Hail Damage – A 2019 Case Study and Lab Trials

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This white paper summarizes a talk given by James Rand at the 2020 NREL Photovoltaic Reliability Workshop, 26 February 2020.

Case Study: Severe Hail Damage

Core Energy Works (CEW) was contracted by Duke Energy to evaluate a hail damaged site in rural North Carolina. The site experienced a storm in 2019 that resulted in exceptionally large hail balls that did significant damage to the site and to the surrounding area. Photos from social media of the hail event are shown in Figure 1.

Figure 1: Photos of hail taken from social media from North Carolina hailstorm. For reference a baseball has a diameter of approximately 75mm (3”). “Baseball” size hail was reported in the local media as well[1]. Other weather-related sites reported 70 mm (2.75”) hail for this storm.

Figure 2: Photo of the hail damaged modules and site details.

[1] “Wicked Storm Unleashes Fury”, Roanoke-Chowan News-Herald, Published 5 June 2019 .

Figure 2 and Figure 3 show that modules with broken glass were found spread throughout the array, interspaced with modules with intact glass. Some information on the storm can be extracted from the photographs taken of the damaged modules. The impact that initially broke the module was clearly identifiable and is typically the largest impact site. After the glass was broken, subsequent strikes disrupted the broken glass and left visible marks. Figure 3 shows the range of hail diameters estimated from the size of these secondary impact marks. Because the secondary impact marks are larger than the actual diameter of hail, a correction factor was calculated by firing hail balls with known diameter at a broken panel and measuring the resultant pattern in a laboratory environment. The average hail diameter was found to be 44mm (1.7") with a range of 26mm (1.0") to 56mm (2.2") for the small sample of panels evaluated. Social media reports suggest hail reached 75 mm in size (3").

In addition to the size of the hail, the number of hail strikes was estimated by counting the secondary impacts. The average number of secondary strikes per panel ranged from 28 to 87, with an average of 47 impacts per panel. These numbers represent only the number of hail impacts AFTER glass broke and represents a lower limit to the number of hail impacts each module received.

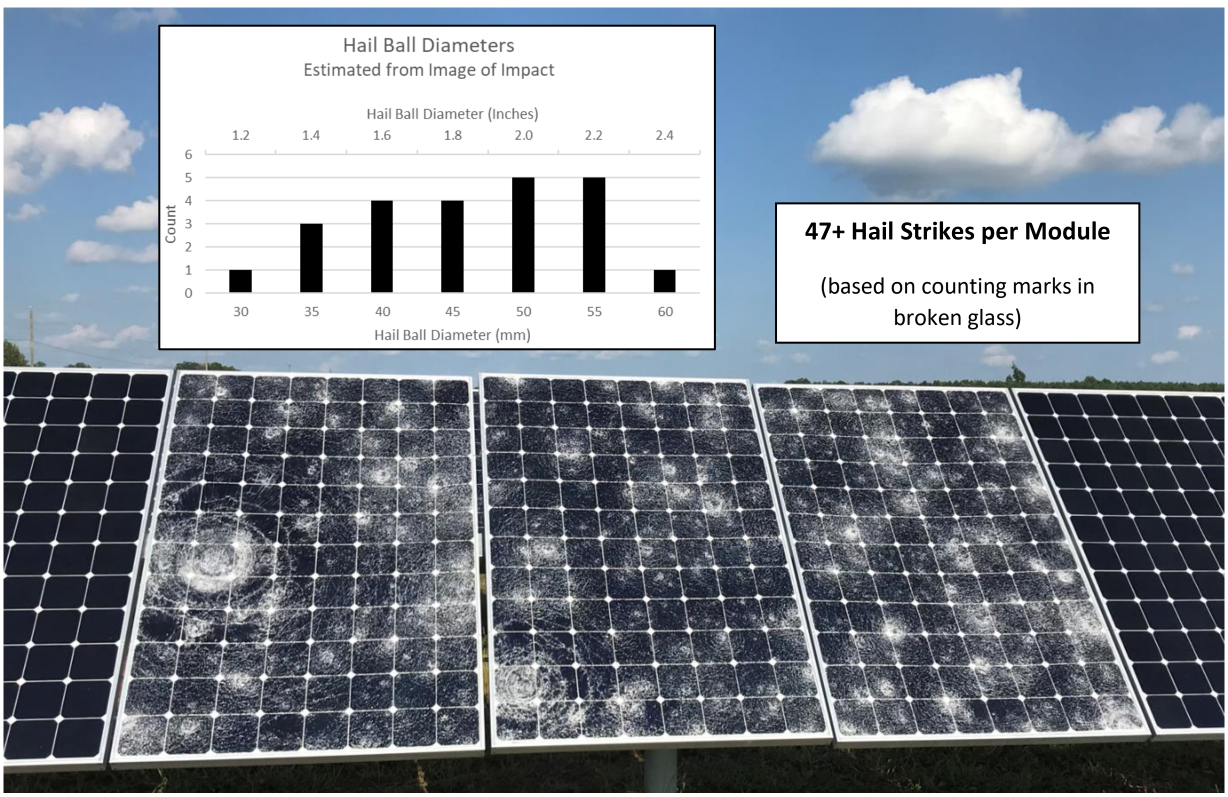


Figure 3: Estimating the hail ball size from the impact left on the broken glass.

