The Outdoor Test Facility is one of several locations where NREL researchers deploy and study various PV technologies in an outdoor setting. *Photo by Josh Bauer, NREL 59047*

PV Module & System Reliability Research

While photovoltaic (PV) technologies have experienced widespread success and adoption, continued growth of these technologies—especially new PV technologies—requires ongoing improvements to their reliability and the testing procedures, data, and standards that underpin them.

To better understand and address failure mechanisms of PV modules and systems, NREL conducts testing, models failures, analyzes performance data, helps to develop standards, and convenes expert stakeholders. This work is focused both on improving the performance of industry-dominant PV technologies and rapidly de-risking new PV technologies so they can be proven reliable without decades of field testing.

Core Competencies and Capabilities

- **Accelerated Testing and Modeling**—NREL develops accelerated tests to replicate known failure mechanisms and to discover new failure mechanisms. Recent work has focused on combined accelerated stress testing (C-AST), which applies multiple stressors simultaneously (heat/cold, moisture, UV, current bias, mechanical stress, etc.) to more closely replicate years of outdoor exposure in only weeks or months. Concurrently, we are co-developing thermomechanical models with Sandia National Laboratories to help understand the underlying physics of PV failures. Both of these efforts are informed by detailed characterization of failures from fielded samples. Our goal is to better understand observed failures and to anticipate new failures, especially in new PV technologies.

- **Outdoor Testing**—To complement our laboratory testing, NREL also conducts outdoor testing of PV modules and systems. Working with Sandia National Laboratories, NREL maintains the U.S. Department of Energy Regional Test Centers, which offer PV module manufacturers locations in different U.S. climate zones in which to validate their modules' reliability. Our PV Lifetime Project provides a similar, publicly available dataset from fielded modules. NREL also evaluates and compares the performance of monofacial and bifacial PV modules on a single-axis tracking system.

- **Performance and Reliability Analysis**—Ultimately, PV reliability is realized in the performance of large, fielded systems over many years. NREL developed RdTools™—a set of open-source software—to analyze PV system performance data for degradation rates and soiling effects. Using RdTools and other techniques, our PV Fleet Performance Data Initiative is collecting and analyzing multi-year data from dozens of large PV systems to better estimate performance and degradation rates across the entire U.S. solar fleet. As bifacial modules have become more common, NREL researchers have also co-developed Bifacial Irradiance, a practical tool for modeling bifacial gain.

- **Industry Engagement**—Each year, NREL convenes an international workshop for PV reliability researchers and industry experts. All who attend the PV Reliability Workshop (PVRW) must present a talk or poster, creating a highly interactive forum for discussion of the latest issues in PV reliability. NREL is also a lead partner in the Durable Module Materials Consortium, which brings together national labs, universities, and industry to discover and de-risk new materials and designs for PV modules.
- **International Standards**—NREL helps to organize the International PV Quality Assurance Task Force (PVQAT), which defines quality assurance standards that can differentiate PV products according to their durability in various climates and creates manufacturing guidelines for consistent quality.
- **Circular Economy**—NREL is studying new module materials and designs that could be optimized for recycling, refurbishment, or other reuse in a circular economy for energy materials. Maintaining reliability while improving circularity of modules is a key focus of this work.

Recent Publications

Outdoor PV Performance

Dirk Jordan, et al. "PV field reliability status—Analysis of 100 000 solar systems," *Progress in Photovoltaics* (2020), https://doi.org/10.1002/pip.3262.

Dirk Jordan, et al. "Photovoltaic failure and degradation modes," *Progress in Photovoltaics* (2017), https://doi.org/10.1002/pip.2866.

Bill Marion, et al. "Measured and Modeled Photovoltaic System Energy Losses from Snow for Colorado and Wisconsin Locations," *Solar Energy* (2013), https://doi.org/10.1016/j.solener.2013.07.029.

Accelerated Testing and Failure Analysis

David Miller, et al. "Degradation in Photovoltaic Encapsulation Strength of Attachment: Results of the First PVQAT TG5 Artificial Weathering Study," *Progress in Photovoltaics* (2020), http://dx.doi.org/10.1002/pip.3255.

Michael Deceglie, et al. "Light and Elevated Temperature Induced Degradation (LeTID) in a Utility-scale Photovoltaic System," *IEEE Journal of Photovoltaics* (2020), https://doi.org/10.1109/JPHOTOV.2020.2989168.

M. Kempe, T. Lockman, and J. Morse, "Development of Testing Methods to Predict Cracking in Photovoltaic Backsheets," *IEEE 46th Photovoltaic Specialists Conference* (2019), https://doi.org/10.1109/PVSC40753.2019.8980818.

Wei Luo, et al. "Analysis of the Long-Term Performance Degradation of Crystalline Silicon Photovoltaic Modules in Tropical Climate," *IEEE Journal of Photovoltaics* (2018), https://doi.org/10.1109/JPHOTOV.2018.2877007.

Combined accelerated stress testing (C-AST) chambers can subject PV modules to heat, cold, moisture, UV, current bias, and mechanical stress, often simultaneously. *Photo by Peter Hacke*

Power Electronics and System Engineering

Ramanathan Thiagarajan, et al. "Effects of Reactive Power on Photovoltaic Inverter Reliability and Lifetime," *IEEE 46th Photovoltaic Specialists Conference* (2019), https://doi.org/10.1109/PVSC40753.2019.8980568.

Peter Hacke, et al. "A status review of photovoltaic power conversion equipment reliability, safety, and quality assurance protocols," *Renewable and Sustainable Energy Reviews* (2018), https://doi.org/10.1016/j.rser.2017.07.043.

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