A Decade of Testing at PVEL: Product Types Over Time

2010

The early days

- P-type mono and multi, thin film and CPV technologies
- All cells are 156mm with 3 busbars
- Monofacial only

2012

Limited cell innovation

- Half-cut cells introduced for early-adopter testing
- Incremental cell design improvements
- New backsheet and encapsulant materials

2014

Significant cell advances

- 8 different cell technologies tested, including n-type PERT, p-type PERC, heterojunction (HJT)
- 3 different cell sizes and 4 busbar combinations

2016

PERC begins to dominate

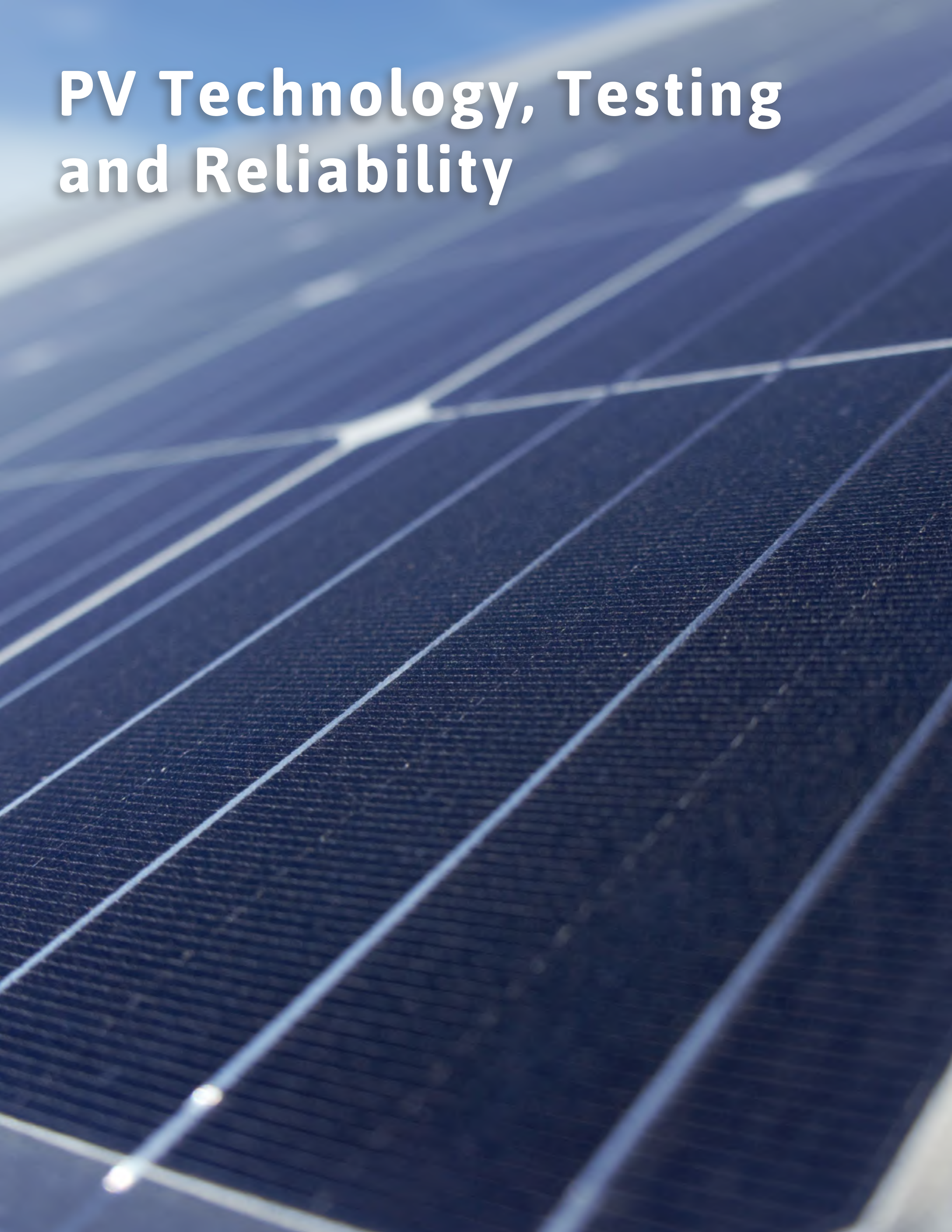
- Product mix tested is fairly consistent as manufacturers validate PERC cell technologies
- Larger cells are introduced (up to 161.7mm)

