# From Random to Repeatable: Inside the Hail Stress Sequence for PVEL's PV Module Product Qualification Program

When a Texas solar farm suffered a record-breaking $70MM USD in hail damages in 2019, alarmed insurance providers sent the regional solar market into turmoil around damage and replacement coverage. Yet results from PVEL's field and lab testing indicate that certain PV modules withstand hailstorms better than others.

## Executive Summary

This white paper explains how PVEL's hail stress sequence replicates the impact energy of natural hail and simulates field conditions to assess PV module durability. The sequence is a required test in PVEL's newest version of its PV Module Product Qualification Program (PQP).

## Hail is a Growing Problem

A single hailstorm can be devastating, and climate change is likely to bring bigger storms—and more hail—every year:

- The greatest contributor to insured losses from thunderstorms worldwide is now severe hail, defined as hail larger than 25 mm in diameter. [1]
- More than 6.2 million U.S. properties were affected by one or more hail events in 2020, with nearly $14.2 billion in claims.[2]
- Meteorologists are forecasting more frequent hailstorms in Europe and Australia. Globally, hail severity (e.g., hailstone size) is expected to increase.[3]

*Hail damage at a solar project in California*

> As a global industry, we must consider natural catastrophes like hailstorms in the context of a changing climate.
>
> It is time to futureproof solar projects for new weather patterns that are difficult to predict yet impossible to ignore.
>
> **Kevin Christy**
> Head of Innovation and Operational Excellence, Americas
> Lightsource bp

## Risk Mitigation Requires Rigorous Testing

Solar asset owners and investors want to know whether a PV module can survive a hailstorm without experiencing glass breakage. They also want to understand the longer-term performance impacts for modules that remain intact but experience cell damage.

Although baseline hail testing has been performed on solar modules since the 1970s, there is a lack of field-representative testing to support module deployment in hail-prone regions.

**PVEL's hail stress sequence addresses this information gap. The test is designed to help:**

- PV module buyers benchmark the hail resistance of different products and procure bills of materials (BOMs) that are appropriate for their projects.
- Insurers assess equipment-specific hail damage risk to inform their rates and premiums in specific project locations.

[1] Grieser, J. & Hill, M. (2019). How to Express Hail Intensity – Modeling the Hailstone Size Distribution, Journal of Applied Meteorology and Climatology, 58(10), 2328-2345. https://doi.org/10.1175/JAMC-D-18-0334.1

[2] Samanta, A., Wu, T., & Cheatham, B. (2021). The Hail Hazard and Its Impact on Property Insurance. Verisk. https://www.verisk.com/insurance/capabilities/weather-risk/hail-and-severe-thunderstorm-risk/

[3] Raupach, T., Martius, O., Allen, J., Kunz, M., Lasher-Trapp, S., Mohr, S., Rasmussen, K., Trapp, R., & Zhang, Q. (2021). The effects of climate change on hailstorms. Nature Reviews Earth & Environment, 2, 213-226. https://doi.org/10.1038/s43017-020-00133-9

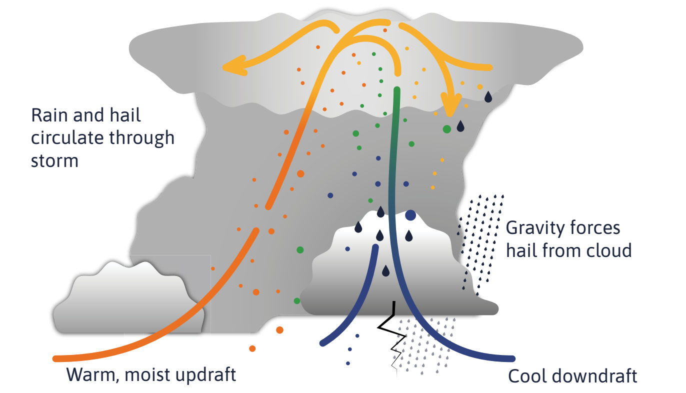
# Hail Basics for Solar Professionals

Hail occurs during thunderstorms, which are often triggered by an updraft, or upward movement of warmer, moister, less dense air from the surface as it rises above colder, dryer, denser air aloft. Updrafts and downdrafts push raindrops throughout the thunderstorm, where they freeze, melt, re-freeze and stick to one another. Once the hail is too heavy to be supported by the updraft, gravity forces it out of the cloud, as shown in the diagram below.

