SOLAR ENERGY 101

Hail risk to utility scale photovoltaic systems

Considerations for hail risk, stowing strategies, and tracker design

Crawford®

Global Technical Services

Executive summary

Hail has become a significant financial threat to utility-scale photovoltaic (PV) systems, with recent events revealing that traditional standards are inadequate for modern hail risks. For example, the 2019 Midway solar farm incident caused damage to around 400,000 modules, resulting in losses of USD 70 million and indicating increasing severity and potential impact. This has led to a tightening insurance market with rising premiums and deductibles for projects in high-hail areas.

Current IEC 61215 testing evaluates only 25 mm (1 inch) hailstones, failing to reflect the larger hailstones, which often exceed 50–100 mm (2–4 in), found in regions like West Texas and parts of southern Europe. Studies show that these larger stones carry significantly more energy than IEC standards require, and module durability alone cannot prevent losses during extreme conditions.

Research indicates that hail stowing is the most effective mitigation strategy. By tilting tracker-mounted modules at 50–80°, projects can reduce damage during hail events, as evidenced by data from severe storms that show stowed arrays avoid catastrophic damage better than unstowed ones.

Insurers are increasingly recognising automated hail stow as vital for risk control. Evidence based stow programs, such as those utilising forecast-driven activation, help secure improved insurance terms. Case studies show that automated stow can cut severe convective deductibles by 50% with minimal production impact.

Emerging concepts like the FLAP (face to face laydown) tracker may also enhance hail resilience, although further testing is needed.

This guide outlines hail risk and stowage strategies for PV assets, emphasising the necessity of robust hail mitigation in project design, operations, and insurance approaches. Hail stow is essential for protecting PV systems in high risk areas.

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Author

Dr Ceyla Asker
Renewable Energy Loss Adjuster
ceyla.asker@crawco.co.uk

Introduction and background

Hail constitutes one of the most financially significant natural perils affecting utility-scale photovoltaic (PV) systems.

Prior to 2019, the solar industry exhibited a general tendency to underestimate the risk of hail, relying excessively on insurance and IEC module standards, which were found to be inadequate in dealing with extreme events.

This vulnerability was brought to the fore by the 2019 hail event at the Midway solar farm in Texas, where approximately 400,000 modules sustained damages amounting to USD 70 million. This event, amongst others, demonstrated that array orientation during hail events, rather than module-level durability alone, governs real-world damage outcomes.

