FY 2021

ANNUAL REPORT

New Results and a Renewed Consortium

DuraMAT
Durable Module Materials Consortium

Energy Materials Network
U.S. Department of Energy

NREL

Sandia National Laboratories

BERKELEY LAB
Lawrence Berkeley National Laboratory

SLAC NATIONAL ACCELERATOR LABORATORY

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About DuraMAT

The Durable Module Materials Consortium (DuraMAT) launched in November 2016 with 5 years of funding from the U.S. Department of Energy's (DOE's) Solar Energy Technologies Office (SETO). DuraMAT is a multi-lab consortium led by the National Renewable Energy Laboratory, with Sandia National Laboratories, SLAC National Accelerator Laboratory, and Lawrence Berkeley National Laboratory as core research labs. DuraMAT's overarching goal is to discover, develop, de-risk, and enable the rapid commercialization of improved materials, designs, predictive tests, and models for photovoltaic (PV) modules that increase performance, extend lifetime, and enable new applications. We work in partnership with our 15-member industry advisory board and the technical management team at SETO.

DuraMAT Director's Letter

DuraMAT started working groups on glass/glass packaging and cell cracking in Fiscal Year (FY) 2021 in order to coordinate work and results from multiple projects. Our industry advisory board identified these two topics as the most important questions for us work on. Technical results are highlighted throughout this report, and the new projects awarded for FY 2022 address many of the challenges to making 50-year, high-energy-yield modules that were identified in these working groups.

There are some advantages to a virtual consortium used to remote meetings in these crazy times. We made the best of it! We were able to get back in the labs full time, bring on some new staff, and continue to publish as our projects mature. I am so grateful to all our researchers and support staff for making this happen. DuraMAT continued our outreach and communications efforts virtually with invited and contributed talks at NIST/UL, PVRW, PVSC, the TeraWatt Workshop, PVSEC, ModuleTech, and many others. At the end of FY 2021, DuraMAT had 36 published journal articles and over 130 presentations.

We are looking forward to another 6 years of DuraMAT and making progress toward our goal to accelerate a sustainable, just, and equitable transition to zero-carbon electricity generation by 2035. Specifically,

- 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 goal of enabling high-energy-yield, 50-year modules is challenging, but critical for the energy transition. It becomes more difficult with the performance improvements and new module designs that are evolving in parallel. Improving PV modules' outdoor durability and our ability to predict reliability requires more durable materials and designs, better tests to screen for weaknesses, robust modeling, more materials and module characterization data, and a way to combine all these data with historical performance data to extract meaningful results. One of our big questions for very long-term durability is studying how different degradation mechanisms—some very slow, some rapid—will interact over 30–50 years of outdoor service. Here are our key results from FY 2021:

- **Glass/Glass Packaging**
  - Several studies based on high-voltage bias and damp heat exposure have shown a higher risk for photo-induced degradation (PID) and corrosion with traditional ethylene-co-vinyl acetate (EVA) encapsulants. Illumination reverses some of the PID effects, emphasizing the need for field-relevant accelerated testing.
  - The industry is moving toward co-extruded and mixed encapsulant systems for glass/glass packaging with promising results, so these are high priority for study in FY 2022.
  - There are indications of better mechanical stability and longer lifetime in well-designed and carefully manufactured packages. We see considerable variability in performance of lab-produced and small-scale prototype packages compared to commercial products with good quality control.
  - DuraMAT published a review paper documenting the community's current understanding of glass/glass packaging reliability.
- **Mechanics and Cell Cracking**
  - Cracks will occur in most modules. "They are never good, but they are not always bad." – J. Medbray
  - Our research should focus on understanding crack propagation in most cases because we need to know when and how cracks can lead to power loss.
  - Cyclic loading and repeated vibrations appear to have a stronger effect on propagation than individual large wind gusts.
  - Power loss is related to the accumulation of damage in cells and interconnects.
- **Effects on High-Efficiency Cells**
  - Highly efficient cells rely on optimal front and back surface passivation for their performance. These passivation layers are often very sensitive to ultraviolet (UV) radiation.
  - Packaging that includes UV blockers can protect the cells, but with a trade-off in initial cost and early performance. However, early studies suggest that the benefits of UV protective packaging result in more power over the lifetime of the module due to a lower degradation rate.
- **Combined Stressors**
  - Stresses occur in combinations in the field, and some of the combinations can be very difficult to accelerate, or even replicate, in the lab.
  - Combined stressors have helped us understand PID effects, UV stress effects, cell and interconnect cracking, backsheet failures, encapsulant performance, and balance-of-system degradation.
  - All balance-of-system components and combinations need to be tested together—they are not all compatible.
- **Accelerating Results**
  - Our research needs to be shared rapidly in order to remain relevant in a quickly evolving field.
  - We have found that combining accelerated testing, detailed material and module characterization, and multiscale modeling can yield results more quickly, especially when they can be verified against samples obtained from the field.
  - Always use caution when trying to extrapolate lab data to field performance. Taken out of context, it is quite easy to make incorrect conclusions from laboratory data based on testing under conditions not seen in the field. Damp heat testing remains a good example of a test that can provide useful information but is not predictive of field performance on its own.

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 Working Groups

One of the things DuraMAT strives to do is stay up to date on the most important questions facing our community. This last year we focused on two key questions:

When does a cell crack become damaged?

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

DuraMAT leadership challenged a small group of early-career researchers to organize working groups around these topics in order to maximize the impact that DuraMAT can have in these areas, both short term (1 year) and long term (5 years). Here, we provide a short summary of what these two working groups achieved this last year. After 6 months, these working groups resulted in highly focused and well-coordinated research proposals to the DuraMAT lab call to ensure we have impact over the next 3 years. Both groups presented webinars on their results after the first year, available here: *https://www.duramat.org/webinars.html*.

DuraMAT Cell Cracks Working Group

Many photovoltaic (PV) modules have cracks, and we know that cracks are never good, but they are not always bad. How do you know if the cracks in your modules will eventually lead to power loss? Cracks can originate from different events, ranging from manufacturing to transportation, installation, maintenance, and severe weather events. The widespread and rapid adoption of PV technology means more modules are deployed in regions prone to damaging weather. This working group brought together subject matter experts from universities, national laboratories, and industry through periodic meetings and webinars to facilitate discussion on this pressing issue. The meetings covered topics including cell crack detection and characterization, overassessing the impact of cell cracks on electrical performance, and mitigating the effects of cracked cells. DuraMAT researchers are using the outcomes and ideas of the working group meetings in current research proposals, focusing on understanding damage accumulation in cells and interconnects of cracked modules and impacts on electrical power to improve the reliability of future PV modules.

DuraMAT Glass/ Glass Modules Working Group

This group spent the past year discussing unique aspects of emerging glass/glass (G/G) packaging schemes. The group consists of approximately 30 participants from industry, academia, and national labs, including members interested in silicon PV and thin-film technologies. The group discussed durability issues in the older generation of G/G modules that must be mitigated, such as mitigating degradation risks from EVA encapsulants, optimizing glass thickness for weight vs. stiffness, and using mounting schemes compatible with G/G architecture. The group aligned on several areas of known challenges, as well as questions that are yet unanswered, and a research roadmap was summarized at a DuraMAT webinar. This roadmap helped launch successful proposals that are now studying mixed encapsulant systems, mitigation for ultraviolet ionization damage in high-efficiency cells, and the mechanical behavior or interconnects in G/G packages. The past year's outcomes represent significant progress in the community's consensus on the status and possible path forward for G/G packaging. However, it is clear that the technology is continuing to evolve with increasing deployment, and continued discussion will likely be fruitful in this dynamic area.

What is next? For this next year, we plan to continue our working groups, shifting our focus slightly. The general topics and contact information for the organizers are provided below. We hope you will join us for future discussions!

Topic 1: Predictive Modeling

CONTACTS

Elizabeth Palmiotti, Sandia National Laboratories, *ecpalmi@sandia.gov*
Martin Springer, National Renewable Energy Laboratory, *martin.springer@nrel.gov*

Topic 2: Glass/Glass Modules and Cell Cracking

CONTACTS

Xin Chen, Lawrence Berkeley National Laboratory, *chenxin0210@lbl.gov*
Soňa Uličná, SLAC, *sulicna@slac.stanford.edu*

DuraMAT Fiscal Year 2021 Financial Report

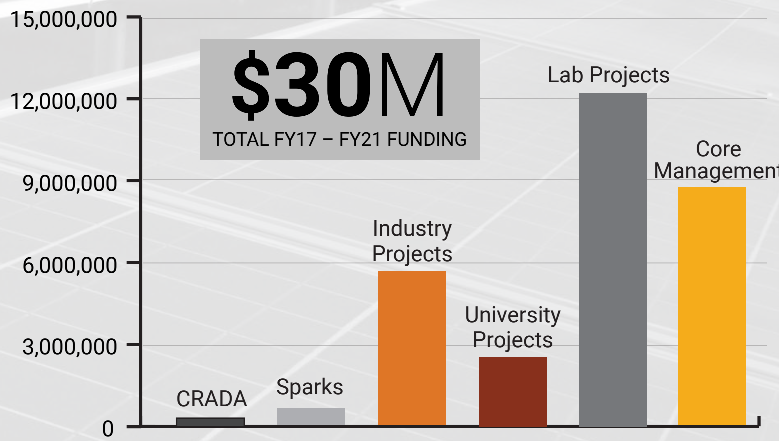
DuraMAT focused on executing awarded work and project closeout as we wrapped up our first phase and started planning the second phase of the DuraMAT program. DuraMAT awarded 49 separate projects to a mix of national lab, university, and industry recipients. Of the $30 million in total federal funding, $21.3 million went directly to research projects, as shown in Figure 1. The remaining $8.7 million was allocated to technical management of the consortium and a DuraMAT postdoc conducting research at each lab.

Figure 2 shows the distribution of the research funds within our core objective areas. These core objectives are prioritized by our industry advisory board, a rotating group of individuals representing a variety of interests across the solar industry.

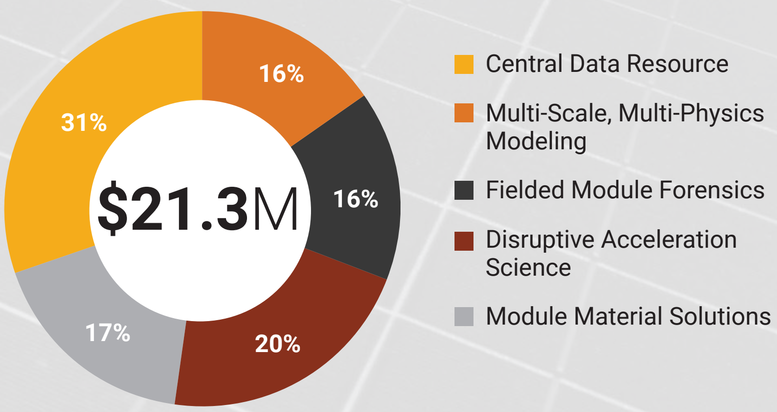
We have extended the program through FY 2022 to allow for the conclusion of research projects, including our new collaboration with PVEL, Luminace, and Core Energy Works committed to investigating bill of materials across the industry. With this project, we anticipate meeting our 10%, $3.3-million cost share goal!

