SAND2019-1998D

Discover, Develop, and De-Risk module materials, architectures, accelerated testing protocols, data analytics, and financial models to reduce the LCOE of solar energy

Multi-Scale Multi-Physics Modeling for PV Reliability

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DuraMAT Capabilities

1. **Data Management & Analytics, DuraMAT Data Hub**
2. **Predictive Simulation**
3. **Advanced Characterization & Forensics**
4. **Module Testing**
5. **Field Deployment**
6. **Techno-Economic Analysis**

Modeling Capability Goals

- A suite of simulation tools and workflows and a community of experts, used to generate data to expand the durability test space and help interpret and enrich existing test/experimental data
- Partnered with **Data Analytics**, **Advanced Characterization & Forensics**, and **Module Testing** capability areas

Accomplishments

- Developed full-scale module mechanical models for c-Si glass-backsheet and glass-glass thin film architectures, and validated against experimental loaded deflection data
- Collected data for EVA and Polyolefin encapsulants necessary to populate constitutive models; computational implementation in progress

Outcomes and Impact

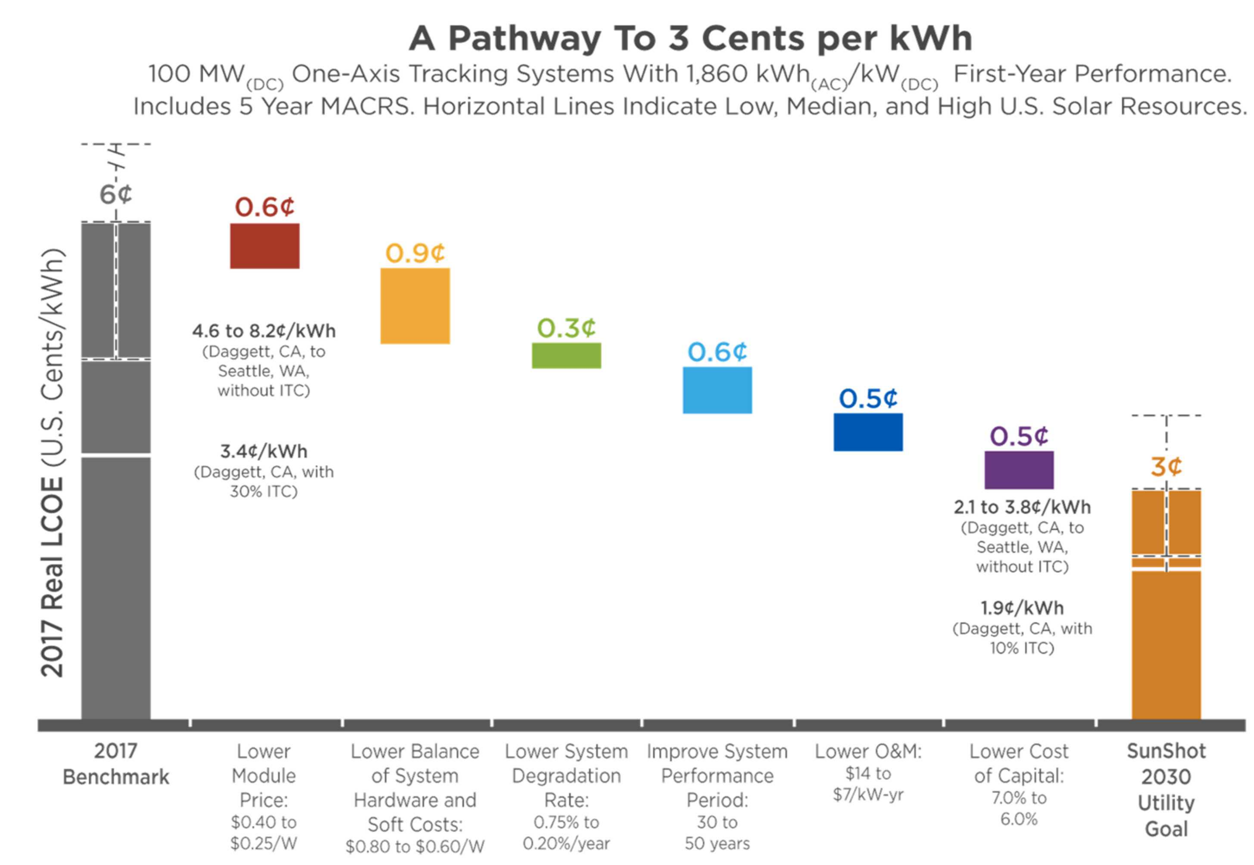
- Predictive models enable smarter service life predictions and accelerated test specification
- Informs best practices for material choice and module design, and aids interpretation and identification of new degradation mechanisms
- Reduces costs by optimizing all phases of module deployment: design, testing, production, service life