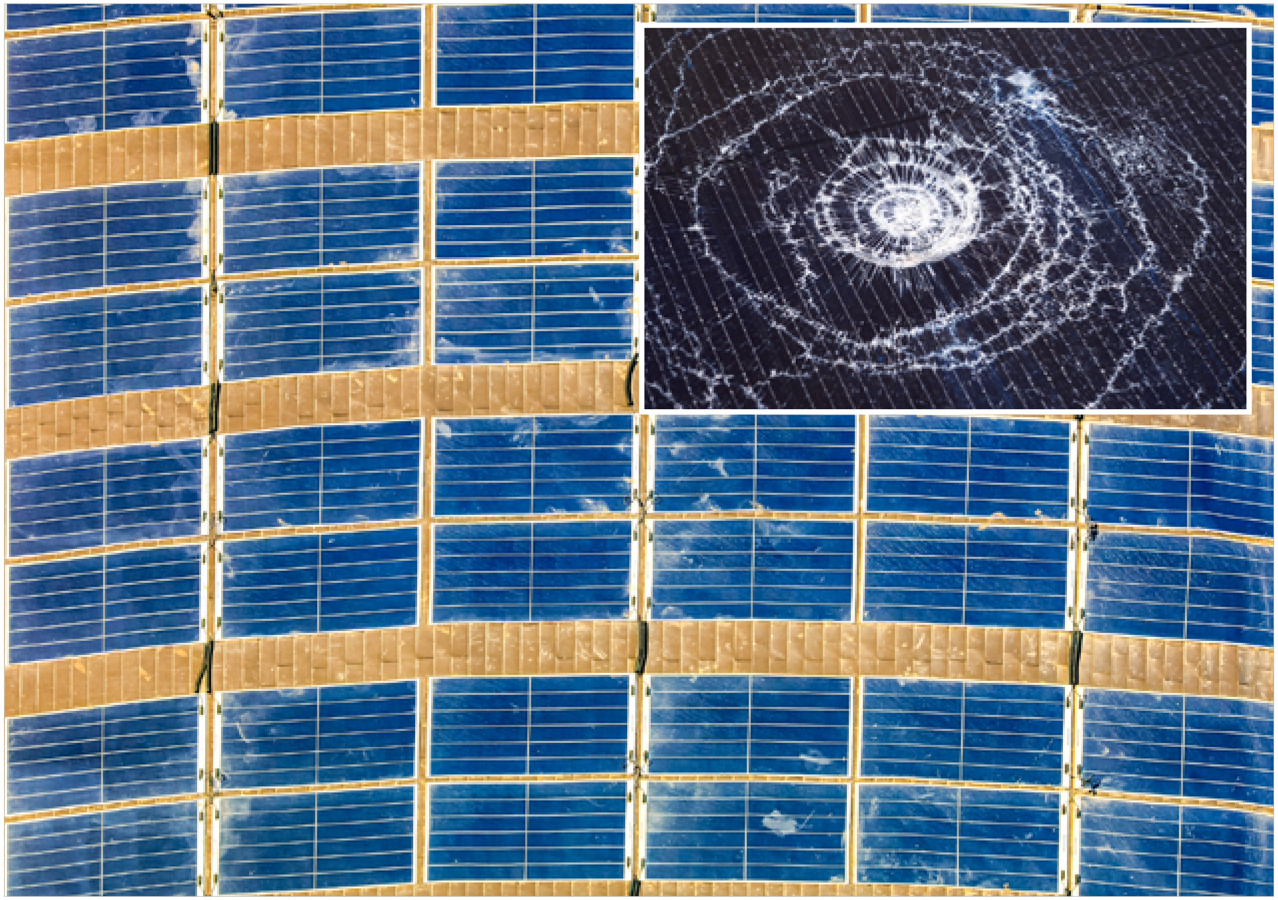
FIG 01 - Hail Risk around the world (Copyright / Sources: Swiss Re CatNet® and its Licensors. “CatNet® is a registered trademark of Swiss Reinsurance Company Ltd.)

Introduction and background (cont.)

In the aftermath, hail insurance premiums increased substantially, coverage limits were reduced, and in some cases insurance became unavailable altogether. This made new projects difficult or impossible to finance without robust protective measures and guarantees.

As demonstrated by CatNet hailstorm analysis, the global risk of hail is found to be highly uneven and concentrated in a small number of regions. This risk is especially evident in regions that experience frequent severe convective storms, such as west Texas, the Texas panhandle, and the U.S. Great Plains.

Elevated levels of hail risk have also been observed across parts of southern and central Europe (including northern Italy, the Alpine region and surrounding countries), driven by intense summer thunderstorms.



Hail definitions and metrics

The National Oceanic and Atmospheric Administration (NOAA) employs a classification system that categorises hail severity according to the diameter of the hailstone.

Hail with a diameter greater than 19 mm (0.75 ins) is defined as severe hail, while hail exceeding 50.8 mm (2 ins) is classified as significant hail. These thresholds are utilised extensively by meteorologists, insurers and risk engineers to evaluate the potential for damage.

The employment of object analogues is a customary practice in order to provide context regarding the severity of hail.

In certain regions of the United States, hailstones measuring over 75 mm (3 ins) are no longer regarded as anomalous occurrences. These events have been linked to return periods that occur more frequently than the 500-year threshold, thereby challenging historical assumptions employed in risk modelling.

Hail definitions and severity metrics (cont.)

Table 1. Hail diameters and corresponding damage impact [1]

Size code	Typical HailDiameter (mm)	Maximum diameter (mm)	Description	Intensity category	Probable Kinetic Energy (J/m2)	Typical damage impacts
H0	5	5-9	Pea	Hard hail	0-20	No damage
H1	5-15	10-15	Mothball	Potentially damaging	>20	Slight general damage to plants, crops
H2	10-20	16-20	Marble, grape	Significant	>100	Significant damage to fruit, crops, vegetation
H3	20-30	21-30	Walnut	Severe	>300	Sever damage to fruit and crops, damage to glass and plastic structures, paint and wood scored
H4	25-40	31-40	Pigeon's egg > squash ball	Destructive	>500	Widespread glass damage, vehicle bodywork damage
H5	30-50	41-50	Golf ball > Pullet's egg	Destructive	>800	The whole sale destruction of glass, damage to tiled roofs, significant risk of injuries
H6	40-60	51-60	Hen's egg	Destructive	-	Bodywork of grounded aircraft dented, brick walls pitted

Hail definitions and severity metrics (cont.)