## Hail Strikes are Random

The inside of a hailstorm cloud is constantly moving and changing. It is impossible to forecast when hail becomes too heavy to stay in the cloud, where it will land, or its size upon impact. While there are climatological models for the probability of certain hail sizes in a given region, hail strikes are completely random.

**As a result, solar power plants are not uniformly affected by hailstorms. Different areas of a utility-scale project will suffer more or less damage from the same event. For example, in a hail-damaged solar farm recently assessed by PVEL, replacements were required for 15% of modules.**



*Natural hail formation process*

## Hailstone Size is Not the Only Factor for Damage

The most important driver for hail damage is impact energy, or kinetic energy. This is the amount of force that the hail inflicts upon an object and how that object is able to react. Variables that affect impact energy include:

- **Hail size**
  While meteorologists focus on diameter when assessing storm severity, natural hail is not uniformly spherical. The surface area of two natural hailstones with the same diameter may vary substantially depending on their shape.
- **Mass and density**
  Hail that is smaller in diameter can be denser and more destructive than larger, slushy hail that may weigh less. Laboratory-made hail is extremely dense, so its impact energy is usually far greater than naturally occurring hail. Density of naturally occurring hail can range from about 0.32 g/cm$^3$ when slushy to almost 1.0 g/cm$^3$ when solid.
- **Speed**
  Hail may fall at terminal velocity, which is the maximum attainable speed of an object as it falls under the force of gravity. However winds as well as differences in air pressure, density, and surface area can change the speed of hail upon ejection, and thus increase or decrease its impact energy.
- **Angle of incidence**
  The angle of a hail strike affects the direction and distribution of the strike's force across the surface area of the module. A module mounted at 0° will be subject to higher impact energy and incur more damage than the same module stowed at a 30° or 60° tilt.

*The factors noted above are not comprehensive. Other factors such as the drag coefficient, shape, air density, etc., can also affect impact energy.*

## Comparing the Impact Energy of Strikes with Manufactured Lab Hail vs. Natural Hail

**This table shows that strikes from hail manufactured in the lab can have much greater impact energy than strikes from naturally occurring hail of the same size.**

With all other factors held constant and an angle of 0°, the impact energy of hail 25 mm in diameter with roughly solid ice density and at terminal velocity is only 2.0 joules.

This is the baseline diameter considered sufficient for hail testing according to the IEC 61215 standard. If the density of the ice is reduced to .64 g/cm$^3$, then the impact energy drops to 1.0 joules.

Meanwhile, 50 mm hail, double the diameter, and the size of a chicken egg, has over 15 times the impact energy. Grapefruit-size hail at 100mm in diameter has over 16 times the impact energy of 50mm hail.

| Hailstone Size | | Lab-Made Hail PVEL-measured density: 0.92g/cm$^3$ | | | Natural Hail *Example density: 0.64g/cm$^3$ | |
|---|---|---|---|---|---|---|
| Comparison | Diameter (mm) | Mass (g) | Terminal velocity (m/s) | Impact energy (J) | Mass (g) | Impact energy (J) |
| Bottle cap | 25 | 7.5 | 23.0 | **2.0** | 5.2 | **1.0** |
| Golf ball | 45 | 43.9 | 30.7 | **20.7** | 30.5 | **10.1** |
| Chicken egg | 50 | 60.2 | 32.3 | **31.4** | 41.9 | **15.4** |
| Baseball | 75 | 203.2 | 39.5 | **158.4** | 141.0 | **78.1** |
| Grapefruit | 100 | 481.7 | 46.1 | **512.1** | 335.0 | **247.0** |

**Hail density can range from 0.32 to almost 0.99 g/cm$^3$ in the field*

# Inside the Hail Stress Sequence for PVEL's PQP

## Step 1: Factory Witness and Intake

- Test samples are witnessed in production from the opening of raw materials through every step of the manufacturing process until palletization with tamper-proof tape and shipment to PVEL.
- Once received at PVEL, modules undergo flash testing and electroluminescence (EL) imaging to measure their power output and physical condition.