Initial Testing by Electroluminescence

Sometime after the hail event, the site was visually inspected and 301 modules with intact glass were randomly selected for electroluminescence (EL) imaging. The modules were EL imaged in place on the rack. The EL results highlighted three classes of modules with intact glass: (1) undamaged; (2) lightly damaged; (3) storm damaged. Modules with broken glass could be easily visually identified as storm damaged due to the clear impact areas. Undamaged modules had little or no solar cell cracking as a result of the storm. Lightly damaged modules were defined as modules with some damage that could not be clearly attributed to storm damage; the cracked cells had no clear impact center or star patterned cracks and may have resulted from rough handling during packaging, transportation, and installation. Storm damaged modules could be identified through EL by the clear impact points and star patterned cracks. Examples EL images from all three types of modules are shown in Figure 4, below:

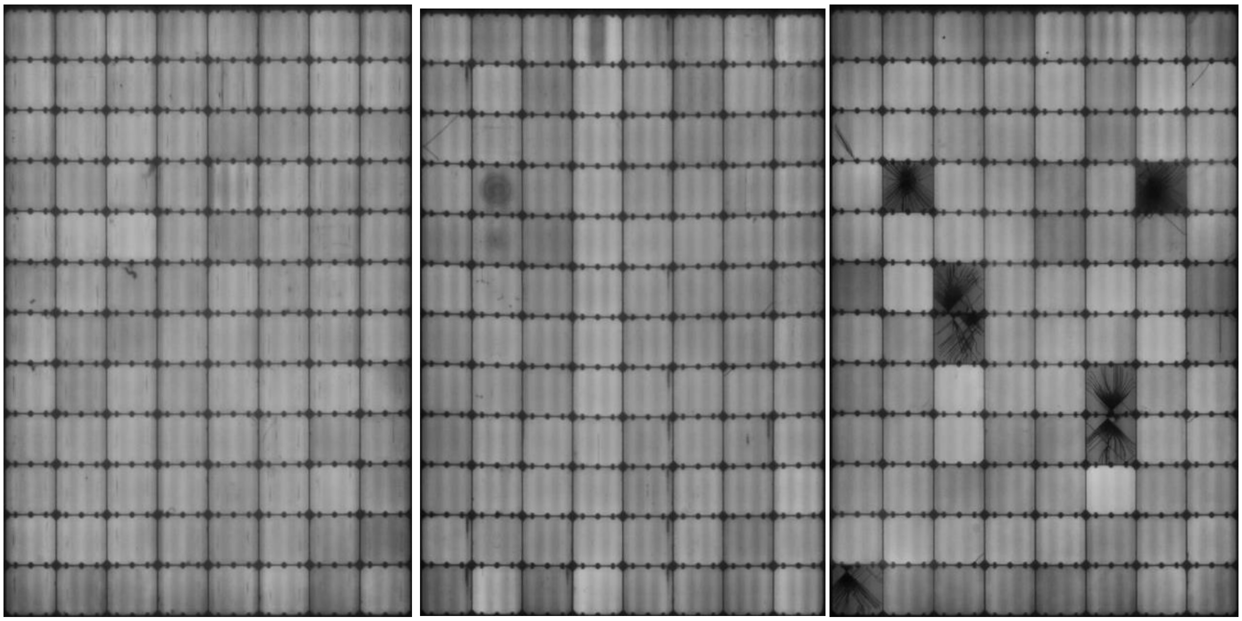


Figure 4: Example EL images taken on modules with unbroken glass: Undamaged (left;, lightly damaged (center); storm damaged (right).. shows the distribution of the 301 EL samples between these three categories. Most module with intact glass were undamaged (61.5%). This is quite an impressive result given that they were hit with on the order of 50 hail balls as big as 60mm!

Table 1: Results for a random sample of 301 EL images on modules with intact glass

	Undamaged	Lightly Damaged	Storm Damaged
Module Count (301 total)	185	19	97
Percent of Modules Tested	61.5%	6.3%	32.2%

An analysis of the physical distribution of undamaged modules vs modules with broken glass across the site reveals no correlation between the density of modules with broken glass and the probability that modules with unbroken glass in the same area will be undamaged (see Figure 5, below). In other words, you cannot conclude that regions with high glass breakage also have high levels of cell damage within the modules that do not have broken glass in the same area.

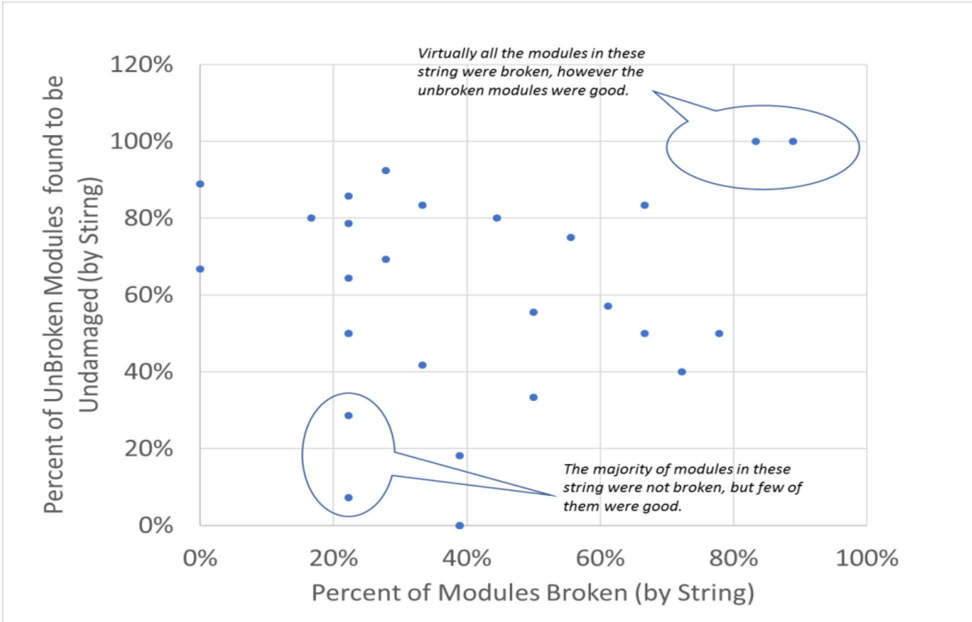


*Figure 5: The percent of undamaged modules vs modules with broken glass for each of the strings tested. The data suggests that the percent of modules with broken glass is **not** a good indicator that modules in the same string are damaged.*

A follow up visit was conducted in which 100% of the 19,950 modules were counted as one of three categories: (1) broken glass; (2) unbroken good; (3) unbroken damaged. Figure 6, below, shows the results of the 100% inspection grouped by tracker number. Modules with broken glass are easily identified visually. However, visual inspection is not able to distinguish between a storm damaged and undamaged module when the module glass is unbroken. An alternative inspection method is needed as discussed in the next section.