Capability Development

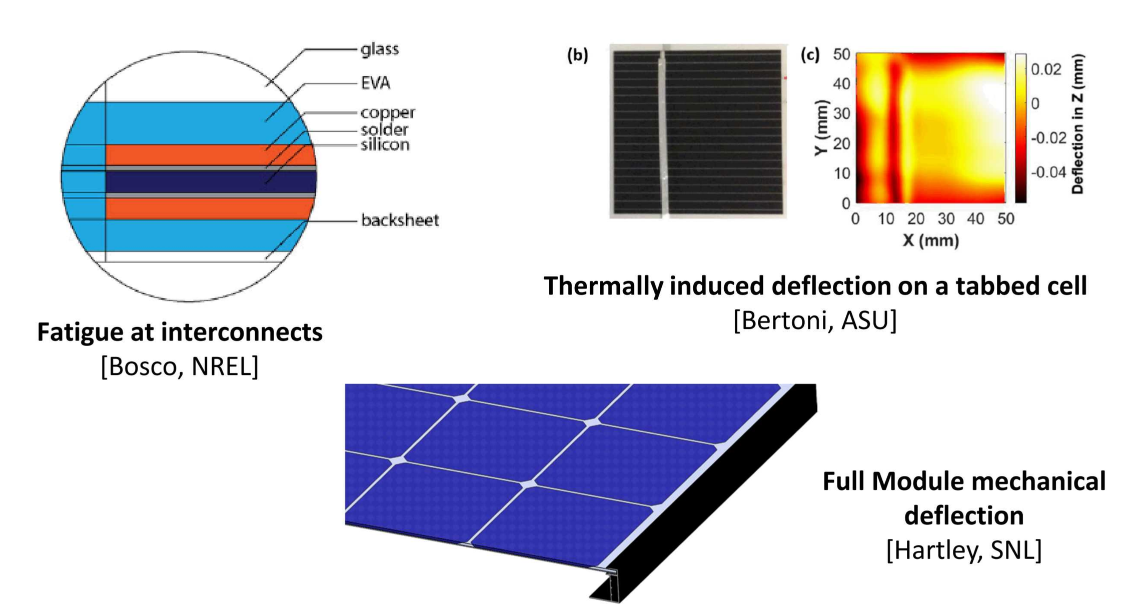
Failures in deployed photovoltaic modules occur by complex physical mechanisms

- **Motivation:** A predictive model is needed to better understand how module deployment environments induce the damaging thermal-mechanical stresses leading to module degradation, via delamination, cell fracture, and solder bond fatigue- among other mechanisms.
- **Capability vision:** A module-scale modeling capability capturing key degradation physics at the length- and time- scales of interest, tightly coupled with experimental material and module characterization efforts to receive information for model validation while enriching interpretation of measurement results. The final validated and informed capability would enable accurate lifetime predictions, efficient accelerated test specification, and optimized module material selection and design for durability.
- **Current development efforts and accomplishments:** Full-scale module mechanical models developed and validated against experimental deflection data, for c-Si, glass-backsheet and thin-film glass-glass module architectures. Data to populate viscoelastic encapsulant constitutive models collected. Next steps include computational implementation of encapsulant viscoelasticity, and an application case to correlate full module scale modeling insights against mini-module experiments.