Size code	Typical HailDiameter (mm)	Maximum diameter (mm)	Description	Intensity category	Probable Kinetic Energy (J/m2)	Typical damage impacts
H7	50-75	61-75	Tennis ball > cricket ball	Destructive	-	Severe roof damage, risk of serious injuries
H8	60-90	76-90	Large orange > Soft ball	Destructive	-	Severe damage to aircraft bodywork
H9	75-100	91-100	Grapefruit	Super Hailstorm	-	Extensive structural damage. Risk of severe or even fatal injuries to persons caught in the open
H10	>100	>100	Melon	Super Hailstorm	-	Extensive structural damage. Risk of severe or even fatal injuries to persons caught in the open

PV module hail standards and test parameters

IEC 61215-2 hail impact test

According to IEC 61215, product designs must withstand 11 impacts of a 25 mm (1 ins) ball of ice traveling at terminal velocity, which results in an impact force of 1.99 joules.

In comparison, a 45 mm (1.75 ins) ice ball, moving at 30.7 m/s, delivers approximately 20 joules and a 75 mm (3 ins) ice ball, moving at 39.5 m/s, delivers approximately 158 joules. These values are significantly higher than the baseline certification requirement and represent impacts which punch holes straight through the modules, in contrast to the dents and cracks which manifest with smaller projectiles. [2]

In real-world conditions, the speed of falling hailstones can be altered by wind, turbulence, and updrafts. Furthermore, many natural hailstones are irregular in shape rather than perfectly spherical. These irregularities result in alterations to the effective drag coefficient, Cd, leading to deviations from the idealised calculations.

Despite the inclusion of a hail impact test within the IEC standard, the evaluation method employed is a simple pass/fail assessment, rather than a probabilistic analysis of survival. The test is limited in scope, as it only considers a restricted range of impact energies, typically up to the baseline certification point. Optional higher-energy testing is not part of the standard procedure.

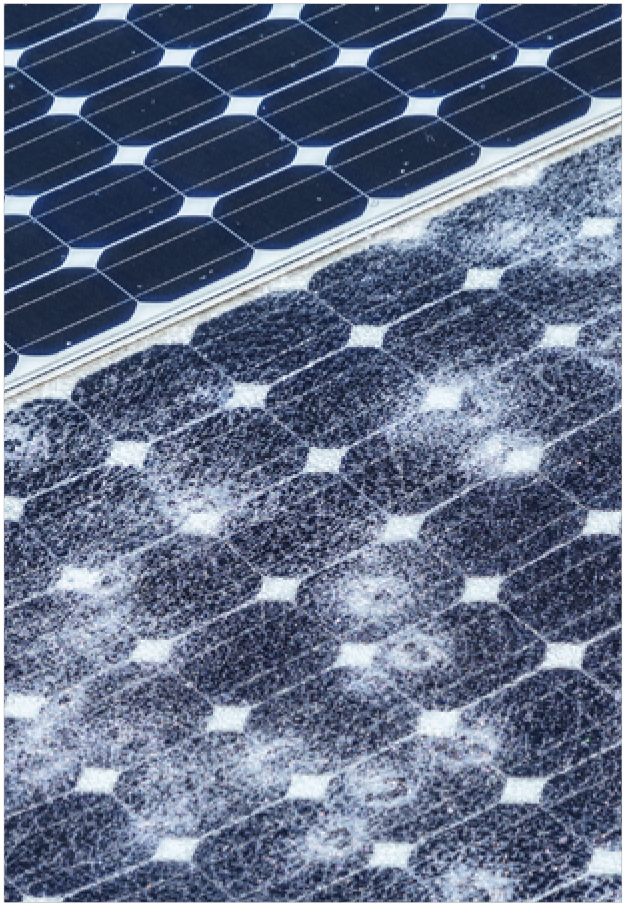
The effectiveness of the product in relation to larger hailstones, i.e. those measuring 50 mm or 75 mm (2 ins or 3 ins) and greater, has not been guaranteed. The energy output of these larger hailstones has been measured to be in the range of 20 to over 100 joules per impact. Indeed, the standards do not delineate particular survival thresholds for hail significantly exceeding 25 mm (1 ins) in diameter falling at high velocities. This emphasises that IEC compliance guarantees only a modicum of hail resistance and does not ensure resilience to extreme hail events, which can only be mitigated by stowing the modules. [3]

Experimental and numerical studies on hail impact

Advanced experimental and numerical studies have investigated the relationship between hail size, velocity, and PV module failure.