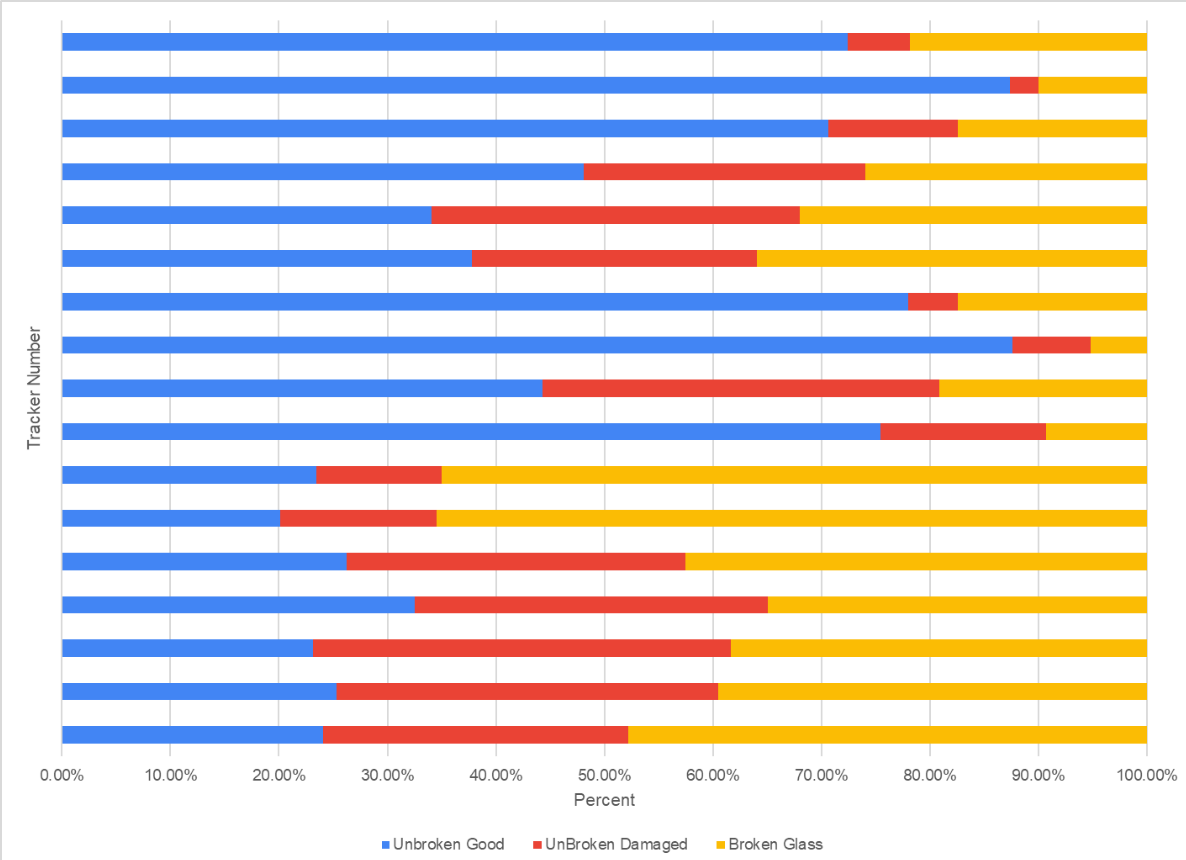


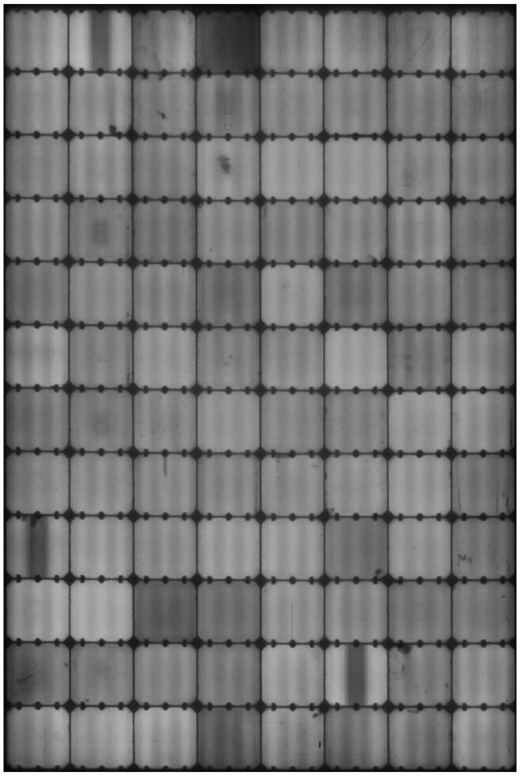
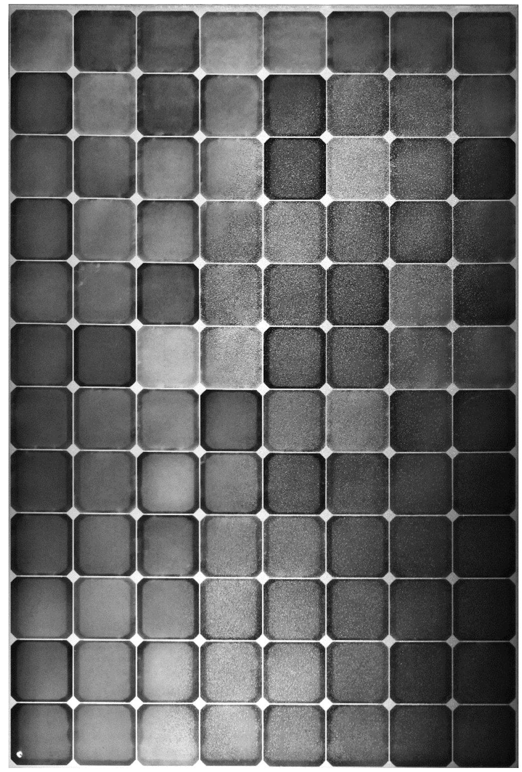
Figure 6: Classification of 100% of modules at the site as "unbroken good"; "Unbroken damaged"; or "Broken glass" and grouped by tracker number. The data shows a range of damage from as little as 13% damaged to as much as 80% storm damaged. There are approximately 1000 modules in each tracker section.