## Step 2: Hail Strikes

- Test samples are struck by a 50 mm lab-manufactured ice ball at terminal velocity (32 m/s) in 11 different locations at a 0° angle as per the IEC 61215 hail test procedure.
- The simulated hail strikes deliver an impact energy of 31.4 joules, which is comparable to the approximate impact energy of a 77 mm strike with the same density at terminal velocity at 30°.[4]

## Step 3: Dynamic Mechanical Load (DML)

- The mounted modules are subjected to 1000 cycles of alternating positive and negative loading at 1000 Pa, which simulates wind loading in the field.
- Dynamic mechanical loading articulates existing cracks, creating inactive areas or increased series resistance. It is representative of mechanical stress in the field from wind loading over time.

## Step 4: Environmental Stress

- Modules are placed in environmental chambers and subjected to 50 thermal cycles from +85°C to -40°C, with current injected into the module as the temperature rises.
- Modules are then subjected to 10 cycles of humidity freeze - high heat and high humidity, followed by a rapid drop to freezing temperatures.
- This step simulates an acceleration of natural, daily temperature changes and other environmental conditions that cause hail-induced cracks to propagate through cell metallization.

## Characterizations after Every Step

- Power loss is measured with precision flash testing.
- Detailed visual inspection is conducted to identify damage.
- Wet leakage testing is performed to verify electrical safety.
- EL images are taken to reveal cell-level damage, which is typically not visible by eye.

## How PVEL Ensures Test Repeatability

Hail strikes are random in the field, but testing in the lab must be repeatable for buyers to benchmark the test results of different bills of materials (BOMs). To ensure consistency, PVEL:

1. **Directionally freezes ice blocks to ensure uniform density of manufactured hail.**
   This process avoids inclusion or impurities that could affect the consistency of hail strikes.

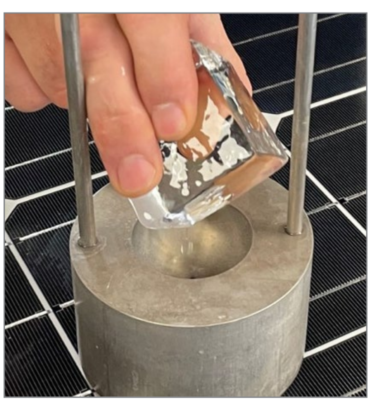
2. **Directionally melts ice blocks into spheres to maintain uniform sizes of manufactured hail.**
   PVEL forms 50 mm spheres from ice blocks with custom-machined molds immediately prior to strike. This prevents excessive melting and ensures uniform size and density across all tests.

3. **Utilizes a specialized canon to fire hail strikes.**
   Hail strikes are conducted with a laser-sighted hail cannon mounted on a purpose-built tracked electric table that enables rapid, accurate lateral and vertical positioning.

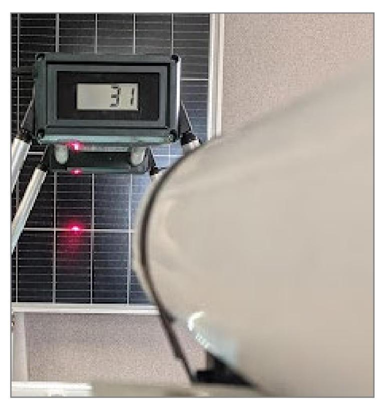
4. **Verifies accuracy of strikes in real-time.**
   PVEL utilizes a chronograph to measure strike velocity and validate the impact energy of each strike.

[4] Heymsfield, A., Szakáll, M., Jost, A., Giammanco, I., & Wright, R. (2018). A Comprehensive Observational Study of Graupel and Hail Terminal Velocity, Mass Flux, and Kinetic Energy. Journal of the Atmospheric Sciences, 75(11), 3861-3885. https://doi.org/10.1175/JAS-D-18-0035.1


*Directionally frozen ice block*


*Mold for directional melting*


*PVEL's manufactured hail*



*Chronograph for measurement*

# A Field-Representative Test in a Laboratory Environment

**PVEL's empirically derived PQP test scope utilizes 50 mm ice balls launched at terminal velocity because we found in our testing that this protocol differentiates high-performing BOMs from standard and low-performing BOMs.**

Strikes with an impact energy of 31.4 joules will break the glass of modules that are likely to fail in the field while more durable modules remain intact. Because lab-created ice balls can be more uniform and dense than natural hail, the impact energy of a 50 mm ice ball is comparable to a natural hailstone as large as 100 mm in diameter, depending on their density, impact angle and other factors discussed previously.