In a representative study, the impact of hailstones with diameters up to 50 mm (2 ins) on PV panels measuring 2000 mm × 1000 mm with front glass thicknesses ranging from 3.5 mm to 4.2 mm was simulated. Impact velocities ranged from 40-100 m/s, thus significantly exceeding the IEC test conditions. The findings demonstrated that when hail velocities exceeded approximately 70 m/s, equivalent stress and deformation in the glass increased sharply, particularly in the central impact zone. [4]

A series of experimental tests were conducted in order to ascertain the parameters surrounding hailstone fracture. It was demonstrated that the fracture occurred when the kinetic energy of the hailstone exceeded approximately 95 joules. This is equivalent to a hailstone diameter of approximately 42 mm (1.6 ins), impacting at a velocity of 73 m/s. These values exceed the parameters established for standard certification, yet they align closely with field observations from recent catastrophic hail events. [5]



Role of front glass thickness

Front glass thickness is a critical parameter influencing hail resilience. Anonymised hail durability test data indicate that PV modules with thinner front glass (e.g. ≤3.2 mm) are less resilient to large-diameter hail, than modules with thicker glass (e.g. 3.5–4.0 mm).

The reduction in thickness of glass decreases its cross-sectional area, thereby reducing its capacity to absorb impact energy. This reduction in thickness also renders the glass unable to undergo full tempering through conventional processes, thus necessitating the development of alternative methods to enhance its strength.

However, even modules with thicker glass are vulnerable when subjected to perpendicular impacts from large hailstones. This finding serves to reinforce the conclusion that the thickness of glass alone is incapable of mitigating the risk of extreme hail, and that effective stowing strategies must be implemented in order to preserve the safety of the structure.

Stowing

The utilisation of hail stow has been demonstrated to be a highly effective strategy for the protection of contemporary solar projects in regions characterised by a high incidence of hail.

The hail stow protocol involves the tilting of solar trackers to their maximum angle without passing through flat, with a default east-facing orientation recommended for the majority of U.S. locations. This orientation aligns with the predominant wind directions encountered in a typical severe convective storm.

During periods of active hail events, the priority should be given to hail stow in order to maximise protection. Although many severe hailstorms do not result in damage due to hail stow, these "null events" are seldom documented. [6]

A notable instance of this phenomenon transpired in Fort Bend County, Texas, on 15-16 March 2024, when three solar projects – namely Cutlass I, Cutlass II, and Old 300 – were subjected to hailstorms with accumulations reaching up to 100 mm (4 ins), including two events with return periods greater than 500 years. [7]

All three projects implemented hail stow and suffered minimal to no damage, in contrast to the nearby Fighting Jays project. A minor malfunction, attributed to a tracker motor issue, resulted in damage to unstowed rows which serves to underscore the significance of comprehensive system functionality.

It has been demonstrated that the strategic positioning of modules at acute angles during hailstorms can substantially mitigate the adverse effects of severe weather conditions, thereby underscoring the pivotal role of hail stow protocols in enhancing the resilience of contemporary solar energy projects.

Principles behind hail stow

The kinetic energy of a hailstone is proportional to $\frac{1}{2}mv^2$, indicating that both the size (mass) of the hail and its velocity significantly influence the potential for damage. However, the normal component of impact velocity, that is to say the component perpendicular to the surface of the module, is the dominant factor in the fracture of glass.

When tracker-mounted PV modules are oriented horizontally (0° tilt), as is common near solar noon, hail impacts are nearly perpendicular, thereby maximising both impact energy transfer and exposed surface area.

Conversely, stowing modules at the maximum tracker angle (typically 50–80°) has been shown to reduce the projected area and convert perpendicular impacts into glancing strikes, thereby substantially reducing the effective kinetic energy imparted to the glass on contact.

Empirical evidence from recent hail events confirms that arrays stowed at high tilt angles experienced negligible damage even under hail sizes exceeding 75–100 mm (3-4 ins), whereas unstowed arrays suffered widespread glass breakage.