Using UV Fluorescence to Identify Broken Modules

Given that approximately 14,000 modules had intact glass on the site, and potentially 30% of those modules were storm damaged, testing of individual modules was needed. Doing EL on all 14,000 would have been time consuming and costly. Fortunately, these modules had an EVA formulation and other materials compatible with UV fluorescence detection of cracked cells (UVF). If oxygen can diffuse to the EVA, an oxidation process occurs that destroys the chemical compounds responsible for fluorescence[2]. In an un-damaged cell, oxygen can only diffuse to the frontside EVA through the gaps between cells. However, for cracked cells, oxygen can penetrate along the cell cracks and react with the EVA creating an 'image' of the cell cracks[3].

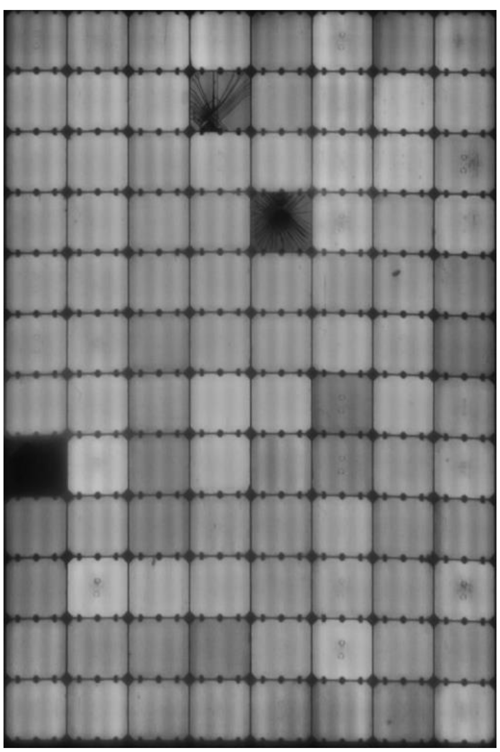
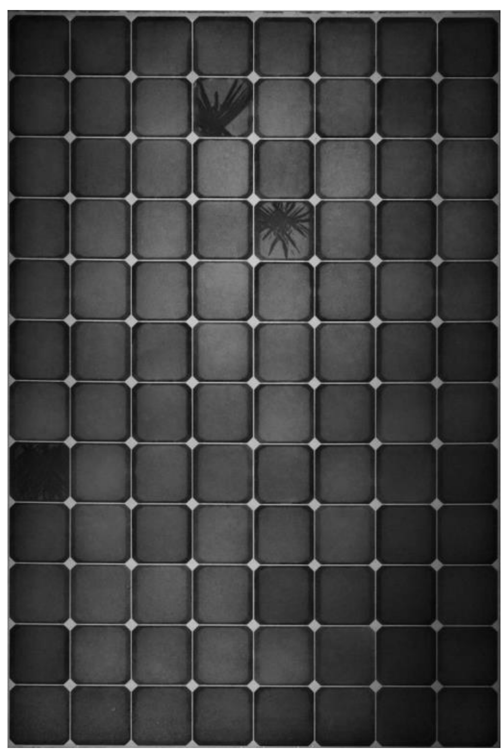
[2] F. J. Pern, "Factors that affect the EVA encapsulant discoloration rate upon accelerated exposure," Solar Energy Mater. Solar Cells, vol. 41/42, pp. 587–615, 1996

[3] M. Kontges, S. Kajari-Schroder, and I. Kunze, "Crack Statistic for Wafer-Based Silicon Solar Cell Modules in the Field Measured by UV Fluorescence", IEEE Journal of Photovoltaics, vol. 3, No. 1, January 2013

EL UVF

Figure 7: EL (left) and UVF(right) of the same un-damaged module. Please note that UVF is not sensitive to variations in EL due to electrical factors.

EL UVF

Figure 8: EL(left) and UVF(right) of storm damaged module, UVF clearly shows location and nature of cracked cells.

Figure 7 and Figure 8 above show EL and UVF images of undamaged and storm damaged modules. The UVF clearly reveals every cracked cell, and the pattern of the cracked cells. UVF measurements are contactless and rapid. The storm damaged modules with intact glass were identified rapidly and at low cost without dismounting or disconnecting the modules.

Using UVF, the full effect of the hail storm on the entire site was found (Table 2, below). In total, 48.5% of modules on the site were found to be good, and 51.5% were damaged by the storm. The project was able to save approximately 10,000 modules from the landfill with a cost effective and rapid assessment.