The graph below shows the ranges of hail sizes covered by PVEL's testing in the context of recorded observations of hail strikes in the U.S. Because impact energy is nearly impossible to accurately measure in the field, diameter is useful for correlating lab testing to field conditions.

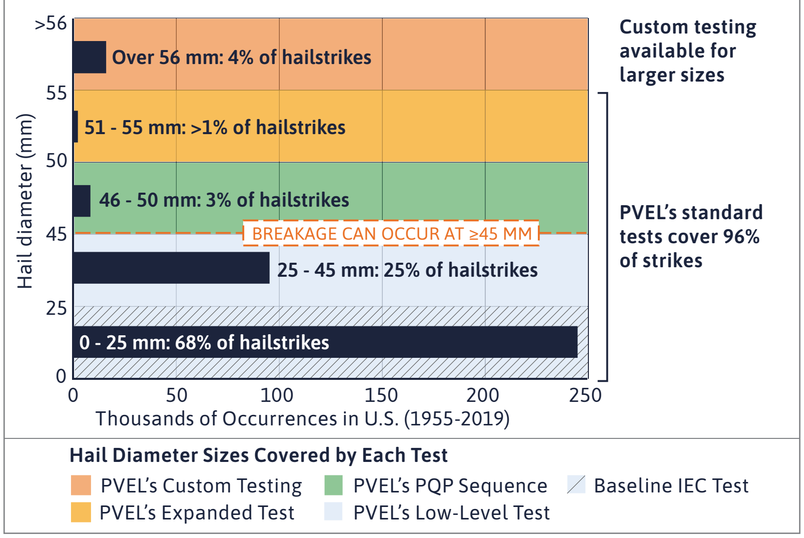
## Beyond the PQP's Hail Stress Sequence

The PQP (shown below) informs projects around the world, but risk assessment for a plant in Texas will not be the same for a plant in Italy, India or Australia. Those with hail concerns and high risk profiles may benefit from additional testing in PVEL's expanded hail stress sequence. This protocol incorporates hail strikes of 50 mm at 40 m/s velocity, which represents a 55% increase in impact energy over the PQP's hail test.

**PVEL strongly recommends expanded testing for projects in regions that are prone to severe hail and/or projects that cannot obtain hail insurance.**

PVEL's optional low-level hail test with strikes of 40 mm at 32 m/s velocity is also available. This represents about 50% less impact energy than the PQP's test protocol. PVEL can also provide customized project-specific hail studies.

**Hail Size Diameter by Number of Occurrences, U.S.[5]**




[5] NOAA/Storm Prediction Center, Severe Weather Database. https://www.spc.noaa.gov/

## The PVEL PV Module PQP

**Factory Witness, Characterizations and Light-Induced Degradation Measurement**

| Thermal Cycling | Damp Heat | Backsheet Durability Sequence | Mechanical Stress Sequence | Hail Stress Sequence | Potential-Induced Degradation | LETID Sensitivity | PAN File & IAM Profile | Field Exposure |
|---|---|---|---|---|---|---|---|---|
| TC 200 | DH 1000 | DH 1000 | Static Mechanical Load | Hail Strike | 85°C, 85%RH MSV (+ and/or –) 192 hrs | LETID 162 hrs (75°C, Isc-Imp) | PAN File | Field Exposure 6 Months |
| Characterization | Characterization | UV 65 kWh/m² | Dynamic Mechanical Load | Characterization | Characterization | Characterization | IAM Profile | Characterization |
| TC 200 | DH 1000 | Characterization | Characterization | Dynamic Mechanical Load | | LETID 162 hrs (75°C, Isc-Imp) | | Field Exposure 6 Months |
| Characterization | Characterization | TC 50 + HF 10 | TC 50 + HF 10 | Characterization | | Characterization | | Characterization |
| TC 200 | Stabilization 80°C, Isc, 48 hrs | UV 65 kWh/m² | Characterization | TC 50 + HF 10 | | LETID 162 hrs (75°C, Isc-Imp) | | |
| Characterization | Characterization | Characterization | | Characterization | | Characterization | | |
| | | TC 50 + HF 10 | | | | | | |
| | | UV 65 kWh/m² | | | | | | |
| | | Characterization | | | | | | |
| | | TC 50 + HF 10 | | | | | | |
| | | UV 6.5 kWh/m² | | | | | | |
| | | Characterization | | | | | | |