During the 2022 hailstorm at the Prospero I & II solar projects in West Texas, hailstones measuring approximately 50–75 mm (2-3 ins) impacted the site. Arrays stowed at steep angles (up to ~60°) sustained substantially less damage than unstowed or low-tilt arrays. Damage was primarily concentrated in areas where hail size approached the upper end of this range.

Subsequent laboratory impact testing and probabilistic modelling conducted by NEXTracker in collaboration with the Renewable Energy Test Centre (RETC) demonstrated that impacts from 3-inch (75 mm) ice balls resulted in a survivability rate of over 90% for PV module glass when arrays were stowed at around 75°, compared with significantly higher breakage rates at lower tilt angles.

These findings, summarised in the kWh Analytics 2024 Solar Risk Assessment, suggest that raising the stow angle from ~60° to ~75° could reduce the expected hail-related damage to modules by almost an order of magnitude. [8, 9]

Principles behind hail stow (cont.)

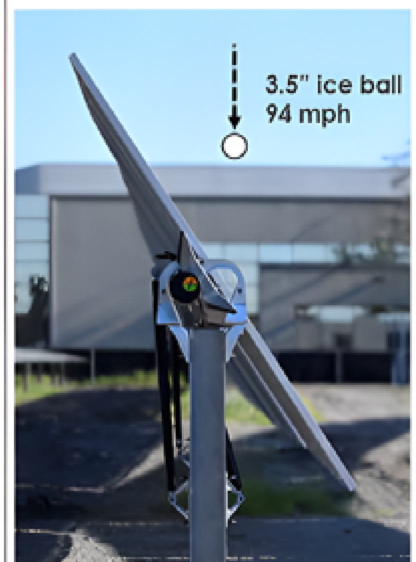
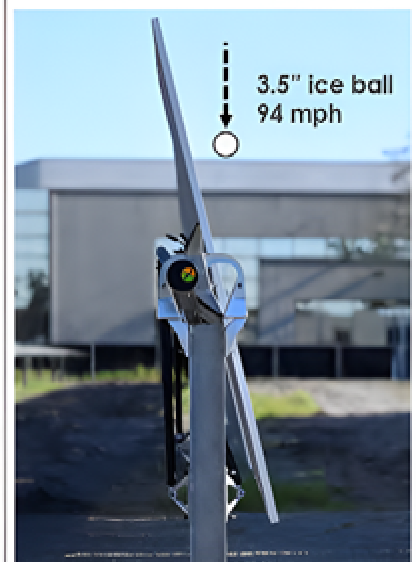
	50° stow	60° stow	75° stow
Tracker angle stow conditions at test site			
Effective Kinetic Energy	121 J	73 J	20 J
Est. Breakage Probability	33%	8%	1%

FIG 03 - Tracker angles stow conditions at test site [8, 9]

Commercial hail stowing practices and capabilities

Modern single-axis tracker systems commonly support defensive stow angles ranging from 50° to 80°, with some vendors offering maximum tilt angles approaching 77–80°.

It is customary for these stow positions to be executed automatically in response to severe thunderstorm warnings, hail probability forecasts, or radar-based alerts.

Leading tracker vendors, including NEXTracker, FTC Solar, Array Technologies, and Terrasmart have incorporated hail stow logic into SCADA-compatible software platforms. These systems facilitate the following:

- The stowing of the vessel should be undertaken in a direction that is consistent with the anticipated storm approach and hail probability
- The process of rapid stow execution is frequently accomplished within a time frame of minutes
- It is imperative to circumvent instances of flat orientations during stow transitions

Insurers are progressively acknowledging these capabilities as paramount risk controls, contingent upon the provision of documented procedures and periodic functional testing.