Table 2: Total statistics for entire site after UVF analysis

Module Class	Percentage of total (%)
Undamaged	48.5%
Storm Damaged -Broken Glass	30.4%
Storm Damaged - Internal Cell Damage (glass intact)	21.1%

Testing Modules Indoors with High Energy Hail Strikes

A study is presently underway to examine the vulnerability or tolerance of different module designs to hail damage. CEW obtained five types of panels from a variety of manufacturers. Hail strikes were emulated in the lab by firing round ice balls at panels with a pneumatic hail cannon. The panels were mounted per manufacturers specifications. Two separate tests were conducted: a hail damage threshold test, and a hailstorm test. The data presented represents only one module per test. No replication studies have yet been conducted. However, the data is still instructive. This type of rough handling study is a continuation of the work initially funded by DOE and SunPower and has continued with this hail testing with funding from CEW and SunPower.

Hail Damage Threshold Test

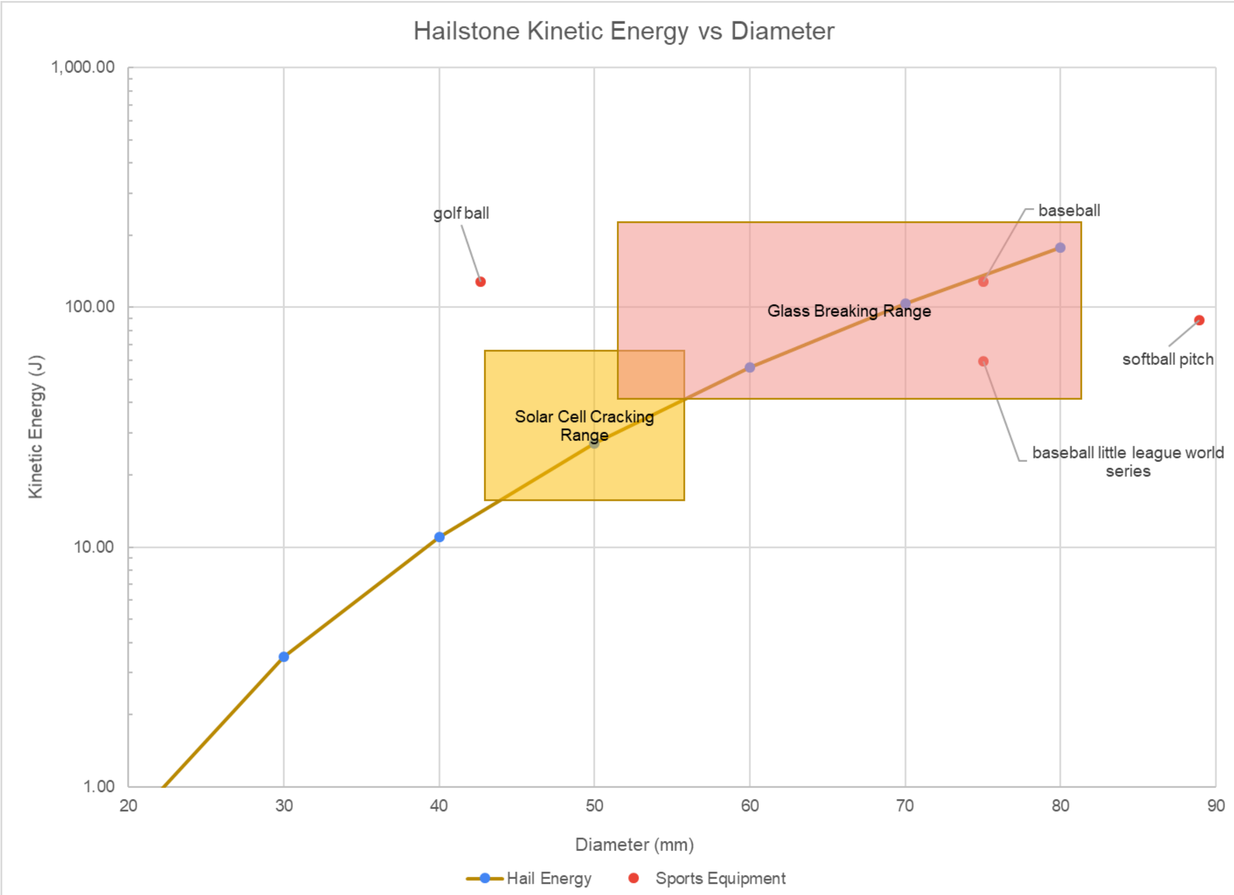


Figure 9: The natural behavior of hail ball in terms of energy (x axis) vs size (y axis) is shown based on calculating terminal velocity of a sphere. The range for solar cell cracking and glass failure are marked. Included for reference are a few common human launched spheres.

In the hail damage threshold test, increasingly energetic hail impacts were fired at modules under test to emulate the kinetic energy of larger and larger hail balls. The kinetic energy (E_K) of a projectile is given by $E_k(J) = \frac{1}{2}mv^2$, where m is the mass of the ice ball in grams and v is the velocity in m/s. The velocity is given by the equation for terminal velocity of a sphere[4], where $v = \sqrt{\frac{4 \cdot \rho_{ice} \cdot d \cdot g}{3 \cdot \rho_{air} \cdot c_w}}$, where ρ_{ice} is the density of ice (870 kg/m^3), ρ_{air} is the density of air (1.2 kg/m^3), d is the diameter of hail, and c_w is the air drag coefficient, for a slightly rough sphere 0.5. The mass of a sphere of ice is given by $m = \frac{4 \cdot \pi \cdot \left(\frac{d}{2}\right)^3}{3} \cdot \rho_{ice}$. Using all three equations, a plot of hail diameter vs energy at terminal velocity can be calculated (Figure 9).

For these tests, 38mm (1.5”) ice balls were used, and the air pressure in the cannon was varied to change the velocity. For this study hail ball velocities of 24 m/s (54mph) to 56 m/s (125 mph) were used.