2018 to present

Major cell and module advancements

- 8 different cell sizes
  125mm, 156mm, 156.75mm, 157.25mm, 158.75mm, 161.7mm, 162mm, 166mm
- 8 different cell technologies
  p-type mono Al-BSF, p-type multi and mono PERC, n-type mono PERT, HJT n-type mono, p-type bifacial mono PERC, n-type bifacial mono PERT, CdTe
- Cells with 5 different counts of busbars
  3, 5, 6, 9, 12
- Monofacial and bifacial glass-glass modules
- Monofacial and bifacial glass-backsheet modules
- 4 different cell interconnection types
  Standard ribbons, ECA (shingled), interdigitated backcontact (IBC), metal wrap-through (MWT)

PV Technology, Testing and Reliability



Trends in PV Module Manufacturing

In only a few years, the PV module manufacturing landscape has changed dramatically. From the rapid ascendance of PERC cell technology to increased adoption of bifacial products, PV module buyers face an increasingly complex marketplace. The results in this year's Scorecard demonstrate that developers, investors and asset owners are directly affected when manufacturers adopt new processes or begin using new components. **PVEL has observed three important trends in PV module technology that are particularly important for downstream stakeholders to consider from a risk-mitigation perspective.**

1. Large-scale adoption of PERC cell architectures

Passivated emitted rear contact (PERC) cells have quickly replaced the once-predominant aluminum back surface field (Al-BSF) cells.

Risks

Some PERC cells are susceptible to light and elevated temperature induced degradation (LeTID), which can reduce energy yield by as much as 10% in the field. Susceptibility to boron-oxygen destabilization may also be a concern.

Rewards

PERC cells are higher efficiency and usually perform better in low-light and high-temperature conditions, and they can be produced at comparable costs to Al-BSF.

2. New cell designs: more busbars, round interconnect wires, larger wafers, half or third-cut cells

Manufacturers are now using cells with up to 4x more busbars than in 2012, new types of interconnect wires, various wafer sizes, as well as half-cut or smaller cells.

Risks

Some new cell designs are more susceptible to microcracks and may require difficult-to-implement process changes on manufacturing lines that lead to increased defect rates.

Rewards

New cell designs are driving higher efficiencies and nameplate power ratings in PV modules, and leading to decreased costs.

3. New module designs: thinner frames, glass-glass, bifacial, light-redirecting films (LRF)

PV module manufacturers are competing to introduce lighter weight modules, bifacial options, novel designs and physically larger modules.

Risks

Newer module form factors may be more susceptible to damage, and they may not be compatible with existing mounting systems. The industry lacks long-term field data for new components and designs.

Rewards

Lighter modules are easier to transport and install. New designs and materials can increase nameplate power ratings.

As manufacturers rush to bring new technologies to market, PVEL is observing a resurgence of known failure mechanisms, plus new degradation modes.