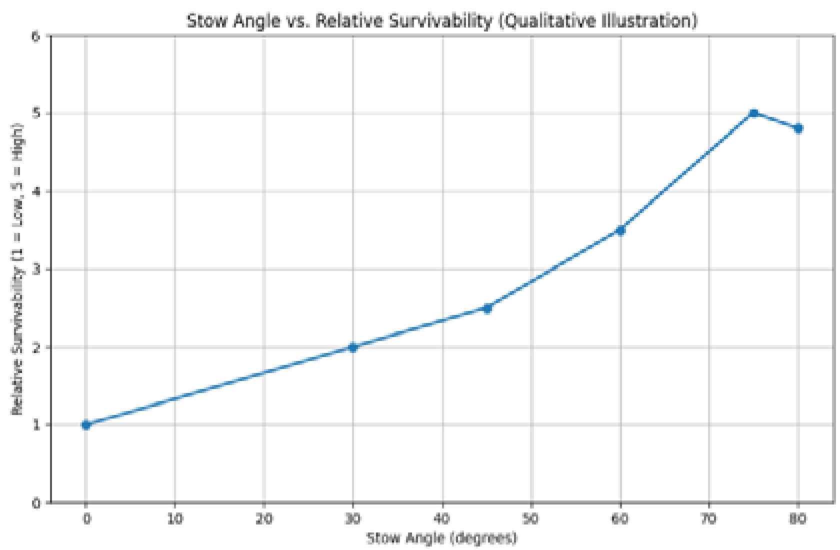


FIG 04 - Stow angle survivability

Wind vs. hail: Design and structural considerations

The achievement of maximum hail mitigation is generally realised through the orientation of the array at the maximum permissible tilt angle facing away from the dominant wind direction. However, it should be noted that this configuration has the potential to increase wind-induced loads due to the larger effective sail area. In addition, the majority of trackers are designed with higher wind ratings on the front surface.

In order to address this trade-off, tracker designs are increasingly incorporating torsional damping, reinforced drive systems, and locking mechanisms. Operational protocols frequently prioritise hail stow over wind stow during active hail events, acknowledging that hail damage typically results in immediate and irreversible module failure, whereas wind-induced damage is more probabilistic and design-dependent. Advanced systems employ sophisticated algorithms which take into account the relative probability of high winds in combination with hail.

Monitoring, alerts, and post-event data collection

In order to achieve effective hail stowing, it is essential to allocate sufficient lead time. Specialised early-warning meteorological services can provide 5–30 minutes of advance notice regarding storm approach direction, expected maximum hail diameter, and probability of impact.

The integration of these alerts into SCADA systems via APIs is now considered best practice, as opposed to manual intervention.

In regions where hail is a frequent occurrence, large-scale PV projects are increasingly implementing hail sensors at a density of approximately one sensor per square kilometre. These sensors facilitate post-event verification, underpin insurance claims, and contribute to industry-wide data initiatives that document both damaging and non-damaging hail events.

Novel tracker concept: FLAP (face-to-face lay-down anti-degradation protection)

The FLAP tracker introduces a folding, multi-linkage structure that enables stow positions beyond simple rotational tilt. In order to provide protection against hail, the panels can be folded face-to-face, thus reducing the exposed glass area and potentially increasing the effective impact resistance through stacking. In certain configurations, the structure can be laid down near the ground, thereby minimising both hail and wind exposure. [10]

The utilisation of ground-locking mechanisms, encompassing mechanical hooks or electromagnetic clamps, serves to further enhance stability by reducing static wind loads and suppressing dynamic instabilities such as vortex shedding and torsional galloping.

While the quantitative hail performance of the FLAP concept remains to be validated through experimental testing, the design demonstrates a potential pathway toward structural hail mitigation that extends beyond angle-based stowing alone.