[4] Swiss Hail Impact Protection Register (HSR), CFIAA Test specification No. 00a General Part A, www.hagelregister.ch

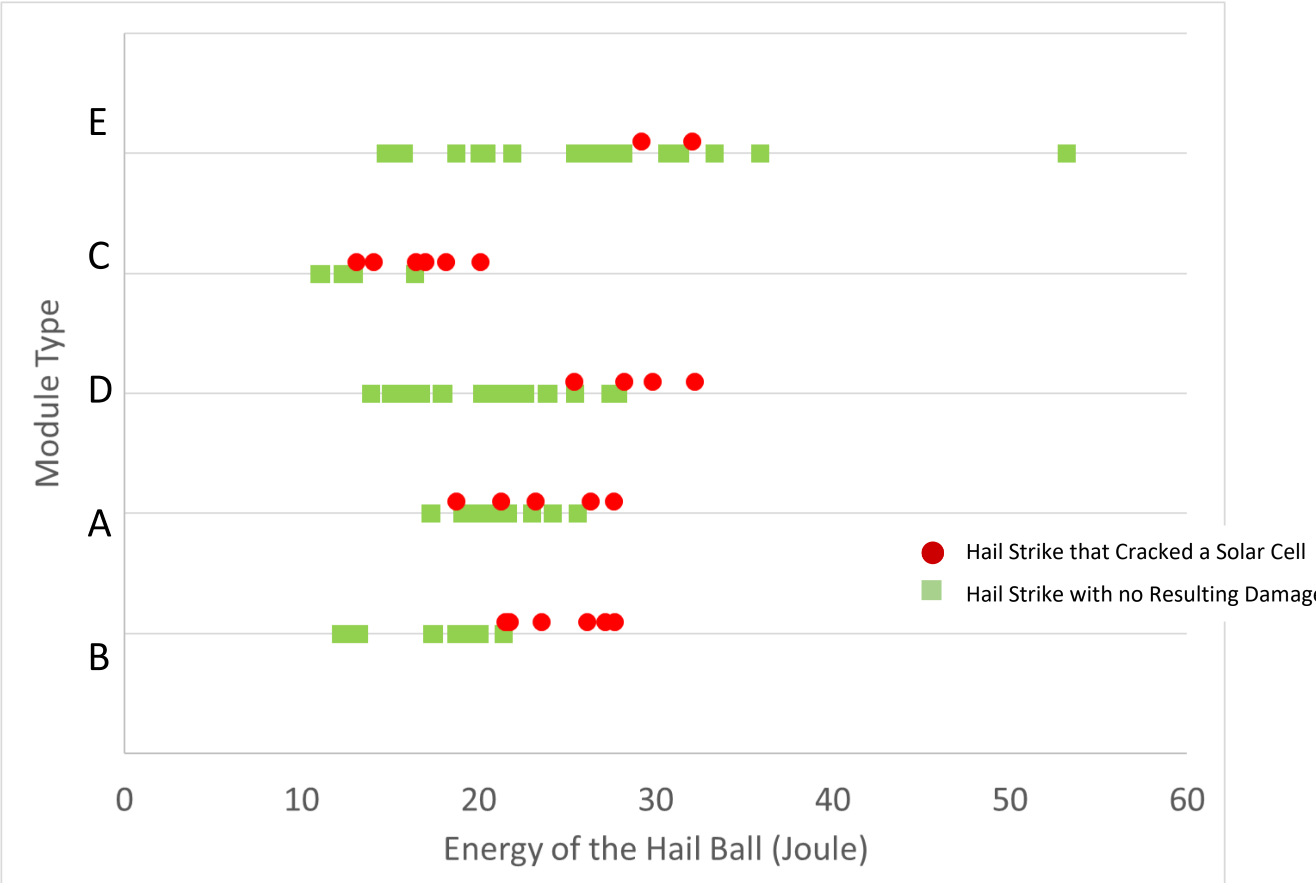


Figure 10: Hail damage threshold testing for five different module types.

In the Hail Threshold Test, modules were subjected to three hail strikes at a given kinetic energy and the energy incremented upward in 2.5J steps with a starting energy of 15J. IV and EL images were taken after each hail shot. If 2 out of 3 shots at a given energy level cracked a solar cell, the damage threshold was reached. Figure 10, above, shows the results for testing five different modules. Green marks indicate a strike caused no damage to the module and red marks indicated a broken/shattered solar cell. For module types E, D, & B, a clear threshold for damage is observed. For module type E no clear threshold was found, the shot energy increased until the module glass failed (i.e. the glass breakage energy threshold was lower than the threshold required to crack a cell for this module design). Please note that a broad or diffuse threshold energy for cell cracking is a likely indicator of a wide variation in pre-existing cell damage (i.e. critical crack length of brittle materials). Such examples may be certain types of half-cell modules where the process used to cleave the cell in two halves may have left micro-cracks of various sizes along the scribe.

The cell damage threshold ranged widely, from 12J to 30J. The equivalent hail diameter ranged from 1.6 inches to 2.24 inches, much greater than the required IEC 61215 minimum testing specification of 1”. The IEC 61215 test does allow for hail impact testing over a range of hail diameter from 12.5 to 75 mm, however, 25 mm is the largest diameter required by the test.

Comparing these indoor results to the storm event discussed previously, where the hail had a median diameter of 1.8” and a maximum of 2.4”, almost all the panels represented in the study would have been heavily damaged. Only module type E would be predicted to survive in such a violent storm.

Hailstorm Stress Test

A secondary question raised from the field case study is how performance is impacted by hail damage. To begin to answer this question a second test was carried out – the Hailstorm Stress Test. The hailstorm stress test consisted of 30J shots across the module, evenly distributed between substrings. The test was designed to measure the effect a severe hail event on module power output. Module IV and EL tests were performed after every hail shot.