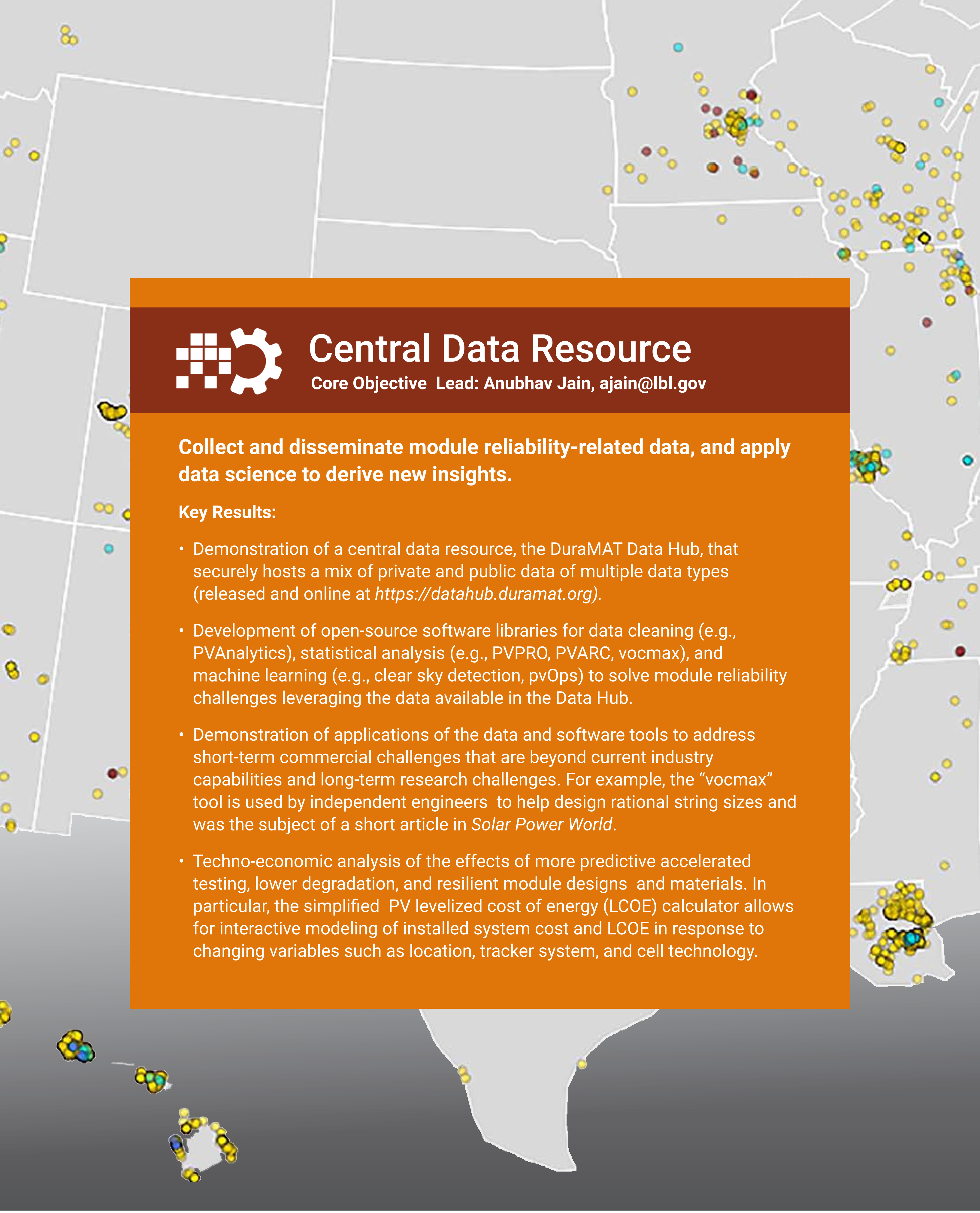
We are very excited that we have been awarded a second phase of this program, which kicked off in October 2021 and will run for the next 6 years. This $36-million addition will expand upon the research completed in DuraMAT 1 and continue to focus on solutions to critical barriers limiting module reliability and durability.

FUNDING DISTRIBUTION TO RESEARCH PROJECTS



FUNDING BY CORE OBJECTIVE





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 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*.
- 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.

Central Data Resource

Core Objective

KEY RESULT

Data Cleaning for Degradation Analysis

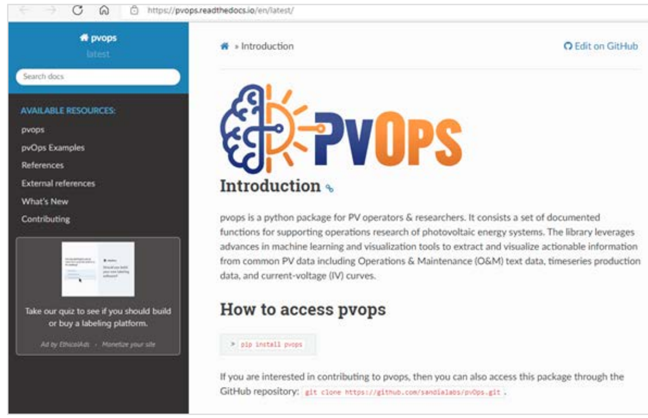
PI: Clifford Hansen (Sandia)

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

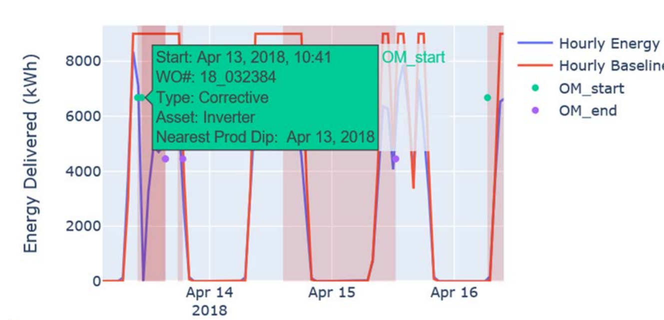
Summary of Result: This project improves the tools used to prepare data for PV system degradation analysis. Data preparation involves filtering to remove low-quality data and labeling times when the system output is affected by external factors, such as inverter outages. Currently, data preparation is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

We have launched the first collaborative, public software library to organize and distribute reusable code for data preparation. We have demonstrated methods to automatically translate textual operations and maintenance records to time series of system condition, an exciting application of state-of-the-art text analytics we call "text to timeseries."

Our work has the potential to automate and democratize the labor-intensive work to prepare data for analysis.



The pvOps documentation homepage (https://pvops.readthedocs.io/en/latest/index.html).



Example result obtained from pvOps. An inverter outage on April 13 was identified from text records as the cause for the drop in hourly energy.

LEARN MORE

See PVAnalytics at *https://github.com/pvlib/pvanalytics* and pvOps at *https://github.com/sandialabs/pvops*.

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

KEY RESULT

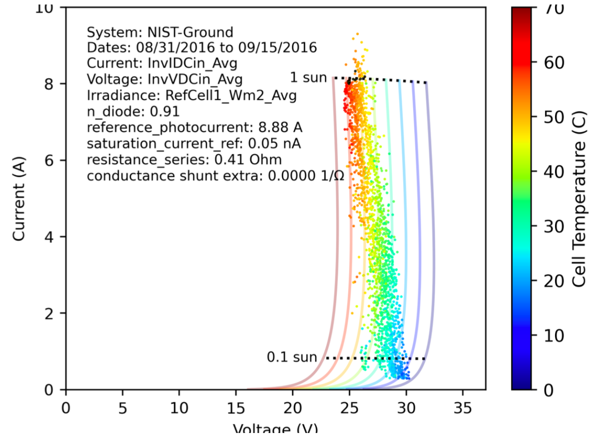
PVPRO: Extracting Module Parameters From Operating Data

PIs: Anubhav Jain (LBNL)

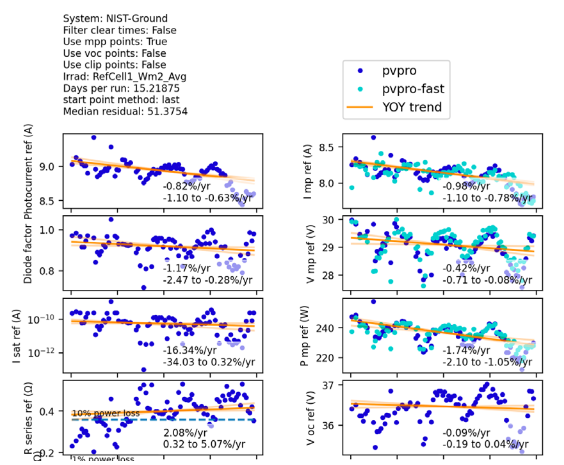
Team Members: Todd Karin (LBNL); Mike Deceglie, Dirk Jordan, Laura Schelhas (NREL); Bennet Meyers (SLAC); Clifford Hansen, Bruce King (Sandia)

Summary of Result: 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. We are testing the PVPRO method on various field data sets and finding qualitative agreement with field observations, but we are in need of better data filtering to account for complex issues, such as sensor drift, that occur in real-world data sets.



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.



PVPRO analysis of a NIST ground-based system. According to the analysis, which ignores potential sensor drift and inverter maintenance issues, about half of the ~1.7% yearly degradation can be traced to photocurrent loss.

LEARN MORE

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

Central Data Resource

Core Objective

KEY RESULT

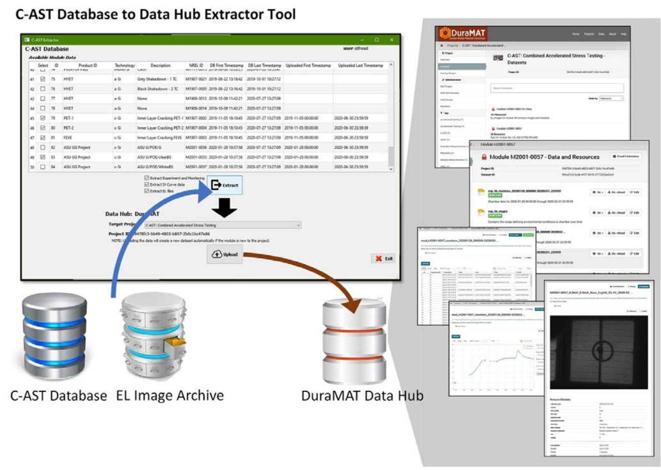
Supporting Collaborative Research for 202 Scientists: Data Hub Design and Deployment

PI: Robert White (NREL)

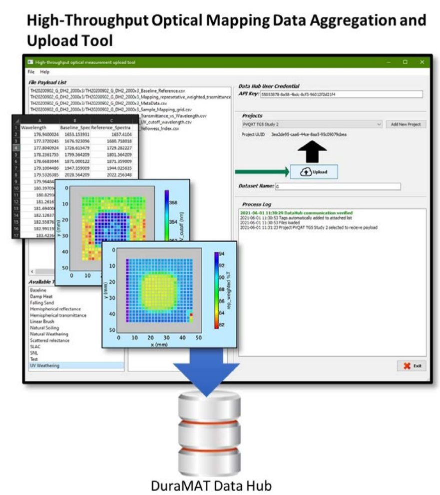
Team Members: Anubhav Jain (LBNL); Rachel Hurst, Nalinrat Guba, Chris Webber (NREL)

Summary of Result: By leveraging expertise and capabilities from across the national laboratory complex, DOE has created a set of virtual laboratories focused on specific research topics to push the frontiers of energy research. Making such a virtual laboratory possible requires constructing a system that can facilitate the sharing of data and ideas securely and efficiently. 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.



