Characterization of Anti-Soiling Coatings for PV Glass : Application of Small-Angle X-Ray Scattering	2018	S. L. Moffitt; R. A. Fleming; C. S. Thompson; M. F. Toney; and L. T. Schelhas	IEEE 45th PVSC
Testing and Analysis for Multiple PID Mechanisms and Stresses	2017	P. Hacke	4th Atlas/NIST Workshop on Photovoltaic Materials Durability
In-Situ Performance Characterization of Photovoltaic Modules during Combined-Accelerated Stress Testing	2019	M. Owen-Bellini, D. B. Sulas-Kern, S. Spataru, H. North, G. Perrin, and P. Hacke	IEEE 46th PVSC
A Fluid-Structure Interaction Solver for Investigating Torsional Galloping in Solar-Tracking Photovoltaic Panel Arrays	2021	E. Young, X. He, R. King, and D. Corbus	AIP Journal of Renewable and Sustainable Energy
A Machine Learning Evaluation of Maintenance Records for Common Failure Modes in PV Inverters	2021	T. Gunda, S. Hackett, L. Kraus, C. Downs, R. Jones, C. McNalley, M. Bolen, and A. Walker	IEEE Access
Towards Validation of Combined-Accelerated Stress Testing Through Failure Analysis of Polyamide-Based Photovoltaic Backsheets	2021	M. Owen-Bellini, S. L. Moftt, A. Sinha, A. M. Maes, J. J. Meert, T. Karin, C. Takacs, D. R. Jenket, J. Y. Hartley, D. C. Miller, P. Hacke, and L. T. Schelhas	Scientific Reports
Nondestructive Characterization of Antireflective	2021	T. Karin, D. Miller, and A. Jain	IEEE Journal of Photovoltaics
Multiscale Modeling of Shingled Cell Photovoltaic	2021	M. Springer, J. Hartley, and N. Bosco	IEEE Journal of Photovoltaics
Silver-Carbon-Nanotube Composite Metallization for Increased Durability of Silicon Solar Cells Against Cell Cracks	2021	O.K. Abudayyeh, A. Chavez, S.M. Han, B. Rounsaville, V. Upadhyaya, and A. Rohatgi	Solar Energy Materials and Solar Cells

Title	Year	Author	Publication Title
Corrosion of Novel Reactive Silver Ink and Commercial Silver-Based Metallizations in Diluted Acetic Acid	2021	A. M. Jeffries, T. Nietzold, L. T.Schelhas and M. I. Bertoni	Solar Energy Materials and Solar Cells
Energy Material Network Data Hubs: Software Platforms for Advancing Collaborative Energy Materials Research	2021	R. R. White, K. Munch, N. Wunder, N. Guba, C. Sivaraman, K. M. Van Allsburg, H. Dinh, and C. Pailing	International Journal of Advanced Computer Science and Applications
Glass/Glass Photovoltaic Module Reliability and Degradation: A Review	2021	A. Sinha, D. Sulas-Kern, M. Owen-Bellini, L. Spinella, S. Ulicna, S. Ayala Pelaez, S. Johnston, and L. T. Schelhas	Journal of Physics D: Applied Physics
A Comparison of Emerging Nonfluoropolymer-Based Coextruded PV Backsheets to Industry-Benchmark Technologies	2021	M. Thuis, N. M. Al Hasan, R. L. Arnold, B. King, A. Maes, D. C. Miller, J. M. Newkirk, L. T. Schelhas, A. Sinha, K. Terwilliger, S. Ulicná, and K. Van Durme	IEEE Explore
Failure Analysis of a New Polyamide-Based Fluoropolymer-Free Backsheet After Combined-Accelerated Stress Testing	2021	S. Ulicná, A. Sinha, M. Springer, D. C. Miller, P. Hacke, L. T. Schelhas, and M. Owen-Bellin	IEEE Explore
A Custom High-Throughput Optical Mapping Instrument for Accelerated Stress Testing of PV Module Materials	2022	I. S. Khan, J. Morse, R. R. White, and D. C. Miller	IEEE Journal of Photovoltaics
Electrochemical Degradation Modes in Bifacial Silicon Photovoltaic Modules	2022	D. B. Sulas-Kern, M. Owen-Bellini, P. Ndione, L. Spinella, A. Sinha, S. Uličná, S. Johnston, and L. T. Schelhas	Progress in Photovoltaics
Glass vs Backsheet: Deconvoluting the Role of Moisture in Power Loss in Silicon Photovoltaics With Correlated Imaging during Accelerated Testing	2022	R. E. Kumar , G. von Gastrow, N. Theut, A. M. Jeffries, T. Sidawi, A. Ha, F. DePlachett, H. Moctezuma-Andraca, S. Donaldson, M. I. Bertoni, and D. P. Fenning	IEEE Journal of Photovoltaics
Chemical and Mechanical Interfacial Degradation in Bifacial Glass/Glass and Glass/Transparent Backsheet Photovoltaic Modules	2022	L. Spinella, S. Uličná, A. Sinha, D. B. Sulas-Kern, M. Owen-Bellini, S.	Progress in Photovoltaics