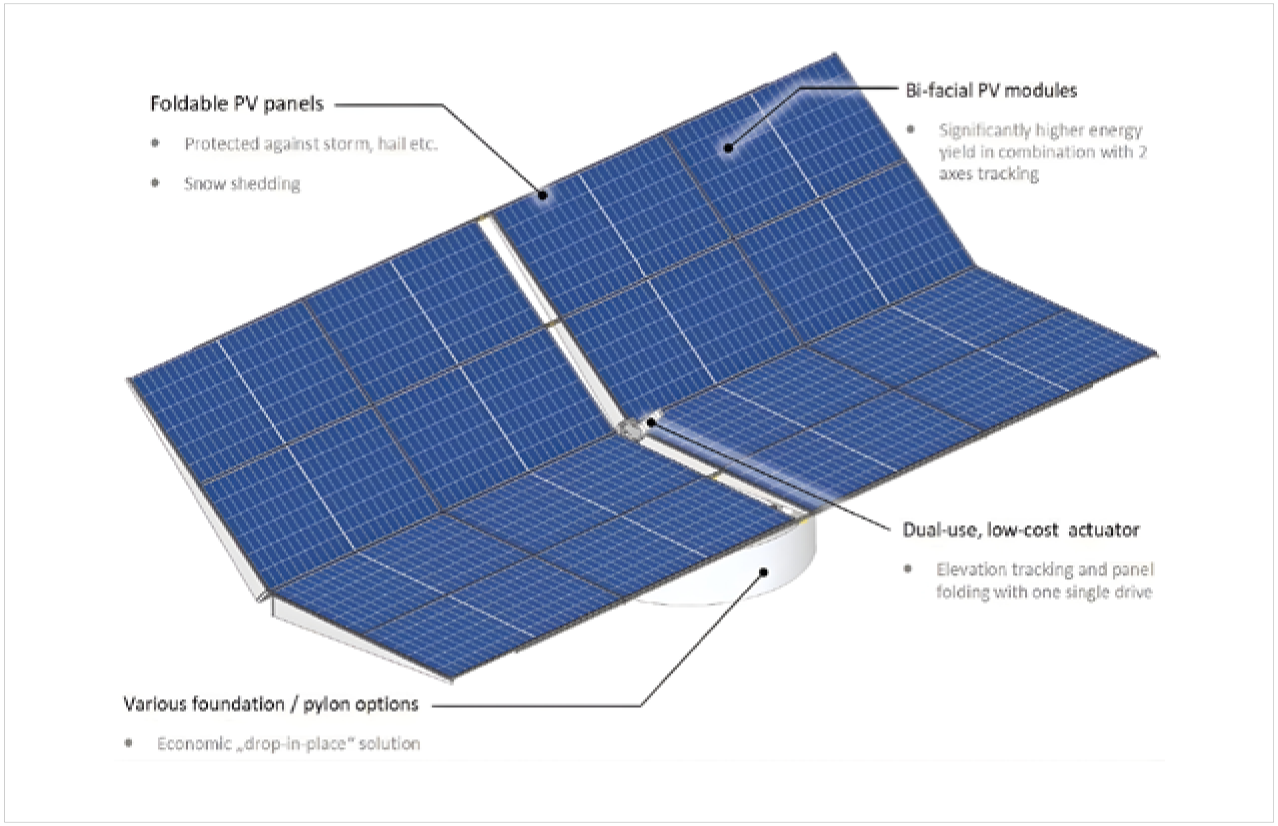


FIG 05 - Overview of the FLAP PV tracker. The FLAP PV allows folding and panel protection during stow and elevation tracking with only one single linear actuator [10]

Insurance considerations

- **Hazard exposure and underwriting considerations:** Utility-scale solar assets are subject to considerable risk from severe convective weather events, particularly hail, which has been shown to result in a disproportionate share of catastrophic losses in comparison to its frequency. Industry analysis indicates that hail events account for a small percentage of total insurance claims by volume but represent more than half of total claim costs when they occur. This highlights the severe impact risk for PV assets. [11]

  It is becoming increasingly evident that insurers are exercising greater caution when it comes to offering coverage for projects in high-hail regions. This caution is often reflected in capacity limitations, elevated premiums, or the imposition of high deductibles. This constrained underwriting environment has prompted developers and insurers to evaluate proactive technological risk mitigation measures that quantifiably reduce potential loss severity. [12]

Insurance considerations (cont.)

- **Proactive hail risk mitigation via automated stow:** The automated stow has been shown to reduce the risk associated with large-loss hail events by materially decreasing expected exposure during peak hazard periods. Independent engineering assessments have demonstrated that positioning modules at protective angles significantly increases survivability compared with horizontal orientations, directly influencing loss profiles embedded within insurance models. [11]
- **Insurance premiums and deductibles:** Collaborative initiatives between technology providers and climate-focused insurers are now translating technological resilience into favourable underwriting outcomes. For instance, a collaboration between NEXTracker and kWh Analytics, a climate insurance provider, enabled a utility project to secure a 50% reduction in its severe convective storm deductible by implementing automated hail stow technology.

This outcome was achieved by quantifying the risk reduction provided by the vendor's Hail Pro system and structuring comprehensive hail coverage contingent on the technology's deployment.

This case study illustrates a broader shift towards data-driven underwriting, where evidence of resilience measures such as automatic stow activation logs and forecast-based controls can justify differentiated insurance terms. This evidence enables insurers to reduce expected loss costs and allocate capital more efficiently, benefiting both carriers and asset owners through lower deductibles and potentially lower premiums.

In addition to deductibles, implementing a proactive stow programme can result in a substantial reduction in property insurance premiums. According to simulations carried out by kWh Analytics, the integration of hail stow strategies at high tilt angles across severe weather watches, warnings, and advisories has the potential to reduce annual insurance costs, with relatively minor consequences for annual production losses. [13]

Conclusions

A comprehensive review of the extant literature, encompassing quantitative analysis, experimental testing, and recent loss experience, has been undertaken to ascertain the most effective and reliable mitigation strategy for utility-scale PV systems exposed to severe hail risk.