Diagrams of the customized tools developed to ease the burden of doing large data extraction and uploading for two main projects: C-AST (top) and High-Throughput Optical Mapping (bottom).



LEARN MORE

The Data Hub can be accessed at *https://datahub.duramat.org*.

Further details can be found in the paper "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*.

Central Data Resource

Core Objective

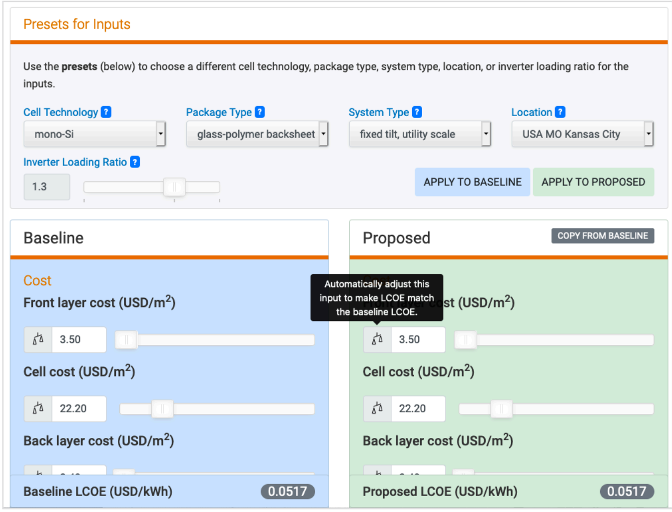
KEY RESULT

Techno-Economic Analysis Support to DuraMAT

PI: Michael Woodhouse and Brittany Smith (NREL)

Summary of Result: Techno-economic analysis (TEA) modeling capabilities can identify high-value opportunities for research in module reliability, durability, and sustainability, and can quantify the value of improvements in these areas in financial and environmental terms. TEA supports decision-making and can be used to identify appropriate and meaningful project milestones for research projects. TEA also uncovers partnership opportunities between researchers and industry stakeholders.

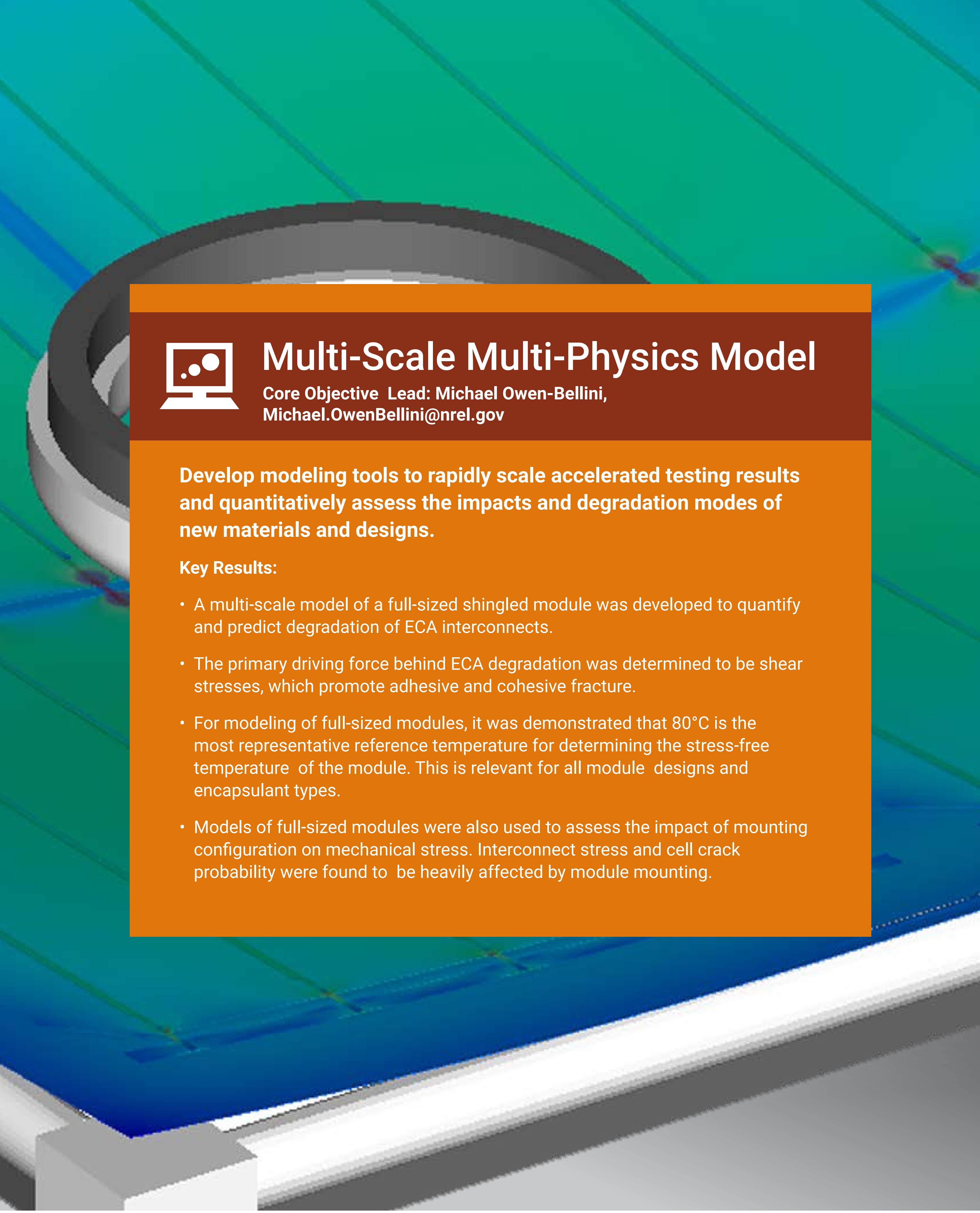
Our approach and capabilities include bottom-up manufacturing and module testing cost analysis, lifetime energy yield and levelized cost of energy (LCOE) modeling, quantitative analysis of cash flows for changing PV module degradation profiles and materials substitution, documentation of module-related operations and maintenance triggers and associated expenses, and expertise on the value proposition of new materials and products, including bifacial, that can offer improved lifetime energy yield. Our TEA expertise will also support circular economy work, particularly in regard to valuing the costs and benefits of different circular processes or initiatives and the sustainability of materials. Finally, we enable the community to evaluate the economic impacts of their own research with a simplified online LCOE calculator that is available within the Data Hub. This calculator enables researchers to evaluate the economic impacts associated with their research, providing adjustable sets of default input values to compare proposed systems to a baseline.



To support analysis of the most common PV life cycle economic metric—levelized cost of electricity (LCOE)—our team has set up the LCOE calculator (screen shot shown) in the Data Hub, and we have expert-level knowledge of NREL's System Advisor Model and Renewable Energy Potential Model.

LEARN MORE

- NREL's solar technology cost analysis: *https://www.nrel.gov/solar/market-research-analysis/solar-cost-analysis.html.*
- Solar Futures Study (reliability factors via DuraMAT): *https://www.nrel.gov/analysis/solar-futures.html.*
- Presentations:
  https://www.nrel.gov/docs/fy21osti/78629.pdf.
  https://www.nrel.gov/docs/fy22osti/80842.pdf.
- DuraMAT online LCOE calculator: *https://www.nrel.gov/pv/lcoe-calculator/* and *https://github.com/NREL/PVLCOE*.



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:

- 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.
- For modeling of full-sized modules, it was demonstrated that 80°C is the most representative reference temperature for determining the stress-free temperature of the module. This is relevant for all module designs and encapsulant types.
- 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.

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

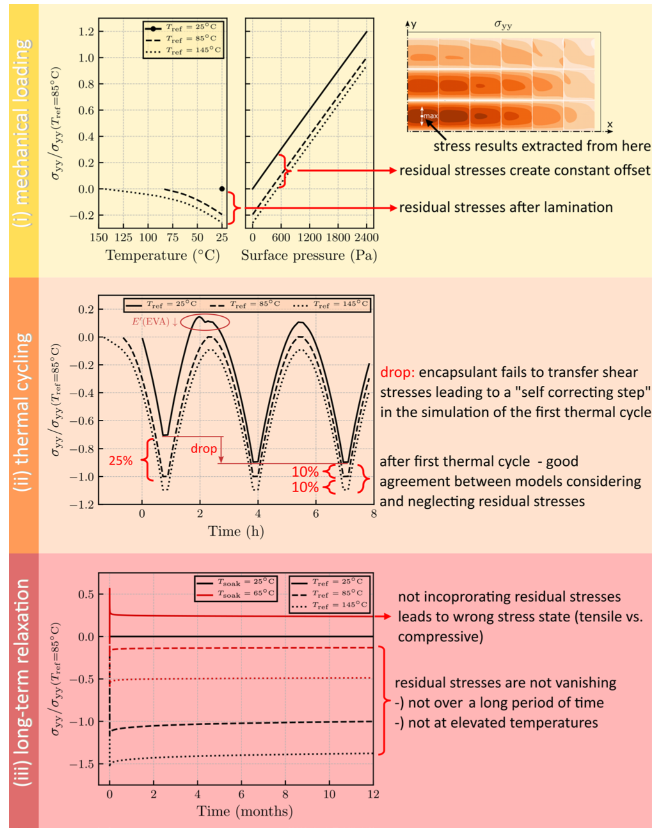
The Effect of Residual Stresses on Thermo-Mechanical Simulation Results: A Unified Constitutive Model for the Degradation of Electrically Conductive Adhesive

PI: Nick Bosco (NREL)

Team Members: Martin Springer (NREL); Kat Han (SunPower)

Summary of Result: Thermo-mechanical simulation of PV modules using the finite element method is a useful tool for evaluating module design features like structural integrity, reliability, and durability. One of the challenges in the numerical modeling of PV modules is the incorporation of residual stresses induced by the manufacturing process. Modeling assumptions and abstractions are necessary to limit model complexity and reduce computational time. However, oversimplifications and incorrect assumptions can lead to erroneous numerical results. Unfortunately, much simulation work still neglects process-induced stresses, which can lead to incorrect predictions and erroneous conclusions during the design process.

We reviewed current modeling practices and compared numerical models that consider residual stresses with those that neglect them. We found that incorporating process-induced stresses is especially important for mechanical loading scenarios, where neglecting the residual stresses led to differences of up to 26% in the predicted stress states. In contrast, simulating accelerated thermal cycling conditions showed better agreement between the different models after the first thermal cycle. Lastly, we explored the long-term relaxation behavior of PV modules and found that residual stresses do not significantly decline over time, even at elevated temperatures. Hence, process-induced stresses affect the stress-strain history of a PV module over its entire lifetime and should be considered in numerical models.



Comparison of thermo-mechanical PV module simulations between models considering residual stresses and models neglecting them for three typical load case scenarios: (i) mechanical loading, (ii) accelerated thermal cycling, and (iii) long-term relaxation.

LEARN MORE

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/*.

Springer, M. and N. Bosco. "On Residual Stresses and Reference Temperatures in Thermo-Mechanical Simulations of Photovoltaic Modules Using the Finite Element Method." *IEEE Journal of Photovoltaics*. (In review).