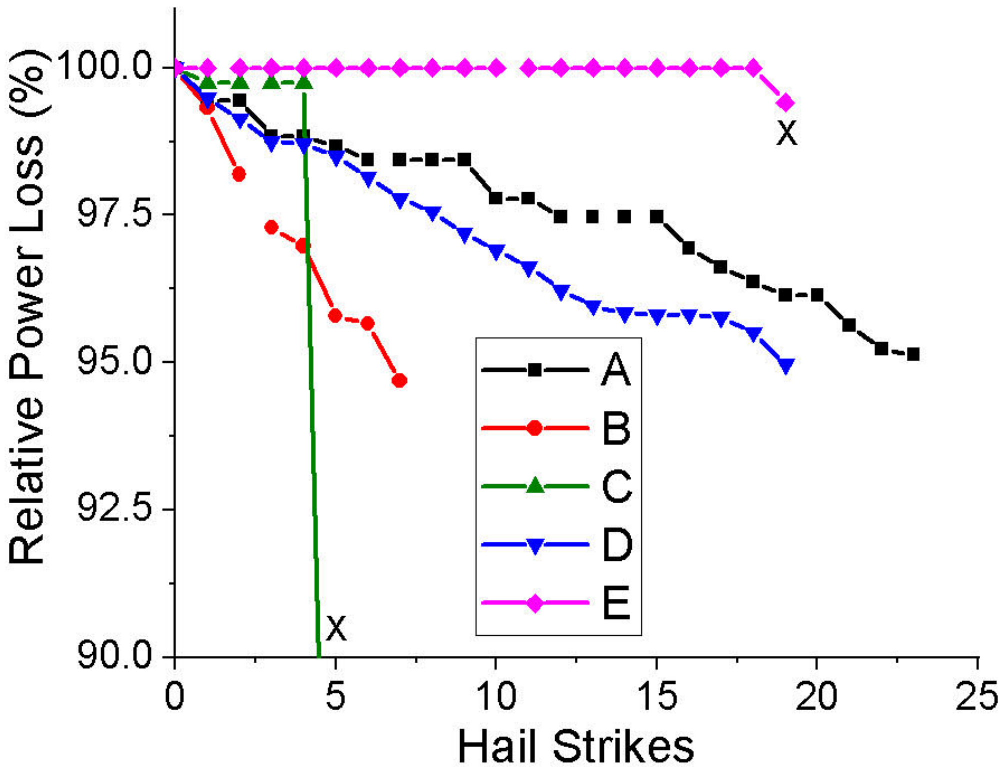


Figure 11: Relative power loss vs number of 30J hail strikes on 5 different modules types.

Figure 11 shows the relative power loss of each module vs the number of 30J hail strikes the module has endured. Modules were shot with consecutive hail balls until either maximum power (P_M) was reduced to 95% of the initial value or the glass failed, whichever came first. Two modules suffered glass failure, type C broke on the 5th shot and type E on the 19th shot. Modules found to have a relatively high cell damage threshold, as determined from the earlier testing, were not necessarily more tolerant to power loss due to that cell damage; type B, for example, lost 5% output power after only 7 hail shots. Other module designs were easily damaged (low cell thresholds) but had performance that was resilient in the face of that cell damage; module A, for example, withstood 25 shots and many cracked cells before failing 5% in power. These results indicate there is an interplay between cell damage threshold energy and cell interconnect topology that will determine the ultimate performance of that module after hailstorm damage. Of course, exposure to hail below the cell and glass breakage threshold is not threatening to module performance, but predicting performance in a storm exceeding the cell breakage threshold will require testing well beyond that required in typical certification testing.

Figure 12 shows the initial and final EL image of each of the 5 modules tested. Note the end point of the test was different for each module, some breaking glass, others reaching the 5% degradation in power.