Cost Drivers



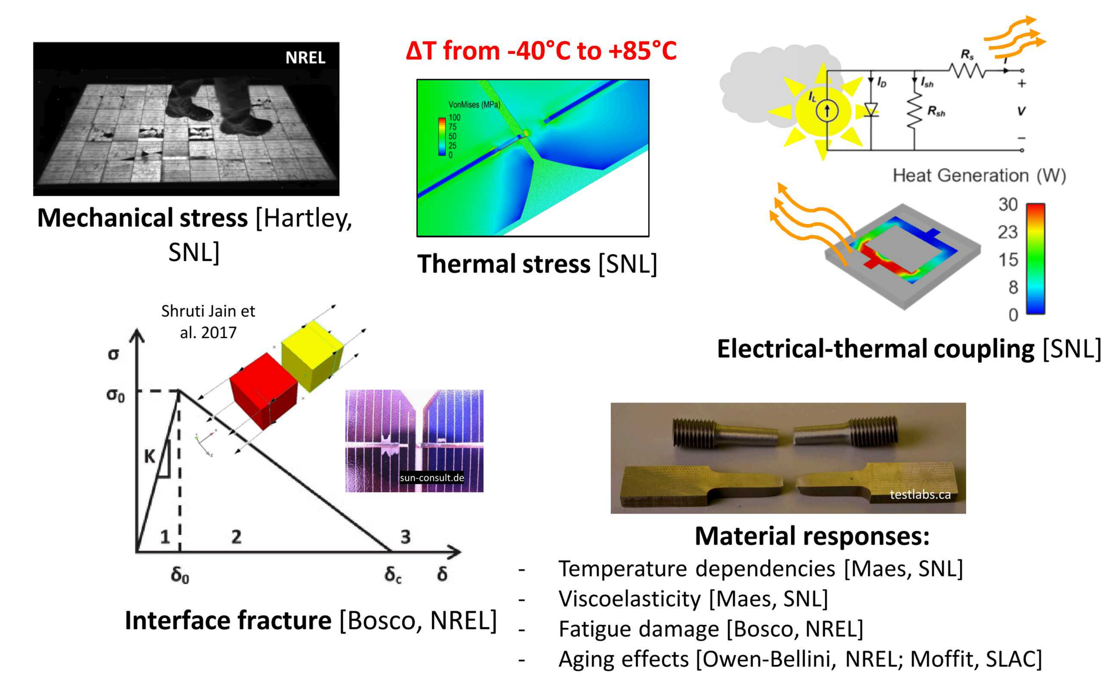
Multi-Scale Modeling Capabilities



Modeling capabilities to predict stressors at various scales of a PV module: from interconnects to cells to full modules

- Multiple scales enable efficient resolution of specific degradation mechanisms. For example:
  - Propagation of full module deflections to stress at specific cell and interconnect positions; to inform detailed, location-specific solder fatigue prediction