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

Optical Detection of Crack Separation in Silicon PV Modules: Measurement of PV Cell Crack Characteristics in PV Modules Using Digital Image Correlation

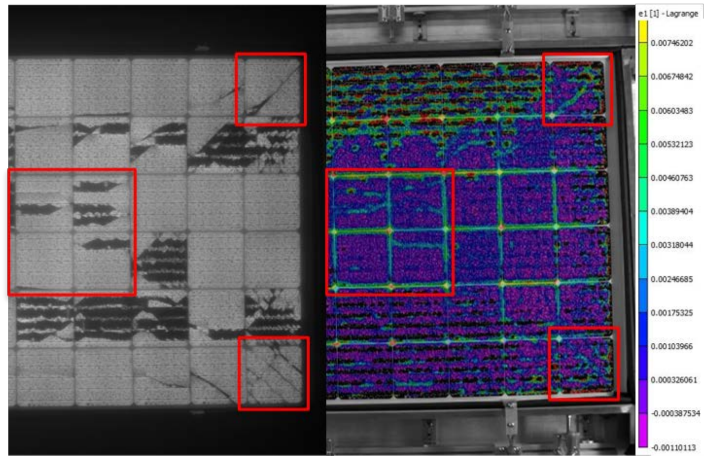
PI: Joshua Stein (Sandia)

Team Members: Jennifer Braid, Charles Robinson (Sandia); Duncan Harwood (D2 Solar)

Summary of Result: Studying the mechanical behavior of silicon cell fractures is critical for understanding changes in PV module performance. Traditional methods of detecting cell cracks, such as electroluminescence (EL) imaging, utilize electrical changes and defects associated with cell fracture to reveal crack locations. However, these methods do not operate at the time or length scales required to accurately measure other physical properties of cracks, such as separation width and behavior under dynamic loads.

Sandia's approach to measuring these properties is to use three-dimensional digital image correlation (DIC) to track in-plane and out-of-plane movements of encapsulated cells at the sub-pixel level. Using DIC, we have demonstrated full-field cell deformation and deflection measurements on PV modules under heating and mechanical load. We detected cell crack separation of tens of microns, with crack locations and electrical isolation of cell fragments verified by EL imaging. Movement is greater for cells with fewer cracks, as the applied strain is distributed over fewer cell fragments.

This work will inform predictive models for crack formation, propagation, and power loss under a variety of weather and loading conditions, and will guide the development of new cell and module materials to mitigate crack formation, propagation, and associated performance loss.



EL and DIC strain images of a PV module at 40°C, -5100 Pa. The strain map shows cell fragment separation of tens of microns, corresponding to cracks identified using EL.

LEARN MORE

- *https://www.duramat.org/digital-image-correlation.html*
- DuraMAT Monthly Webinar, July 2021. "DuraMAT's Efforts on Detecting, Assessing, and Mitigating Power Loss of Cracked Cells."
- NREL PV Reliability Workshop, February 2021. "*Measurement of PV Cell Crack Characteristics in PV Modules Using Digital Image Correlation*."

Multi-Scale Multi-Physics Model

Core Objective

KEY RESULT

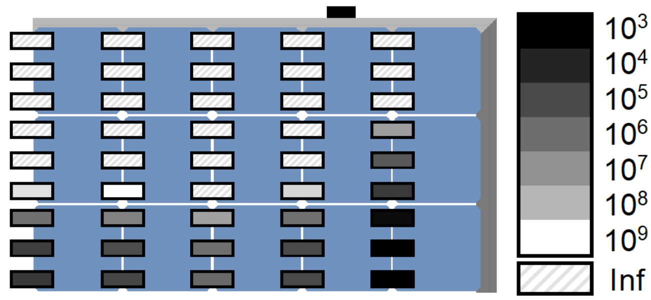
Quantitative Prediction of Module Mechanical Damage Using Computational Models: An Integrated, Multi-Physics, Multi-Scale Modeling Capability for PV Stressors and Failures

PI: James Hartley (Sandia)

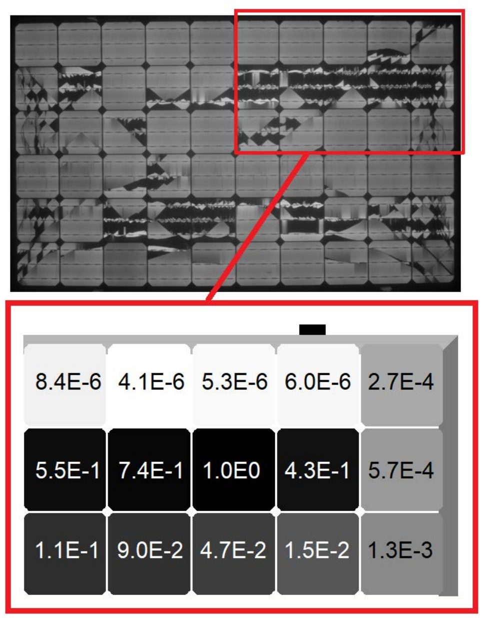
Team Members: Scott Roberts, Farhan Rahman (Sandia); Michael Owen-Bellini, Peter Hacke (NREL)

Summary of Result: 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. 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.



Simulated interconnect fatigue life at each position within a three-busbar module, for ±2.4-kPa load cycles. Interior interconnections exhibit shortened life compared to frame-adjacent positions.



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

LEARN MORE

Hartley, J. 2021. "Effects of Frame Constraints on Internal Module Damage During Mechanical Load Testing." 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). 1359–1364. *https://doi.org/10.1109/PVSC43889.2021.9519057*.

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 materials and design field failures that are not captured by existing standard steady-state or sequential tests.
  - The application-based, nonsubjective (e.g., derived from the diurnal cycle) C-AST method 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).
- Post-examination of specimens (DECS, optical mapping, voltage ionization, and UV-ID DuraMAT projects) confirmed degradation mode(s) resulting from accelerated testing and revealed mechanism-specific insights, improving understanding and corresponding degradation rate model(s).
- Identification and quantification of the effects of UV weathering, damp heat testing, and potential-induced degradation testing to known degradation modes.

Disruptive Acceleration Science

Core Objective

KEY RESULT

Adverse Internal Reaction From Damp Heat Aging Confirmed in Quantitative Optical Mapping: High-Throughput Optical Mapping for Accelerated Stress Testing of PV Module Materials

PI: David Miller (NREL)

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

Summary of Result: Spatial quantification can reveal insights about degraded PV materials and modules that are not apparent from bulk or single-point local measurements. We have created a custom optical mapping instrument that can be used to quantify the transmittance and reflectance of a variety of material, coupon, and MiMo specimens. The instrument uses a 2.5-mm diameter spot size (rather than a test region greater than 1 cm², as in commercial instruments) to allow high-resolution mapping (see Fig. 1). External and internal corrosion processes were confirmed for glass/encapsulant/glass coupons after damp heat aging at 85°C/85%RH for 4,000 hours (see Fig. 2). The stochastic effects of external glass corrosion were quantified for soda-lime glass (Fig. 2d). The interaction between acetic acid (from EVA degradation) and base chemistry (Na, Ca, Mg, and other alkali species) is implied from the difference between EVA-3 in Fig. 2b and TPO-3 in Fig. 2d. A salt product may explain the significantly greater loss of optical transmittance for EVA-3 and soda-lime glass. We reveal the complexity here to motivate further study of damp heat, a popular test in the safety and qualification testing of PV modules that remains to be field validated.

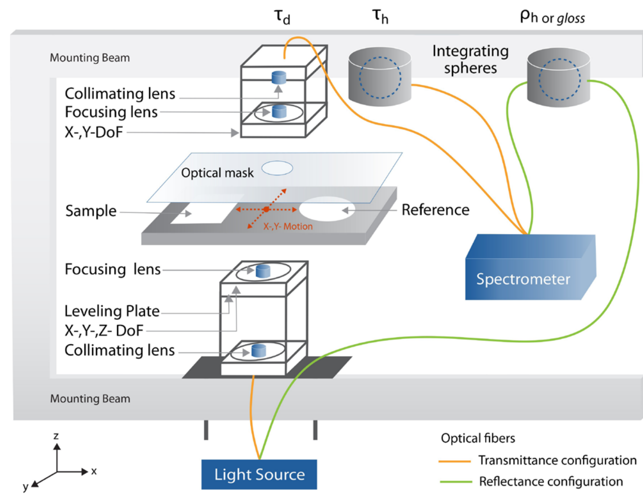


Figure 1. Isometric schematic representing the physical implementation and operational configurations for the custom optical mapping instrument: direct transmittance, τ_d; hemispherical transmittance, τ_h; hemispherical reflectance, ρ_h; and haze (scattered reflectance), ρ_s.

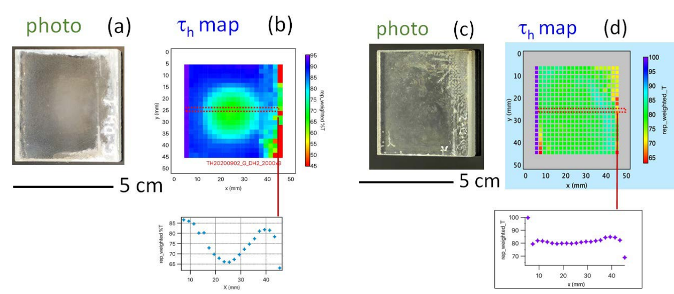


Figure 2. Comparison of glass/encapsulant/glass coupons after damp heat aging for 4,000 hours, including: visual appearance ((a) and (c)) and hemispherical transmittance, τ_h ((b) and (d)). A substantive reduction in transmittance is observed at the center of the EVA-3 + soda-lime glass specimen (in (a) and (b)), relative to the TPO-3 + soda-lime specimen (in (c) and (d)).

LEARN MORE

Khan, N. A. et al. "A Custom High-Throughput Optical Mapping Instrument for Accelerated Stress Testing of PV Module Materials." *IEEE Journal of Photovoltaics*. (In press.) *https://doi.org/10.1109/JPHOTOV.2021.3122925*.

Khan, I. S. et al. 2021. "A Custom High-Throughput Optical Mapping Instrument (OMI) for Accelerated Stress Testing of PV Module Materials." Presented at IEEE Photovoltaic Specialists Conference, virtual. *https://www.nrel.gov/docs/fy21osti/80365.pdf*.

KEY RESULT

Influence of PV Packaging on UV-Induced Degradation of High-Efficiency PV Modules: Module-Level Solutions for Degradation by Ionization Damage

PI: Peter Hacke (NREL)

Team Members: Katherine Hurst, David Miller, Laura Schelhas (NREL); Archana Sinha, Soňa Uličná (SLAC)

Summary of Result: This two-part project aims to test the susceptibility of high-efficiency PV cells to the stress of positive electric potential and ultraviolet (UV) radiation. Here, we summarize the results of the UV portion of this project (see *https://doi.org/10.1016/j.solmat.2021.110959* for part 1: electrolytic corrosion and ion migration into EVA). Through UV screen testing, we first verified that modern cell designs—HJ, IBC, PERT, and PERC cells (including bifacial)—show a greater power decrease than conventional Al-BSF cells due to UV-induced degradation (UVID) (Fig. 1a). In the second round of testing, we studied the UV wavelength-dependent degradation of three cell types (HJ, IBC, and PERT) using five different sharp-cut-on, long-pass UV filters (Fig. 1b). We found an inverse relationship between UV damage and filter cut-on wavelengths, particularly below 345 nm. In the third round of UV exposure, we examined the UVID effect in MiMos using four different encapsulant formulations. Across all cell types, the power loss is higher in MiMos containing UV-transmitting POE encapsulants than in those containing UV-blocking EVA encapsulants (Fig. 1c). Overall, this work has demonstrated and characterized UVID in modern cell designs, while also providing an initial study on packaging solutions to mitigate these degradation pathways.