### Factory Witness

All bills of materials submitted for testing are witnessed in production through every step of the production process from the opening of raw materials packages to final packaging with tamper-proof tape.

### Testing Abbreviations

TC: Thermal cycling
DH: Damp heat
UV: Ultraviolet
HF: Humidity freeze
MSV: Maximum system voltage
IAM: Incidence angle modifier
LETID: Light and elevated temperature-induced degradation

### Characterizations

IV: Flash test at STC
EL: EL image at Isc
LIC: Flash test at 200W/m²
LCEL: EL image at 1/10*Isc
VI: Visual inspection
WL: Wet leakage
Diode: Diode test
Color: Backsheet color measurement
Capacity: Capacity testing

Notes

Not all characterization measurements are taken at each step. PVEL conducts additional field exposure studies and rear side characterizations to evaluate the performance of bifacial modules. Supplementary testing is available for extended hail stress and tracker-specific mechanical stress evaluations.

# PVEL's Initial Findings

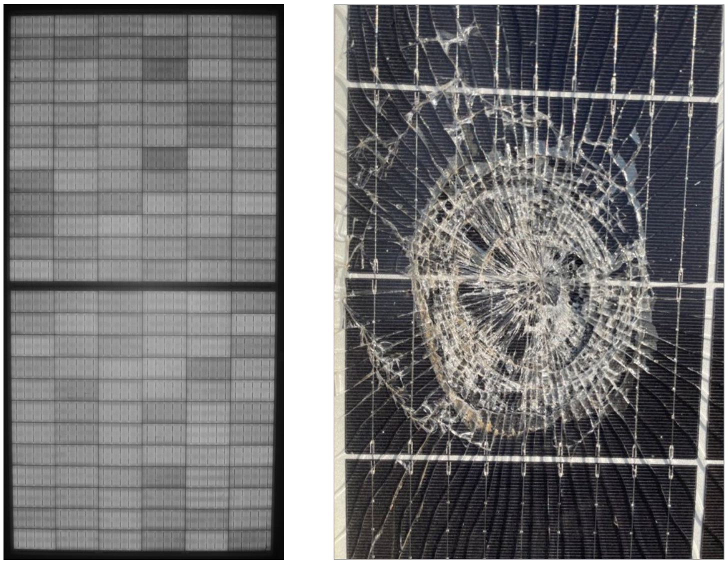
## 1. Certification Testing is Limited

Most hail test certifications use laboratory-created ice balls of 25 mm in diameter at 23.0 m/s, which is the minimum IEC 61215 requirement. These strikes are sufficient for regions of the world that do not experience severe hail. **PVEL has not, thus far, observed glass breakage when conducting hail testing to IEC's baseline certification standard.**

Evidence from the field proves this is not sufficient in certain locations. Rigorous hail testing that goes beyond certification standards to replicate real-world hail impacts is imperative for solar assets in hail prone regions.

## 2. PVEL's Test is on the Cusp of Breakage

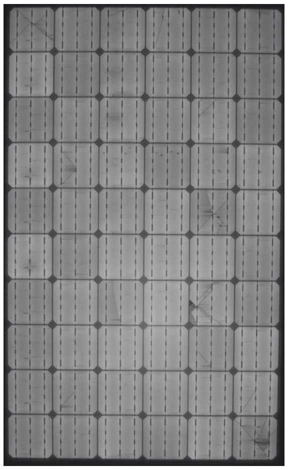
The BOM shown on the right was not damaged by hail testing to minimum IEC standards. It was also undamaged by 50 mm hail strikes at 32 m/s. However, when velocity increased to 35 m/s, which represents an approximate 15% increase in impact energy, the module experienced glass breakage. Comparable results were observed from similar BOMs from other manufacturers.