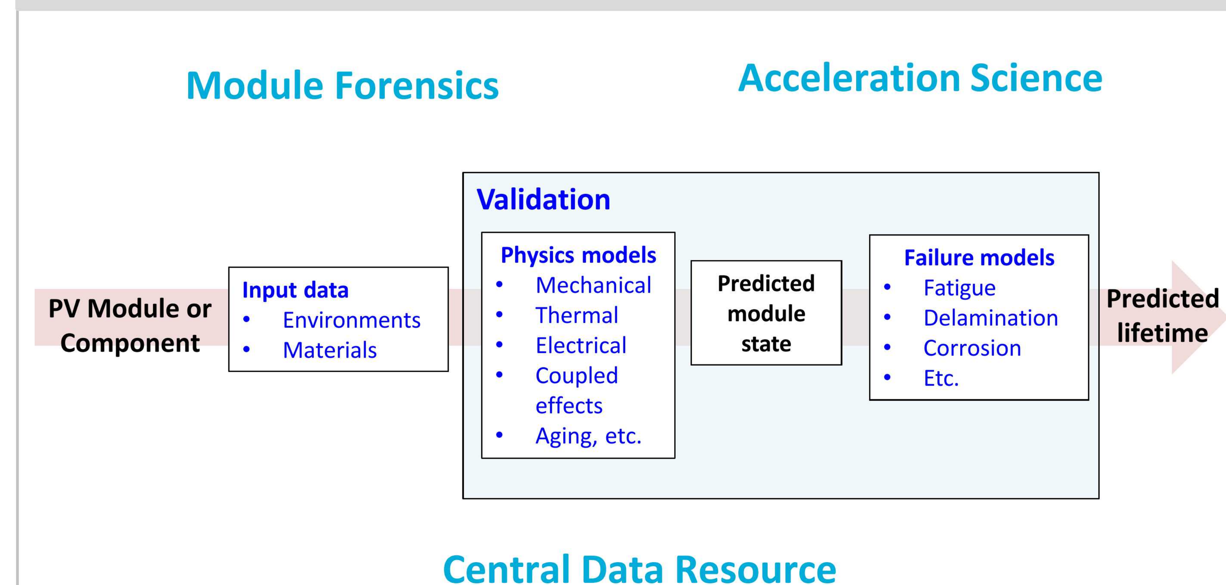
Multi-Physics Modeling Development



Development of physics models for degradation related phenomena

- Degradation physics being implemented include mechanical, thermal, and electrical effects, as well as failure models for material fatigue and interface fracture
- Detailed material response including viscoelasticity and aging are also considered physics of interest

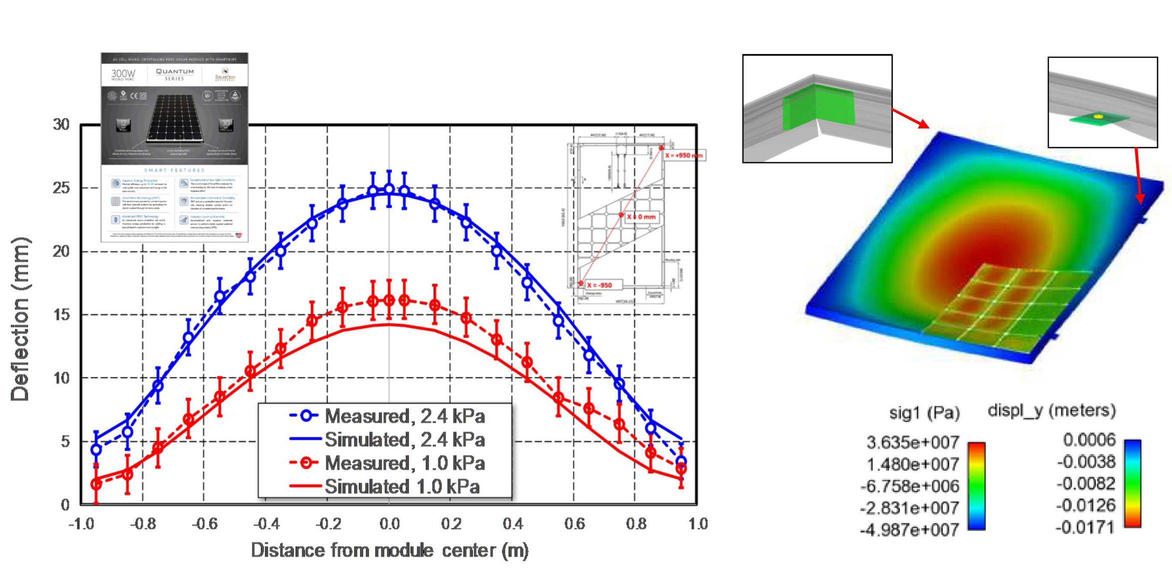
Capability Roadmap



Capability end goal is to accurately predict lifetime for any PV module or component, leveraging module forensics, acceleration science, and data resource capabilities

- Required inputs to generate a lifetime prediction include environmental exposure data and physics models to understand module state, then failure criteria models
- Module forensics, acceleration science, and data resource capabilities provide supporting information for model development, including model validation evidence