(a)

(b)

(c)

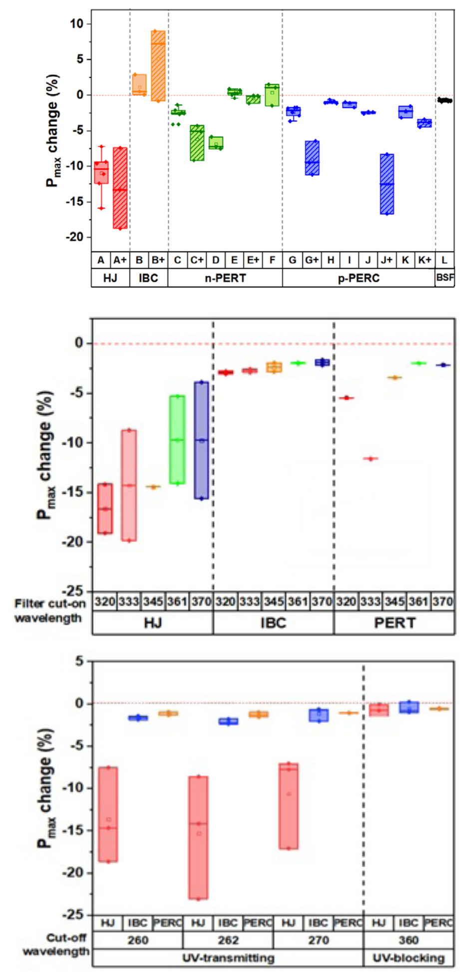


Fig. 1. Change in I-V parameters of the test specimen under UV exposure test (a) round 1: bare cells of different technologies, including rear of bifacial type (+); (b) round 2: bare cells tested under long-pass UV filters; (c) round 3: MiMos with varying encapsulant formulations (UV-transmitting or UV-blocking).

LEARN MORE

Learn more about this project: *https://www.duramat.org/ionization.html*

Hacke, P., D. C. Miller, K. Hurst, S. Moffitt, A. Sinha, and L. Schelhas. "Module-Level Solutions for Degradation by Ionization Damage." Presented at Photovoltaic Reliability Workshop 2020, Lakewood, CO.

Learn more about UV-induced degradation:

Sinha, A., J. Qian, K. Hurst, S. L. Moffitt, L. T. Schelhas, D. C. Miller, and P. Hacke. 2020. "UV Light-Induced Degradation of High-Efficiency Solar Cells with Different Architectures." Presented at IEEE 47th Photovoltaic Specialists Conference, virtual.

Learn more about positive bias high-voltage degradation:

Sinha, A., S. L. Moffitt, K. Hurst, M. Kempe, K. Han, Y. Shen, D. C. Miller, P. Hacke, and L. T. Schelhas. 2021. "Understanding Interfacial Chemistry of Positive Bias High-Voltage Degradation in Photovoltaic Modules." *Solar Energy Materials and Solar Cells* 223: 110959.

Disruptive Acceleration Science

Core Objective

KEY RESULT

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

PI: Michael Owen-Bellini (NREL)

Team Members: Laura Schelhas, David Miller (NREL); Soňa Uličná, Archana Sinha (SLAC)

Summary of Result: 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 uncrosslinked 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.

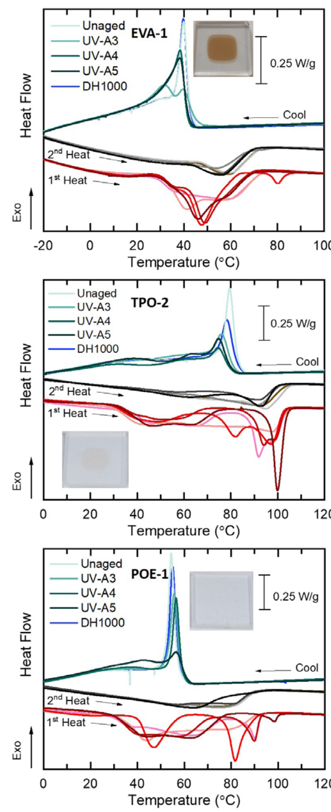


Figure 1: DSC thermograms from the center of the coupon of the "known bad" UV absorber containing EVA-1, high-crystallinity TPO-2 (no UV absorber), and UV absorber containing POE-1. EVA-1 was severely discolored after UV weathering; TPO-2 was less discolored; and POE-1 did not show signs of discoloration. 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.

LEARN MORE

Uličná, S. et al. 2021. "Failure Analysis of a New Polyamide-Based Fluoropolymer-Free Backsheet After Combined-Accelerated Stress Testing." *IEEE Journal of Photovoltaics*. https://doi.org/10.1109/JPHOTOV.2021.3090152.

Owen-Bellini, M. and S. Uličná. 2021. "Understanding Polymer Material Properties for PV Modules Reliability." DuraMAT Webinar, May 10, 2021. https://www.duramat.org/webinars.html.

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.

Disruptive Acceleration Science

Core Objective

KEY RESULT

Simultaneously Applied Stressors Overtly Affect the Accelerated Testing of Balance of Systems Components and PV Modules: Application of Acceleration Science and Validation for Combined-Accelerated Stress Test Development

PI: Peter Hacke (NREL)

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

Summary of Result: 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 a priori. 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 (Fig. 1). 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 Fig. 2, 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.

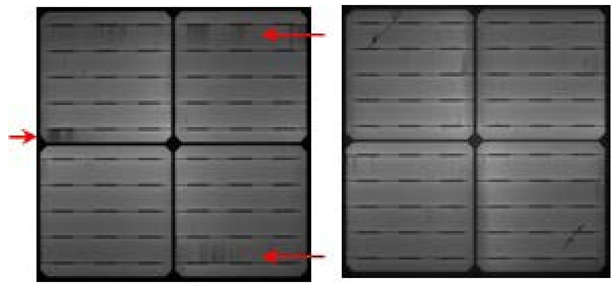


Figure 1. Example of broken grid fingers (red arrows) in cells in a glass/glass module after C-AST relative to a glass/backsheet module exhibiting minimal broken fingers. The encapsulant is a polyolefin.

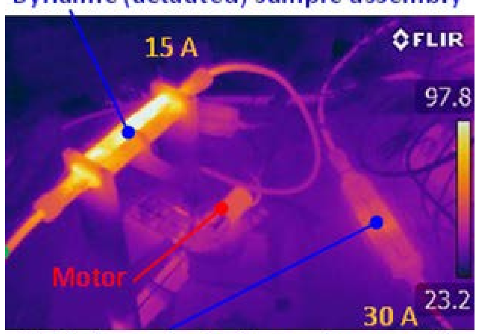


Figure 2: In infrared imaging, we observe a drastically elevated sample temperature occurring at a different location within a branch connector and fuse assembly under both applied current and external mechanical load relative to an assembly at greater current with no external mechanical load.

LEARN MORE

Owen-Bellini, M. et al. 2021. "Advancing Reliability Assessments of Photovoltaic Modules and Materials Using Combined-Accelerated Stress Testing." *Progress in Photovoltaics* 29. *doi.org/10.1002/pip.3342*.

Hacke, P. et al. 2021. "Combined Accelerated Stress Testing and Acceleration Factor Determination." Presented at Photovoltaic Reliability Workshop, 2021. *https://www.youtube.com/watch?v=pd_bWOAV7II&t=2659s*.

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:

- 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.

Fielded Module Forensics

Core Objective

KEY RESULT

Anti-Reflection Coatings for Photovoltaic Module Glass: How Long Do They Last in the Field?

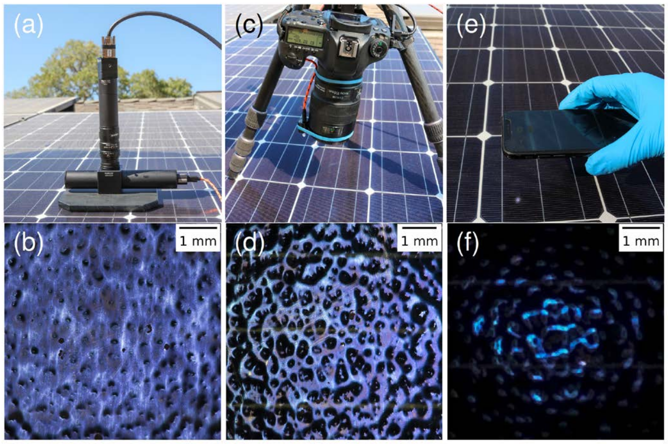
PI: Anubhav Jain (LBNL)

Team Members: Todd Karin (LBNL)

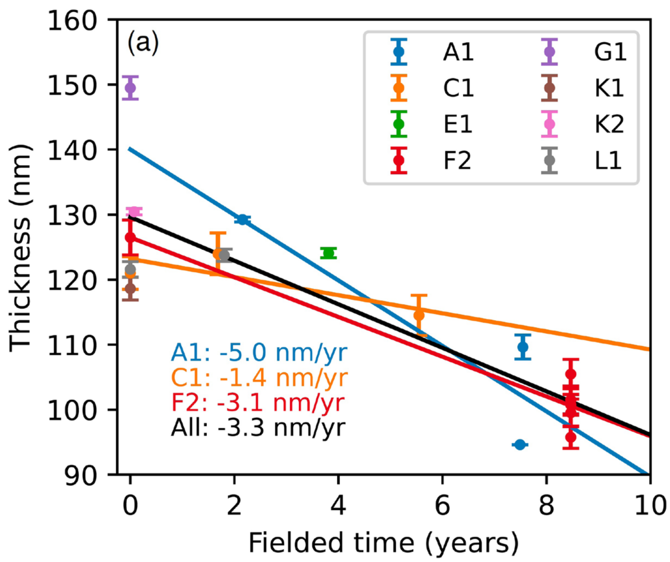
Summary of Result: Anti-reflective coatings (ARCs) on the air-glass interface are used on almost all currently produced PV modules. However, ARC longevity can vary from less than 1 year to over 15 years depending on coating quality and deployment conditions. A technique that can quantify ARC degradation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

We have developed two tools to measure ARC thickness and porosity. The first tool involves taking a reflection spectrum using an integrating sphere. The second tool involves taking an image of the module with an off-the-shelf RGB (red, green, blue) camera. Both measurements are fast, nondestructive, and can be carried out on-site.

Using these tools on fielded modules, we find that uniform film thickness degradation between 1.5 nm/yr and 5 nm/yr can be observed. The 5 nm/yr degradation translates to an 80% loss of the AR coating performance enhancement in as little as 7.5 years. Furthermore, we find evidence that module cleaning can in some cases completely remove AR coatings, and that AR coatings may further be prone to increased soiling.



Experimental setup of the RGB image testing method.