Title	Year	Author	Publication Title
		Johnston, and L. T. Schelhas	
UV-Induced Degradation of High-Efficiency Silicon PV Modules With Different Cell Architectures	2022	A. Sinha, J. Qian, S. L. Moffitt, K. Hurst, K. Terwilliger, D. C. Miller, L. T. Schelhas, and P. Hacke	Progress in Photovoltaics
Photovoltaic Module Antireflection Coating Degradation Survey Using Color Microscopy and Spectral Reflectance	2022	T. Karin, M. Reed, J. Rand, R. Flottemesch, and A. Jain	Progress in Photovoltaics
Automated Defect Identification in Electroluminescence Images of Solar Modules	2022	X. Chen, T. Karin, and A. Jain	Solar Energy
Copper Outdiffusion From Copper-Plated Solar Cell Contacts During Damp Heat Exposure	2022	J. Karas, B. Phua, A. Mo, N. Iqbal, K. Davis, S. Bowden, A. Lennon, and S. Augusto	ACS Applied Materials and Interfaces
Dependence of Adhesion on Degradation Mechanisms of Ethylene Co-Vinyl Acetate Encapsulants Over the Lifetime of Photovoltaic Modules	2022	P. Thornton, S. L. Moffitt, L. T. Schelhas, and R. H. Dauskardt	Solar Energy Materials and Solar Cells
Millions of Small Pressure Cycles Drive Damage in Cracked Solar Cells	2022	T.J. Silverman, N. Bosco, M. Owen-Bellini, C. Libby, and M.G. Deceglie	IEEE Explore
A Study of Degradation Mechanisms in PVDF-Based Photovoltaic Backsheets	2022	S. Uličná, M. Owen-Bellini, S. L. Moffitt, A. Sinha, J. Tracy, K. Roy-Choudhury, D. C. Miller, P. Hacke, and L. T. Schelhas	Scientific Reports
Dark Lock-in Thermography Identifies Solder Bond Failure as the Root Cause of Series Resistance Increase in Fielded Solar Modules	2020	R. Asadpour, D. B. Sulas-Kern, S. Johnston, M. A. Alam	IEEE Journal of Photovoltaics
Evaluation of Bifacial Module Technologies With Combined-Accelerated Stress Testing	2022	P. Hacke, A. Kumar, K. Terwilliger, P. Ndione, S. Spataru, A. Pavgi, K. Roy-Choudhury, G. Tamizhmani	Progress in Photovailtics
Automatic Crack Segmentation in Electroluminescence Images of	2022	X. Chen, T. Karin, A. Jain	2022 IEEE 49th PVSC

Title	Year	Author	Publication Title
Solar Modules and Maximum Inactive Area Prediction			
Evaluating the Durability of Balance of Systems Components Using Combined-Accelerated Stress Testing	2022	D. Miller, G. Perrin, K. Terwilliger, J. Morse, C. Xiao, B. To, C-S. Jiang, P. Hacke	2022 IEEE 49th PVSC
Research and Development Priorities To Advance the Solar Photovoltaic Cost and Performance Targets for Decarbonizing U.S. Electricity Supply	2021	M. Woodhouse, D.Feldman, V. Ramasamy, B. Smith, T. Silverman, T. Barnes, J. Zuboy, R. Margolis	NREL Technical Report
Development of Fixtures and Methods To Assess the Durability of Balance of Systems Components	2022	D. Miller, G. Perrin, K. Terwilliger, J. Morse, C. Xiao, S. Uličná, B. To, C-S. Jiang, L. T. Schelhas, P. Hacke	IEEE Explore
Materials Selection Investigation for Thin Film Photovoltaic Module Encapsulation	2019	T. M. Shimpi, C. Moffett, W. S. Sampath, K. L. Barth	Solar Energy
Open Air Plasma Deposition of Superhydrophilic Titania Coatings	2019	M. Q. Hovish, F. Hilt, N. Rolston, Q. Xiao, R. H. Dauskardt	Advanced Functional Materials
Environmental Influence on Cracking and Debonding of Electrically Conductive Adhesives	2020	M. Springer, N. Bosco	Engineering Fracture Mechanics
Combined Spatially Resolved Characterization of Antireflection and Antisoiling Coatings for PV Module Glass	2020	S. L. Moffitt, C. Riley, B. H. Ellis, R. A. Fleming, C. S. Thompson, P. D. Burton, M. E. Gordon, A. Zakutayev, L T. Schelhas*	ACS Combinatorial Science
Understanding Interfacial Chemistry of Positive Bias High-Voltage Degradation in Photovoltaic Modules	2021	A. Sinhaa, S. L.Moffitt, K. Hurst, M. Kempe, K. Han, Y-C. Shen, D. C. Miller, P. Hacke, L. T. Schelhas	Solar Energy Materials and Solar Cells
Degradation of Copper-Plated Silicon Solar Cells With Damp Heat Stress	2020	J. Karas, L. Michaelson, K. Munoz, M. J. Hossain, E. Schneller, K. O. Davis, S. Bowden, A. Augusto	Progress in Photovoltaics
Tunable Structure and Connectivity of Organosilica Hybrid Films by Using Different Epoxy Based Precursors in Atmospheric Plasma Deposition	2020	R. Morichea, Y. Ding, S. Dong, O. Zhao, R. H. Dauskardt	Applied Surface Science
On Residual Stresses and Reference Temperatures in	2021	M. Springer, N. Bosco	IEEE Journal of Photovoltaics

Title	Year	Author	Publication Title
Thermo-Mechanical Simulations of Photovoltaic Modules Using the Finite Elment Method			
Role of Cation Ordering on Device Performance in (Ag,Cu)InSe2 Solar Cells With KF Post-Deposition Treatment	2021	T. Nietzold, N. Valdes, M. E. Stuckelberger, M. Chiu, T. Walker, A. M. Jeffries, A. Sinha, L. T. Schelhas, B. Lai, W. N. Shafarman, M. I. Bertoni*	ACS Applied Energy Materials
Surface Modification of Backsheets Using Coupling Agents for Roll-To-Roll Processed Thin-Film Solar Photovoltaic (PV) Module Packaging Application	2021	J. Hah, M. Sulkis, M. Kang, Z. Sun, J. Kim, K-S. Moon, M. O. Reese, C. P. Wong*	ACS Applied Materials and Interfaces