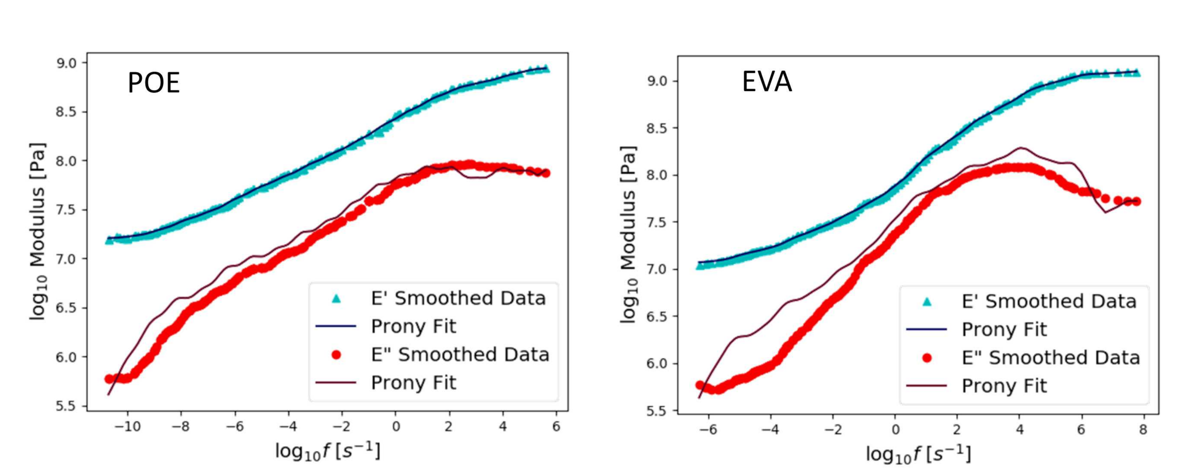
A Module Scale Mechanical Model



Simulated vs. Measured Deflection under load across module diagonal for a c-Si module, with model construction details

- A commercially available module was translated to a finite element model and validated against experimentally collected deflection vs. load data, under IEC61215 pressure loads
- Detailed parameter sensitivity analyses are being performed to develop an understanding of key influential design parameters
- Parallel analyses for a thin-film glass-glass module architecture are also underway

Material Models for Encapsulants

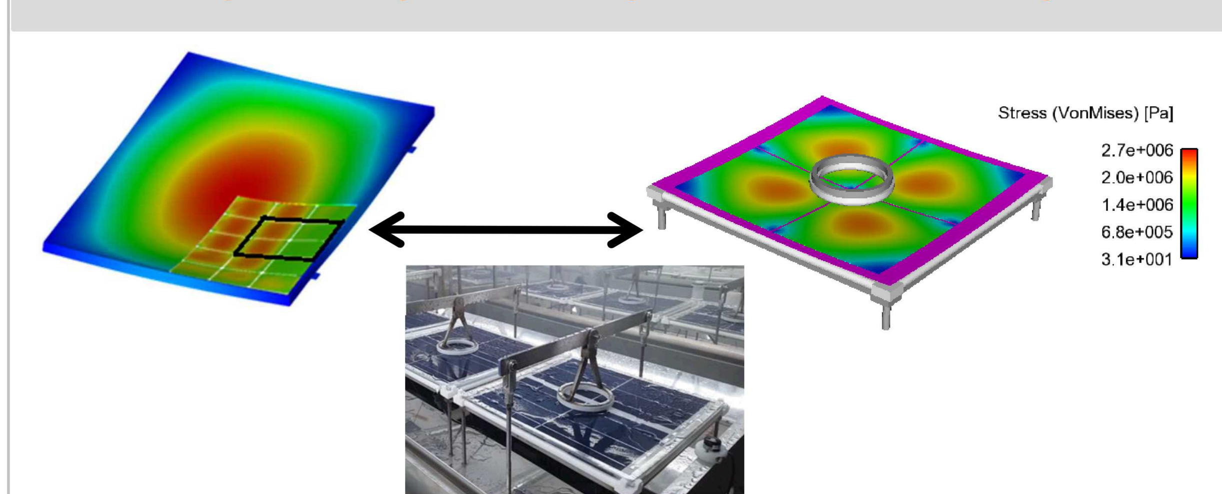


Master curve data and Prony series fit of a commercial polyolefin elastomer (POE) *(left)* and commercial poly(ethylene-co-vinyl acetate) (EVA), fully crosslinked *(right).*

Prony series fits of master curve data capture both the elastic and viscous material responses of polymer encapsulants

- Mechanical and thermal characterization was conducted on two common commercial encapsulants
- Parameters from the WLF time-temperature shift, fitting of coefficient of thermal expansion (CTE) data, and the above Prony series fits will be combined in Sandia's Universal Polymer Model for direct use in cell-scale and module-scale finite element models

Capability Development Next Steps



"Correlation of advanced accelerated stress testing procedures with field data through advanced characterization and data analytics" PI: M. Owen Bellini

A high-fidelity mini-module model provides a testbed for advanced material models and allows comparisons with full module models

- A model application case exists to assess mini-module (commonly used in accelerated testing) representativeness against full module behavior
- Mini-module finite element model will be a useful testbed for implementing new physics capabilities, including but not limited to viscoelastic material models, solder fatigue models, and cohesive zone models for encapsulant delamination