Measured film thickness and extrapolated degradation rates at various locations for modules installed at various times.

LEARN MORE

PVARC has an online software repository located at: *https://github.com/DuraMAT/pvarc.*

Paper on integrating sphere method: *https://ieeexplore.ieee.org/abstract/document/9360841.*

Fielded Module Forensics

Core Objective

KEY RESULT

Digging Into POE vs. EVA Encapsulants' Role in the Durability of Glass/Glass Modules: Investigation of Interfacial Degradation in Glass/Glass PV Modules

PI: Laura Schelhas (NREL)

Team Members: Archana Sinha, Soňa Uličná (SLAC); Laura Spinella, Steve Johnston, Dana Sulas-Kern, Michael Owen-Bellini (NREL)

Summary of Result: Glass/glass PV modules—in which glass covers both the front and back of the module—are growing significantly in commercial popularity. This architecture is anecdotally expected to have greater durability than conventional glass/backsheet modules, yet little research has focused on the degradation mechanisms in glass/glass modules. In this project, we aim to provide chemical, structural, and mechanical insights to enable cutting-edge understanding of the degradation processes at the material interfaces in glass/glass modules. Here, mini-modules using polyolefin (POE) or ethylene-co-vinyl acetate (EVA) encapsulants in glass/glass and glass/transparent-backsheet architectures were stressed under damp heat with positive, negative, or no voltage bias. Using a using a combination of current-voltage measurements, impedance spectroscopy, external quantum efficiency, and spatially resolved luminescence and thermal imaging, we can identify different degradation modes in the mini-modules. A subset of data in shown in Figure 1, highlighting a few of the different degradation modes, including shunting, corrosion, and polarization (see *https://doi.org/10.1002/pip.3530* for more details). An additional set of chemical and mechanical characterization aims to elucidate more details around the mechanisms behind the observed degradation. Figure 2 shows an example X-ray photoelectron spectroscopy (XPS) result for glass/glass mini-modules under positive bias. Similar to previous observations in glass/backsheets, sodium migration to the front silver gridlines is observed. Interestingly, the backside aluminum lines do not have the same affinity. In addition, POE in general reduces the migration of the sodium ions. This future mechanical and chemical characterization aims to complete the story of glass/glass module degradation.

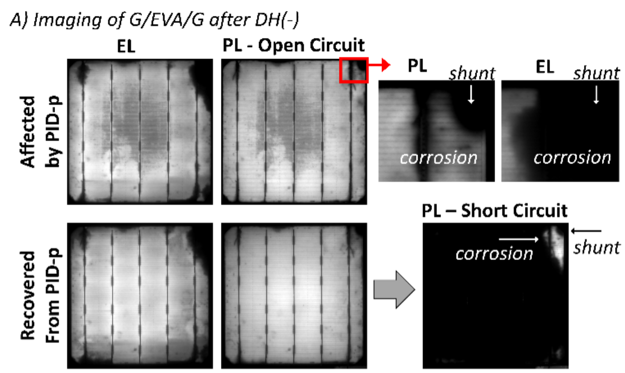


Figure 1. Adapted from https://doi.org/10.1002/pip.3530. Different degradation processes affecting the glass/glass mini-module with EVA under negative bias damp heat (DH-), including contact corrosion, shunting (PID-s), and polarization (PID-p), characterized by electroluminescence (EL) and photoluminescence (PL) imaging.

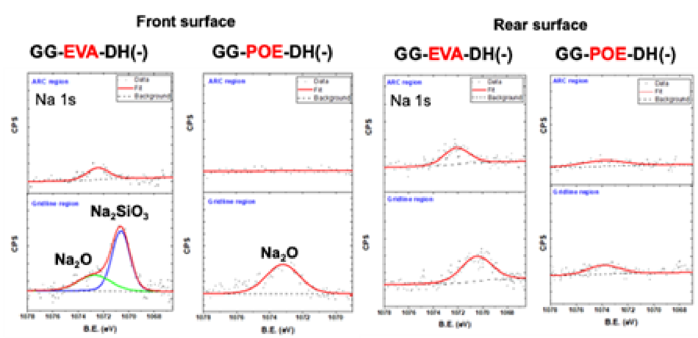


Figure 2. Sodium 1s spectra using X-ray photoelectron spectroscopy (XPS) on glass/glass mini-modules exposed to negative bias damp heat conditions.

LEARN MORE

Publications:

Sinha, A., D. B. Sulas-Kern, M. Owen-Bellini, L. Spinella, S. Uličná, S. Ayala Pelaez, S. Johnston, and L. T. Schelhas. 2021. "A Review of Degradation Modes of Glass/Glass Packaged Photovoltaic Modules," *Journal of Physics* D. *https://doi.org/10.1088/1361-6463/ac1462*.

Sulas-Kern, D. B., M. Owen-Bellini, P. Ndione, L. Spinella, A. Sinha, S. Uličná, S. Johnston, and L. T. Schelhas. "Electrochemical Degradation Modes in Bifacial PERC Silicon Photovoltaic Modules." In review. *https://doi.org/10.1002/pip.3530*.

DuraMAT Webinars:

March 2021 – "*Characterization of Silicon Photovoltaic Module Durability Guided by Luminescence and Thermal Imaging*." Presented by Dana Kern-Sulas (NREL).

September 2021 – "Glass/Glass Focus Group: Modules Technology and Durability Roadmap." Presented by Dana Kern-Sulas (NREL) and Archana Sinha (SLAC).

Fielded Module Forensics

Core Objective

KEY RESULT

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

PI: Mariana Bertoni (Arizona State University)

Team Members: David Fenning (University of California San Diego), James Hartley (Sandia), Jared Tracy (DuPont)

Summary of Result: This project seeks to answer significant open questions about how moisture and stress accelerate the microscopic mechanisms behind module degradation, including delamination, corrosion, and crack propagation. We seek to characterize the evolution of deflection and stress in situ under a variety of temperatures, external bending conditions, and moisture conditions. The ability to evaluate the real-time evolution of stress concentration as a function of external factors will allow for the parametrization of gradients and rates for the various stressors. These data will enable the generation of a database capable of validating and evaluating testing protocols and test sequences as well as de-risking new bills of materials.

We use X-ray topography and water reflectometry detection as nondestructive and reliable methods to monitor the presence and evolution of deflection and moisture in modules ex situ as well as in situ. To model quantitative relationships between moisture ingress and mechanical stress and observed degradation modes (e.g., cracking), we will use supervised machine learning to parameterize known cell-level features, including moisture content, mechanical stress, and cracking/corrosion, from EL/PL.

Outcomes will include refined mechanistic models to predict module degradation, established reliability baselines for introducing and de-risking novel materials and architectures for manufacturing, and evaluation of novel accelerated testing protocols.

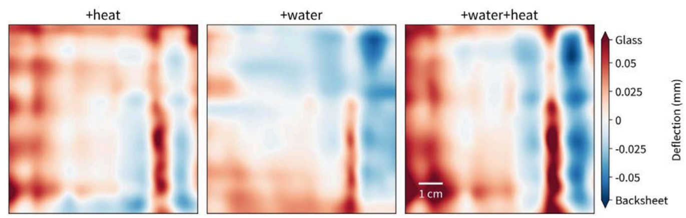


Fig. 1. Heat- and water-induced deflection on a 9 bus bar half-cut bifacial cell minimodule encapsulated with EVA and transparent backsheet.

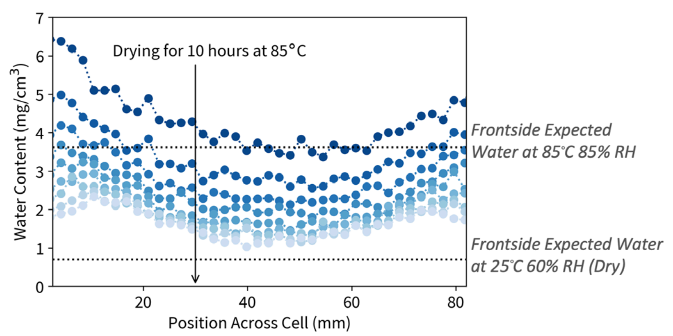


Fig. 2. Water reflectometry scans showing the moisture gradients from edge to center after damp heat soak and drying for the half-cut bifacial cells from Fig. 1

LEARN MORE

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*.

Kumar, R., G. von Gastrow, N. Theut, M. Bertoni, and D. Fenning. 2020. "Quantitative Moisture Mapping To Determine Local Impacts on Module Durability." In Proceedings of the *47th IEEE Photovoltaic Specialists Conference Volume 1*. *https://www.doi.org/10.1109/PVSC45281.2020.9300679*.

Kumar, R. E., 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. 2021. "Glass vs. Backsheet: Deconvoluting the Role of Moisture in Power Loss in Silicon Photovoltaics With Correlated Imaging during Accelerated Testing." *Journal of Photovoltaics* (Accepted).

Fielded Module Forensics

Core Objective

KEY RESULT

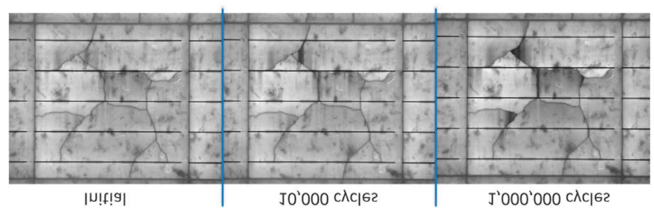
Subwoofers Aren't Just for Heavy Metal Concerts: A Unique Method for Testing How Wind Pressure Affects PV Panels: Effect of Cell Cracks on Module Power Loss and Degradation

PI: Cara Libby (Electric Power Research Institute [EPRI])

Team Members: Mike Deceglie, Tim Silverman, Nick Bosco, Michael Owen-Bellini, Ethan Young, Xin He, Elizabeth Bernhardt, Peter Hacke (NREL); Anubhav Jain, Xin Chen (LBNL); Will Hobbs (Southern Company); Michael Bolen, Daniel Fregosi (EPRI)

Summary of Result: Wind and other routine environmental stressors can turn benign PV cell cracks into harmful ones, which are linked to performance degradation and safety issues. Today, it is not possible to predict crack propagation, and subsequent power loss, based on crack characteristics. Through a combination of physical testing and modeling simulations, we are developing methods to predict long-term power loss from nascent cracks. We first measured PV module deflection and vibration outdoors in response to wind conditions. We then used fluid dynamic simulations to replicate the field conditions and prescribed two levels of accelerated loading tests. A novel apparatus for dynamic mechanical accelerated testing, called DMX, uses subwoofers to apply low-pressure (<200 Pa), realistic-frequency (~10 Hz) sinusoidal pressure cycles to modules. Within hours, test modules can be subjected to the equivalent of multiple years of the roughest wind loading exposure that they might see outdoors. At interim points, we assessed module performance and cell crack characteristics. For the first time, it is possible to directly observe crack progression. In initial tests, cell fragments became totally disconnected over the course of thousands and millions of wind loading cycles, suggesting power loss. This work supports the development of correlations between crack characteristics and power loss.

The dynamic mechanical acceleration (DMX) apparatus enables years of field-relevant mechanical load testing of modules within hours.



EL was collected during a million-cycle, 100-Pa (RMS) test on DMX. Early results show that modest cycles age cracks.