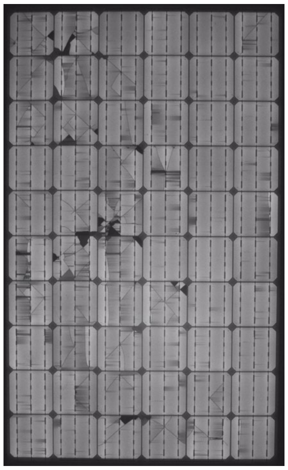
*This BOM was not damaged by the PQP's hail test - 50 mm strikes at terminal velocity, 32 m/s (above left), but it shattered after 50 mm strikes at 35 m/s (above right)*

## 3. PVEL's Results are Field-Representative

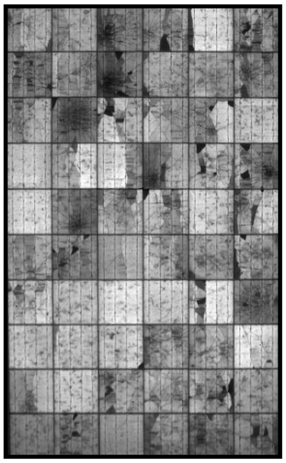
The images below compare results from PVEL's developmental testing for the hail stress sequence to results from a hail-damaged project assessed by PVEL in the field. While the module was completely undamaged by the baseline IEC test, modules tested with more rigorous strikes devised for hail-prone regions show similar field-representative patterns of cell breakage, branching cracks as well as power loss upon completion of the full hail stress sequence.



*BOM shows some damage but no glass breakage and 1.1% power loss after PVEL's required PQP hail test*



*BOM shows significant damage and branching cracks as well as 3.4% power loss after PVEL's expanded hail test*



*As shown in PVEL's field EL image above, damage from natural hail matches damage from PVEL's expanded hail testing*

## Field Findings and Implications

After assessing 1 GW of hail-damaged projects, PVEL has identified three consistent patterns of hail damage:

- In strings that have two or more broken glass modules, the cells of the remaining modules with intact glass are likely to experience severe cracking.
- In large sites (100 MW+) that suffer glass breakage due to hail, it is likely that some areas of the array will not suffer any cell damage.
- Glass breakage and cell cracking will be variable in the areas of the site between the two above extremes.

PVEL's hail stress sequence will help asset owners procure modules with a lower likelihood of being damaged in the hail-affected regions of the array. It will also reveal the modules that are most likely to experience significant power loss due to cell-level damage.

# Conclusions

PVEL’s test is on the cusp: some glass breaks and some does not. When designing a test using our field and lab studies and examining results, our goal is to identify the threshold at which some BOMs are able to perform better than others. Our aim for initial development of the hail stress sequence was to be able to inform buyers which BOMs are robust enough to withstand certain sizes and velocities of hail and which are not.

The hail size and velocities we used in our studies are similar to those we’ve seen in our field testing and in our research about hail events around the world. PVEL's hail testing is intended to help buyers determine if the level of hail resistance in the modules they are considering meets the needs of their particular site.

# Next Steps

PVEL’s PQPs are periodically updated as technical due diligence requirements evolve for solar projects around the world. The hail stress sequence, introduced in 2021, is one of many improvements that PVEL has incorporated into the PQP since its launch in 2012. As technology advances, new field data emerges and buyer needs evolve, PVEL will continue developing new test protocols to support the downstream solar market.

Based on PVEL's lab and field testing and current market conditions, independent hail testing is an important and imperative risk mitigation tool for investors and asset owners that operate in hail-prone regions. As the hail stress sequence is now a required PQP test, PVEL will explore technology and design trends relative to hail damage susceptibility. These results will be shared in future publications.

To learn more about PVEL's hail testing or to sign up as a downstream partner and gain complimentary access to PQP reports contact:
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PVEL
MAKE DATA MATTER.

**Are you concerned about hail damage in an operating asset?**

PVEL provides field testing and EL imaging to help asset owners, O&M providers and insurers fully quantify damage at project sites. Our services guide repairs and support insurance claim resolution. Contact us at info@pvel.com to learn more.

member of group
kiwa