PV Module Failure Modes and Aging Mechanisms

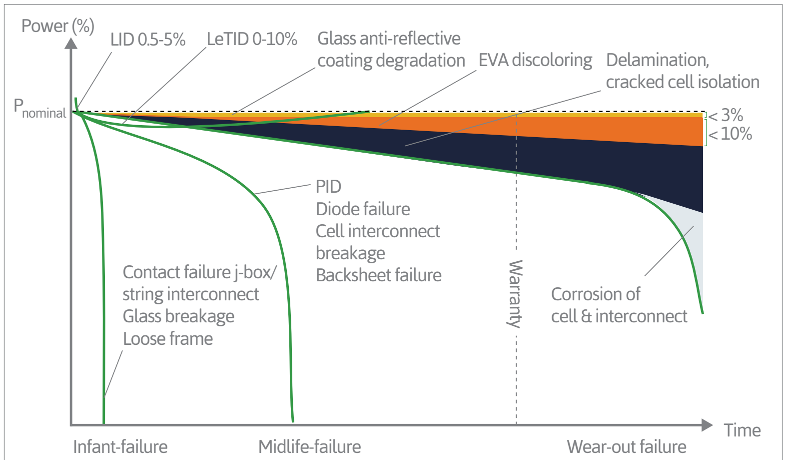
PV modules are vulnerable to a range of failure modes and aging mechanisms. For a PV module to perform reliably for the duration of its modeled lifetime, manufacturers must follow tightly-controlled processes and use quality components. **Premature failure is likely when quality assurance/quality control steps are overlooked or substandard materials are used.**

Lack of long-term field data

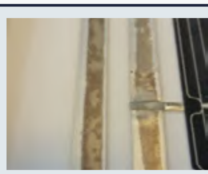
Projects built today utilize technologies and components that did not exist 25+ years ago.

Real-world data that proves the long-term reliability of many recent PV module designs does not exist today.

PV module defects are outlined in the chart to the right. PVEL has identified a selection of field-replicated defects following shipping or stress testing in the table below.



Source: IEA PVPS, 2014; LeTID and backsheet failure added by PVEL, 2019

Failure Mode	Test Sequence	Likely Cause	Project Impact
Glass breakage 	Dynamic mechanical loading (Pg. 20)	Poor frame or glass construction	Increased power loss; safety issues
Unsealing of junction box 	Damp heat (Pg. 18)	Poor component selection and/or improper potting technique	Safety issues
PID 	PID (Pg. 22)	Poor component selection, cell design and/or quality control	Increased power loss
Diode failure 	Thermal cycling (Pg. 16)	Poor diode selection and/or manufacturing quality control	Increased power loss; safety issues
Busbar corrosion 	Damp heat (Pg. 18) and humidity freeze (Pg. 20)	Poor lamination quality and/or component selection	Increased power loss
Delamination 	Damp heat (Pg. 18) and humidity freeze (Pg. 20)	Poor lamination quality and/or component selection	Increased power loss; safety issues

Limitations of Warranties and Certifications

Certifications and warranties are important prerequisites for global market acceptance and financing of solar PV technologies. However, certifications do not ensure the reliable long-term performance of modules in the field, and warranties do not provide full protection from financial losses when modules fail or degrade.

Challenges of warranties

1. **Solvency and responsiveness**
   Warranties do not protect buyers when manufacturers become insolvent or are unresponsive to claims.

2. **Imprecise measurement**
   Measuring power degradation in the field with precision is extremely difficult, so most successful warranty claims are for excessive underperformance or total failure. Warranties typically include a 3% buffer for measurement uncertainty. This 3% reduction in energy yield on top of expected annual degradation can equate to millions of dollars in lost revenue.

3. **Coverage limitations**
   Even when claims are accepted, warranties usually cover the cost of replacement modules only – not costs associated with labor or lost energy production. Due to manufacturing advances, suitable replacement modules may not even be available for older systems, and warranties do not cover the costs of system upgrades to become compatible with current module replacements.

Shortcomings of certifications

Scope limitations

IEC/UL 61730 certifications are focused on safety and non-hazardous operation. IEC 61215 only screens for defects that appear in the first few years of operation.

Golden samples

Manufacturers can submit carefully constructed samples for certification instead of testing their commercially available products, and they can often change component combinations in their module BOM without recertifying.

Slow advancement

Updating certification standards is a multi-year process that cannot keep pace with new failure modes that emerge with technology changes. Specifically, standards have been slow to address PID and LeTID.