LEARN MORE

2021. "Characterization of Wind Loading and Temperature Effects on Cell Cracks." Presented at the DuraMAT Fall Workshop, Sep. 15–17, 2021.

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

Year-Over-Year Characterization of Fielded Modules: DuraMAT Fielded Module Study

PI: Bruce King (Sandia)

Team Members: Josh Stein and Jennifer Braid (Sandia)

Summary of Result: The DuraMAT Fielded Module Study has established a collection of modern photovoltaic modules—selected for technological interest and commercial relevancy—to study material degradation and develop and validate nondestructive field forensics methodologies. One module from each array is selected each year for destructive characterization, while all remaining modules are characterized using nondestructive methods. Characterization prior to deployment and retention of pristine samples of each module minimizes uncertainty as to initial state of the modules, a common limitation of contemporary fielded module degradation studies.

By the end of FY 2021, six arrays had been fielded for 30 months and a seventh had been fielded for 18 months. Year-over-year testing demonstrates that most modules in this study display an initial power degradation rate of 1%–2%/year that slows in subsequent years. This result is consistent with observations from larger arrays of the same types. A single module type from Panasonic is flat year-over-year. In contrast, this same module type displays pronounced yellowing of the backsheet, while most other modules show minimal changes. A library of core samples has been extracted from each module type ranging from no exposure to 2 years, queued for characterization of polymeric materials in FY 2022.

Manufacturer	Rating, W	Initial	Year 1		Year 2	
			Power, W	Rd, %/yr	Power, W	Rd, %/yr
Canadian Solar	300	300 ± 2	295 ± 1	-1.8	293 ± 1	-1.2
Hanwa Q-Cells	300	302 ± 1	295 ± 1	-2.2	293 ± 1	-1.5
Itek	360	358 ± 1	351 ± 1	-2.2	-	-
Jinko	270	273 ± 1	268 ± 1	-1.9	264 ± 1	-1.6
LG	320	319 ± 1	316 ± 1	-0.9	314 ± 1	-0.8

Figure 1: Annual electrical recharacterization is performed in conjunction with polymeric materials characterization. Year-over-year power degradation is consistent with observations from larger arrays.

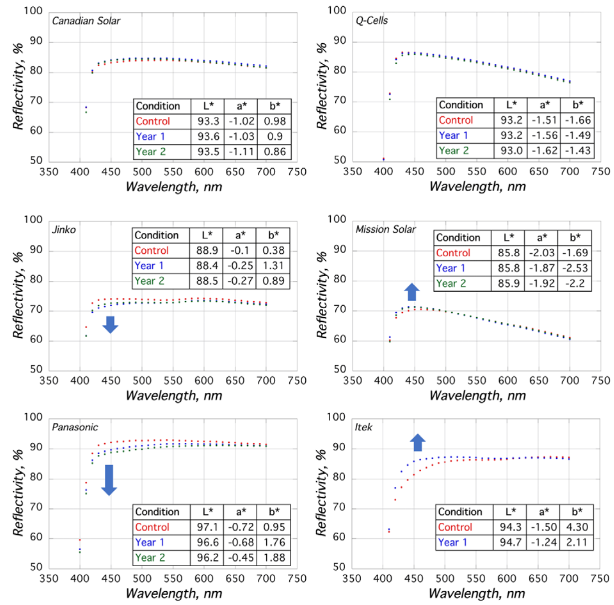


Figure 2: Nondestructive characterization of factors such as backsheet yellowing allows year-over-year tracking of material changes as a result of natural exposure. Several modules display changes in color early in life.

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To learn more, contact Bruce King (*bhking@sandia.gov*) or Josh Stein (*jsstein@sandia.gov*).

Project Webpage: *https://www.duramat.org/field-deployment.html.*

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 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.

Module Materials Solutions

Core Objective

KEY RESULT

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

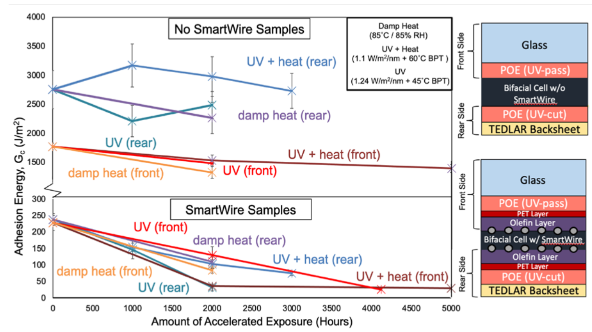
PI: Reinhold Dauskardt (Stanford University)

Team Members: Patrick Thornton, Ziyi Pan, and Oliver Zhao (Stanford University); Laura Schelhas (NREL); Mihail Bora (LLNL); Jared Tracy and Kaushik Roy-Choudhury (DuPont); Paul Roraff (SolarTech Universal)

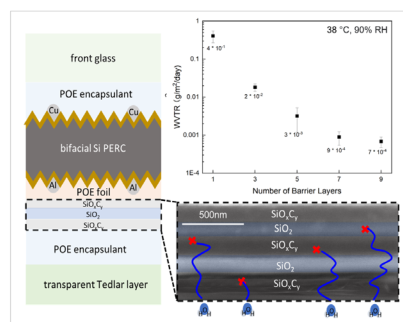
Summary of Result: We are addressing two major challenges through our research. In Thrust 1, we seek to quantify the adhesion and investigate the main degradation mechanisms in polyolefin (POE)-encapsulated bifacial modules, both with and without SmartWire connection technologies, using our advanced interface reliability characterization and modeling capabilities. In Thrust 2, we aim to develop and validate a highly transparent protective back lamination technology with markedly improved adhesion and moisture protection as a back glass replacement.

Here, we use methods such as X-ray scattering, Fourier transform infrared spectroscopy-attenuated total reflection (FTIR-ATR), and adhesion measurement techniques to characterize the chemical and mechanical properties at critical interfaces within bifacial modules as they are aged in field-relevant conditions. In Thrust 2, we develop our open-air plasma-deposited multilayer barrier films for improved moisture barrier properties and adhesion to relevant interfaces by iterating through plasma process conditions and chemical precursors and evaluating their barrier functionality with a water-sensitive infrared camera.

Recent highlights include a comprehensive quantification of adhesion after accelerated exposure to various field-relevant conditions (Figure 1); we have also successfully demonstrated deposition of a multilayer thin-film plasma-deposited barrier with a water vapor transmission rate of 7 x 10^{-4} g/m^2/day and confirmed the formation of smooth, conformal, and highly transparent SiO_2 film (Figure 2).



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.



Full encapsulation structure including novel light-weight transparent back lamination. Bottom right is a cross section SEM image of the multilayer plasma-deposited barrier, which prevents moisture ingress. Graph depicts the WVTR decreasing as the number of barrier layers increases.

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For more information about this work, see: *https://www.duramat.org/module-encapsulation-barrier.html*.

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*.

Module Material Solutions

Core Objective

KEY RESULT

The Connection Between Surface and Bulk Degradation Remains To Be Established After Steady-State Aging of PV Backsheets

PI: Peter Pasmans, Christopher Thellen (Endurans Solar)

Team Members: Naila Al Hasan, David Miller, Laura Schelhas, Kent Terwilliger (NREL); Bruce King (Sandia); Archana Sinha, Soňa Uličná (SLAC)

Summary of Result: As the PV industry rapidly expands across the world, there has been a growing interest in increasing the lifespan and reliability of PV modules. Recently, concern has emerged regarding end of life and recyclability of modules and their component materials, including fluoropolymer-based backsheets. This study examines seven traditional and emerging non-fluoropolymer backsheets, subject to accelerated or natural aging. Based on the microscale appearance in Fig. 1c, some unaged backsheets are readily distinguished between photolytic (A3) and hygrometric (85°C/85%) aging. In Fig. 1b, bulk damage may be correlated with crystalline content and phase transformation enthalpy. Furthermore, in Fig. 1a, the changes in polymer chemical structure at the backsheet surface can be compared between backsheets and test conditions. Although distinct changes have been identified, the correlation between surface and bulk damage remains to be established. The BACKFLIP project will compare the performance and durability of the backsheets through accelerated testing (damp heat, IEC TS 62788-7-2) and natural weathering. Examinations will be analyzed to correlate performance to the microstructure, including discoloration (b*), gloss, macro- and micro-appearance, MiMo I-V performance, EL characteristics, mechanical tensile characteristics, DC breakdown voltage, differential scanning calorimetry (DSC), crystalline structure (wide- and small-angle X-ray scattering), and polymer chemistry (FTIR).

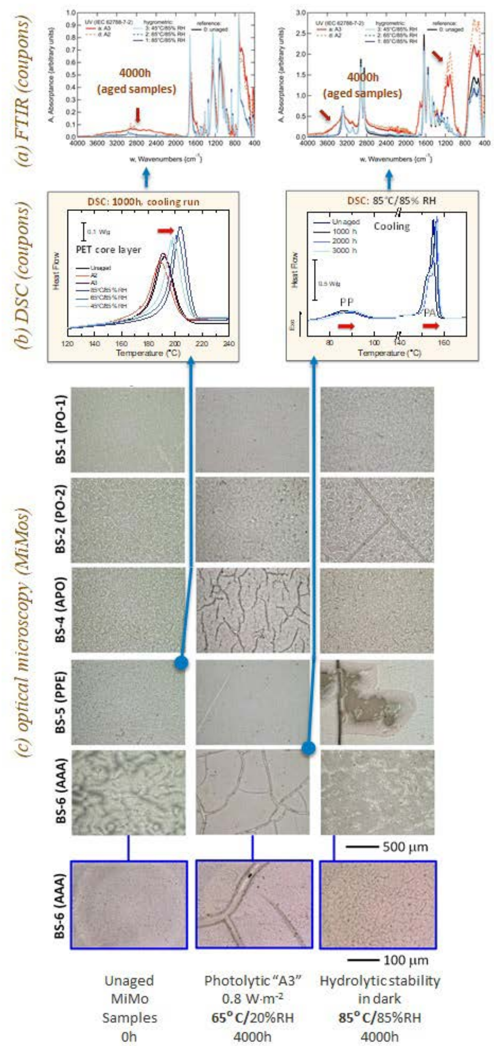

Figure 1. A variety of affected layers (surface or core) and corresponding stress factors (ultraviolet photodegradation, hydrolysis, thermal degradation) have been observed. Representative results are shown for (a) FTIR-polymer chemical structure, (b) DSC-crystalline content, and (c) optical microscopy of the air-side surface.

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Thuis et. al. 2021. "A Comparison of Emerging Nonfluoropolymer-Based Co-Extruded PV Backsheets to Industry-Benchmark Technologies." *IEEE Journal of Photovoltaics* (in press). *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." In *Proceedings of IEEE Photovoltaic Specialists Conference* 1842–1847. *https://doi.org/10.1109/PVSC43889.2021.9518781*.

Module Materials Solutions

Core Objective

KEY RESULT

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

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

Team members: Andre Chavez and Brian Rummel (Osazda Energy and University of New Mexico); Brian Rounsaville and Ajeet Rohatgi (Georgia Institute of Technology); Nick Bosco (NREL)

Summary of Result: 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 (Fig. 1). Composite metallization with short carbon nanotubes (-▲-) 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 (-●-) can equally bridge large gaps ~60 µm upon initial crack, but rapidly levels off to ~20 µm after repeated open- and closed-gap cycles. In contrast, the standard metallization (-■-) 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 (Fig. 2), 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 (-●-) shows greater critical open displacement than the formulation with short carbon nanotubes (-●-) 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.