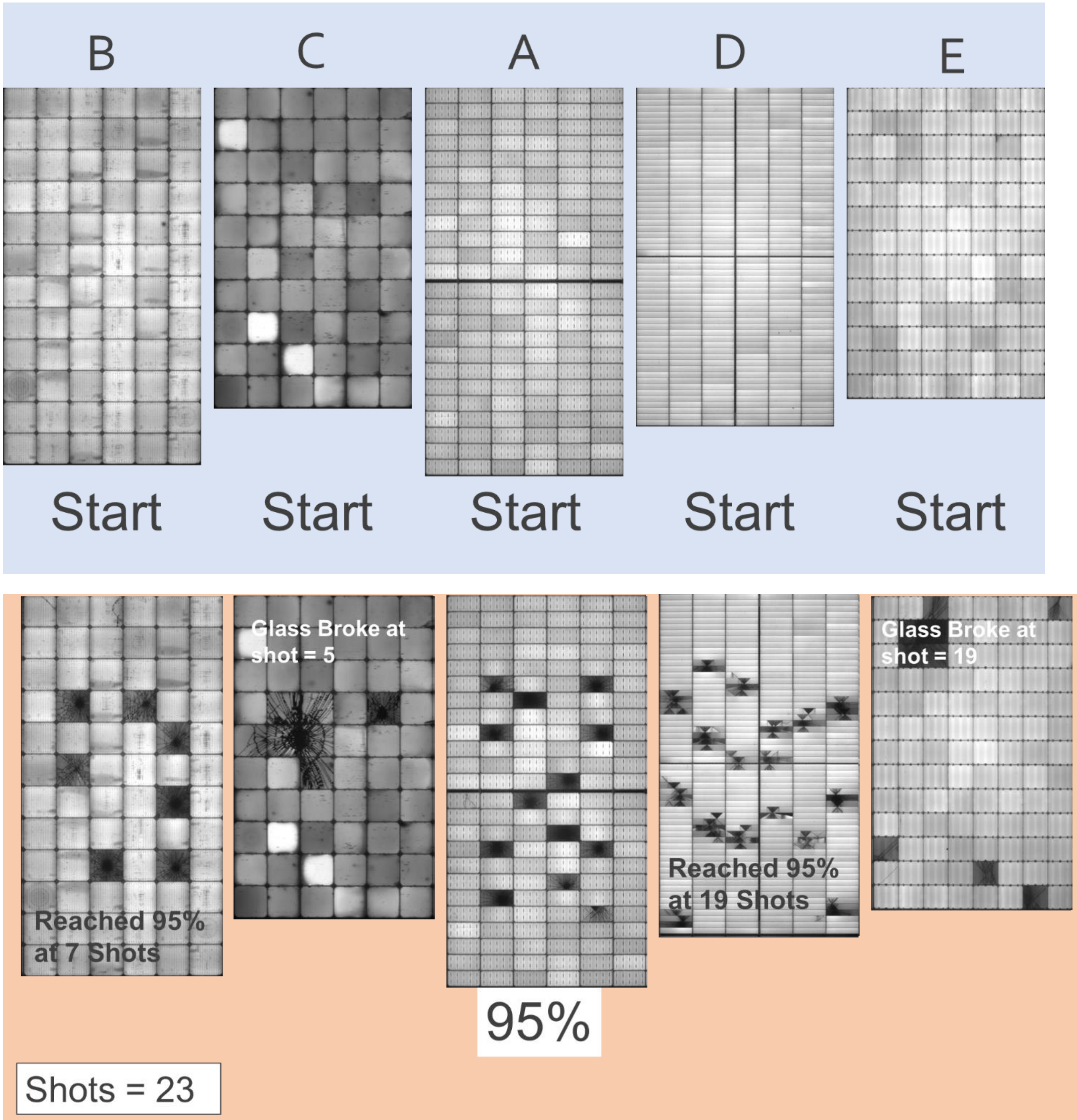


Figure 12. EL images of the five different modules tested. The top images are of the modules just prior to Hail Storm Stress Testing, and bottom image is after testing. The modules endured from as few as 5 shots to as many as 23 before reaching the end point of the test – either broken glass or a degradation of power to 95% of the starting point.

Industry Impact

Hail damage can pose a serious risk to photovoltaic stakeholders. Recent large hail damage insurance claims have resulted in insurance companies dropping or limiting hail coverage[5]. The size and frequency of reported hail has steadily increased over the last 40 years. Observations of hail with diameter > 1.25 inches has increased from ~1600/yr in 1990 to over 3000/yr in 2014. Hail with diameter > 2" has increased from 340 observations in 1990 to 529/yr in 2014[6]. Figure from Allen and Tippet [6] show the increase in reported hail frequency and size over time.

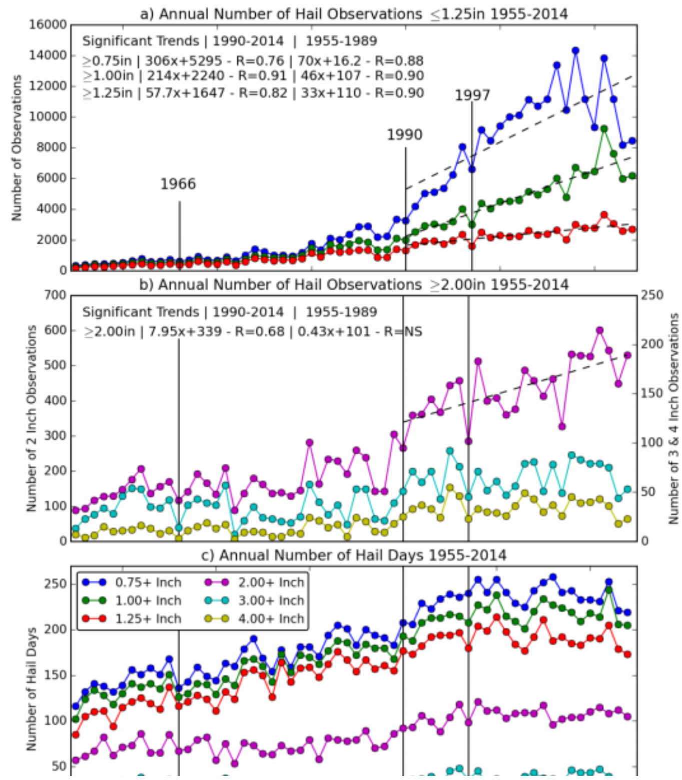


Figure 13: Frequency of hail observations over time by size, from Allen and Tippet

Conclusion

The resiliency of a solar module to hail damage is a critical issue for installations in hail prone climates. The effects of hail can be devastating and can extend beyond broken glass. Hail can result in cracked/shattered solar cells not visible to the eye. Cracked cells can reduce power and potentially cause hot-spots. EL and UVF testing can provide critical information after a hail event to access damage in some cases, but UVF may not be useful in many modern module bills of materials.

There are module designs that are shown to be more tolerant to hail than others. Significant differences are shown to exist in the size of the hail needed to crack solar cells and break glass in the small sample tested here. Furthermore, once solar cell cracks exist, the impact to module power varies greatly from module to module based on the solar cell and module designs.

About CEW

Core Energy Works is an independently owned engineering services company with expertise in all things related to photovoltaic modules. CEW engineers work primarily on modules mounted in the field, having IV tested over 10,000 modules and EL imaged over 5,000 modules at 75 utility and commercial sites across the US. In addition, CEW offers a drone-based IR array imaging service. CEW operates a warehouse in Newark DE with a full suite of module testing capability, from single module testing on AAA pulse tester for STC to evaluating full container loads for quality or potential damage.

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[5] A. Sagar, "Texas hailstorm set to generate $70-$80mn solar loss", The Insurance Insider, https://insuranceinsider.com /articles/129613/texas-hailstorm-set-to-generate-70mn-80mn-solar-loss, October 23rd, 2019

[6] J.T. Allen, M.K. Tippet, The Characteristics of United States Hail Reports: 1955-2014, Electronic Journal of Severe Storm Meteorology, **10**(3), pp1-31, 2015