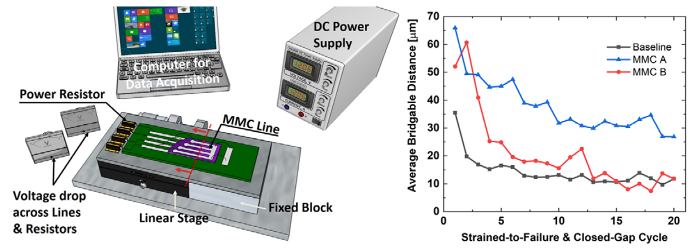

Figure 1. (Left) RACK testing setup to measure the conductance through grid fingers as they are tensilely strained at micrometer increments to failure. (Right) The summary of two different metal matrix composite (MMC) formulations compared to the baseline.

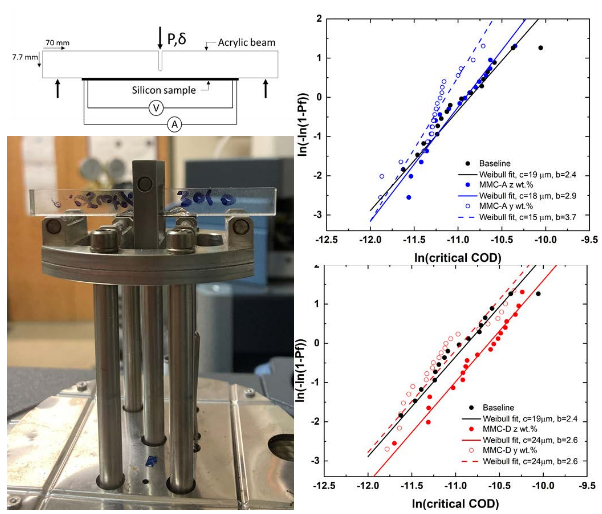

Figure 2. (Left) Three-point bend test setup to measure the conductance through grid fingers as they are flexurally strained at sub-micrometer increments to failure. (Right) The Weibull plots of two different MMC formulations at various CNT concentrations.

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http://www.osazda.com

Abudayyeh, Omar K., Andre Chavez, Sang M. Han, Brian Rounsaville, Vijaykumar Upadhyaya, and Ajeet Rohatgi. 2021."Silver-Carbon-Nanotube Composite Metallization for Increased Durability of Silicon Solar Cells Against Cell Cracks," *Solar Energy Materials and Solar Cells* 225, 111017: 1–7.

Hahn, Sang M. 2021. "Advanced Composite Metallization Using Multiwalled Carbon Nanotubes." In Task 13 Report 4.5 Cell Interconnection and Metallization, International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), pp. 61–65, IEA-PVPS T-13-13:2020 (January 2021).

Hahn, Sang M. 2021. "Optimization of Carbon-Nanotube-Reinforced Composite Gridlines Towards Commercialization." Presented at the 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC).

Module Materials Solutions

Core Objective

KEY RESULT

Challenges in PV Reliability in Glassless Modules: Advanced Material Development to Support Low-Levelized-Cost-of-Energy 25-Year Flexible Photovoltaic Modules

PIs: Hoi Ng (SunPower)

Team Members: Namrata Salunke (SunPower); Mike Kempe and Peter Hacke (NREL)

Summary of Result: Flexible solar panels bring photovoltaic (PV) accessibility in scenarios where restrictions such as load or assembly make it difficult to use conventional glass solar panels. With the removal of glass, the flexible panels are susceptible to damage from environmental elements that a glass frontsheet provides protection from. The goal of this project is to identify and develop materials for flexible panels that can last 25 years in the field. These new materials need to be tested appropriately to determine their performance and lifetime. Use of previously unexplored materials also brings in the need to identify and test for risks that proven module materials would not experience. The project is identifying materials with high probability of success and testing them for lifetime in high-risk scenarios such as ultraviolet, thermal, and moisture exposure. Figures 1 and 2 highlight the variability in the degradation behavior of the materials tested. The learnings from the previous program aimed at finding frontsheet options for flexible panels and the multiple cycle of learnings help with further improvement on test conditions. The outcome will help with understanding how various polymers degrade in various environments, along with guidelines for test parameters that will be helpful for validating new polymers for PV use.

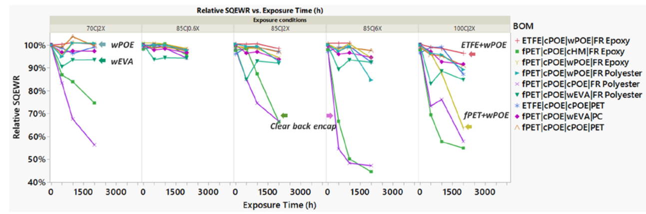

Figure 1. Materials showing various degradation behavior for 2,000-h aging time. Relative solar quantum efficiency weighted reflectance (SQEWR) is used as a measure of degradation.

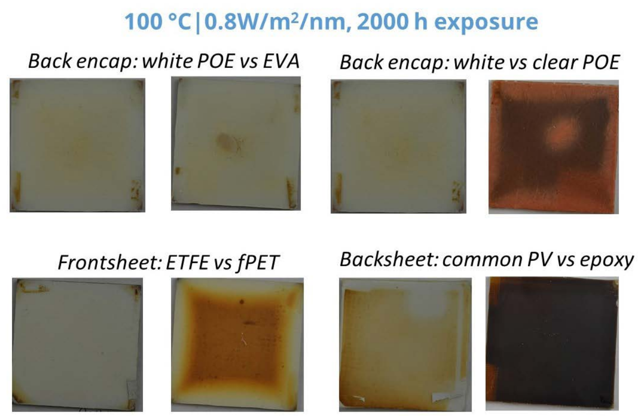

Figure 2. Comparison of the most notable differences in material degradation of various materials for 100°C and 0.8-W/m²/nm conditions after 2,000 h of aging.

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Project Webpage: *https://www.duramat.org/flexible-pv-module-material-development.html.*

DuraMAT Workforce Development

Workforce development is central to DuraMAT's mission. Our DuraMAT Early Career Scientists (DECS) program enables early-career scientists and postdoctoral researchers to participate in research and leadership roles at the national laboratories. Through these roles, early-career researchers can develop skills that will prepare them for careers in the PV industry or national laboratories. Each lab has one or two DECS participants who are primarily funded (>50%) to work on DuraMAT projects. Together, these participants serve as the "glue" that holds the consortium together.

This year, the DECS participants shifted their focus to issues related to double-glass module designs, with a particular emphasis on polymeric components. Soňa Uličná (SLAC) and Michael Owen-Bellini (NREL) delivered a DuraMAT Webinar in May that discussed some of these issues. In addition, the DuraMAT focus groups for glass/glass modules and cell cracking were organized by DECS members Martin Springer (NREL), Dana Kern (NREL), Jennifer Braid (Sandia), Archana Sinha (SLAC), and Xin Chen (LBNL).

The 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. In addition, a number of journal papers have been published in the last year from various member of DECS.

DuraMAT Workshop Fall 2021, Microsoft Teams

The 2021 DuraMAT Fall Workshop took place on September 16–17, 2021. This year's location was the exotic virtual Microsoft Teams space. We had over 70 attendees from national laboratories, universities, and the PV industry. The workshop was scheduled over three half days, with a mix of talks and discussion sessions each day. The talks provided the community with an update on and overview of DuraMAT's progress, and the discussion sessions provided a platform to review how DuraMAT's efforts are addressing current and future issues in PV module material reliability.

DuraMAT Director Teresa Barnes kicked off the three-day event with a summary and overview of the past year. Each day then focused on one or two of the core objective areas. Our core objective leaders gave live overview presentations on each core objective. Each overview presentation was followed by a highlight talk about a project in each focus area. In addition to the live talks, all current DuraMAT project teams submitted prerecorded posters, which were available for on-demand viewing before, during, and after the workshop. Day two featured a keynote presentation from Dirk Jordan on PV analytics and lifetime. Teresa also a led a tech scouting panel, titled What's New and What's Next in PV, with representatives from our industry advisory board (IAB)—Mike Woodhouse (NREL), Jenya Meydbray (PV Evolution Labs), Henry Hieslmair (DNVGL), and Rob Andrews (Heliolytics)—rounding out the panel. Much of the discussion was centered around module bill of materials, emphasizing the importance of knowing as much about the modules as possible. We also heard about efforts to standardize module dimensions and discussed 2020 as the year for big, big, and bigger modules. Finally, as modules last longer, we discussed the importance of understanding end-of-life failures and degradation modes. DuraMAT was encouraged to work hard to both identify and rank these modes as we move forward in our program.

The discussions and breakout sessions are always an important feature of our fall workshops. Much like the talks, each discussion session focused on a core objective area. Discussions were led by our DECS participants and IAB members. One major advantage of the virtual format was the ability to run the discussions in series, allowing motivated researchers to attend all five sessions and not miss a moment of the action. These lively discussions helped identify research areas and problems for the DuraMAT program. Much like last year, trends emerged, and this year's hot topics were again focused on cracks and glass/glass modules; there were also some discussions about climate considerations and lifetime modeling. Stay tuned for this year's working groups, which will be focused on these topics (see DuraMAT working groups to learn more).

As we look toward the next phase of DuraMAT, our IAB was enthusiastic about our progress and impact on the PV community. One IAB member said that "DuraMAT has really hit their stride" and that the projects are producing meaningful results. The IAB continues to push our outreach efforts, encouraging us to do more in this space.

This year, we promise not to jinx ourselves and tell you we look forward to seeing you in person in 2022. Rather, we wish you a safe and healthy FY22.

—Laura Schelhas, on behalf of DuraMAT leadership

Publication and Research Output

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

JOURNAL ARTICLES

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

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Accelerated Applications

Industry-Relevant Research and Tools from DuraMAT

The DuraMat Data Hub

The DuraMAT Data Hub has now been operational for four 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 202 registered users working on 76 projects that encompass 6,092 files (a 23% increase from last year). Public data sets cover areas from soiling maps to PV orientation machine-learning training sets. The Data Hub provides a central point for researchers to archive, search, and obtain experimental and reference data, analysis tools, tutorials, and reports.

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PVAnalytics

A research team from Sandia and NREL has launched the first collaborative public software library for organizing and distributing reusable code for data preparation, called PVAnalytics: *https://github.com/pvlib/pvanalytics*. This resource provides functions for quality control, filtering, feature labeling, and other tools, supporting analysis of PV system-level data.

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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. The tool has applications in predicting module deflection and cell cracking in deployment conditions.

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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 MiMo specimens. The team is interested in receiving samples for further testing (especially toward reflectance) in the next year.

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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.

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Fielded Module Study

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

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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 maximum power loss area. Hundreds of thousands of images can be analyzed very rapidly and without human input. A code repository is available at: *https://github.com/hackingmaterials/pv-vision*.

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PVTOOLS: Interactive Web Site for DuraMAT Tools

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

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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 electricity. The online tool is at: *https://pvlcoe.nrel.gov*.

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DuraMAT
Durable Module Materials Consortium

FY 2021 ANNUAL REPORT

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

duramat.org

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