The conclusion of this review is unambiguous: hail stowing is the most effective and reliable strategy. IEC module certification, which is typically limited to 25 mm (1 ins) hail at velocities below 25 m/s, is insufficient to address contemporary extreme hail events involving hailstones exceeding 50–100 mm (2-4 ins) and velocities above 70 m/s. Indeed, hail stow is the only effective strategy for mitigating extreme hail conditions.

Recent studies have demonstrated the efficacy of commercial tracker-based hail stow systems in achieving tilt angles of 50–80° in a short space of time. These systems are being requested more frequently by insurers and financiers, as their deployment has been shown to materially reduce the risk of catastrophic hail damage.

By demonstrating tangible benefits such as reduced exposure and loss potential, automated stow systems empower projects to secure favourable terms with insurance providers, as evidenced by case studies including a municipal utility project utilising the NEXTracker Hail Pro system, which achieved a 50% reduction in deductibles.

The FLAP tracker, a novel concept, suggests that further reductions in hail risk may be achievable through advanced structural designs, though this assertion requires additional testing and validation.

Summary of key takeaways

- ✓ Extreme hail (>50–100 mm) is now common in major PV regions
- ✓ IEC hail certification is insufficient for modern hail events
- ✓ Hail stow is the only proven mitigation for extreme hail
- ✓ High tilt angles (~75–80°) provide an order-of-magnitude risk reduction
- ✓ Automated stow + SCADA forecasting is becoming standard best practice
- ✓ Insurers increasingly require documented stow procedures and proof of functionality

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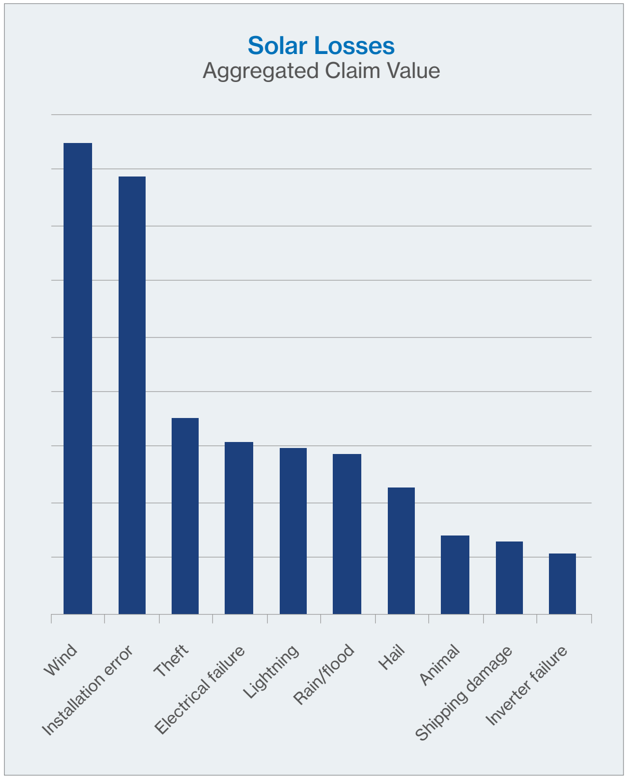
Crawford renewable energy loss database

The Crawford renewable energy loss database captures over 3,000 major losses on renewable energy projects. This database provides valuable insights into the causes and factors contributing to losses in the renewable energy sector, allowing insurers, risk managers and renewable energy project owners to improve their risk management practices.

By leveraging the insights from this loss database you can gain a better understanding of the risks associated with renewable energy projects, identify potential sources of risk and implement effective risk mitigation strategies. This can ultimately lead to more accurate pricing, better claims management and improved industry performance.

Our database provides detailed information on the causes and factors contributing to losses including equipment failures, weather-related events and operational errors. By analysing this data it is possible to identify common patterns and trends and to develop strategies to mitigate these risks and reduce the likelihood of future losses.

Whether you are an insurer looking to improve your underwriting discipline, a risk manager seeking to enhance your risk assessment processes or a renewable energy project owner looking to improve the performance and sustainability of your project, the Crawford renewable energy loss database is a valuable resource.



Crawford renewable energy loss database (cont.)

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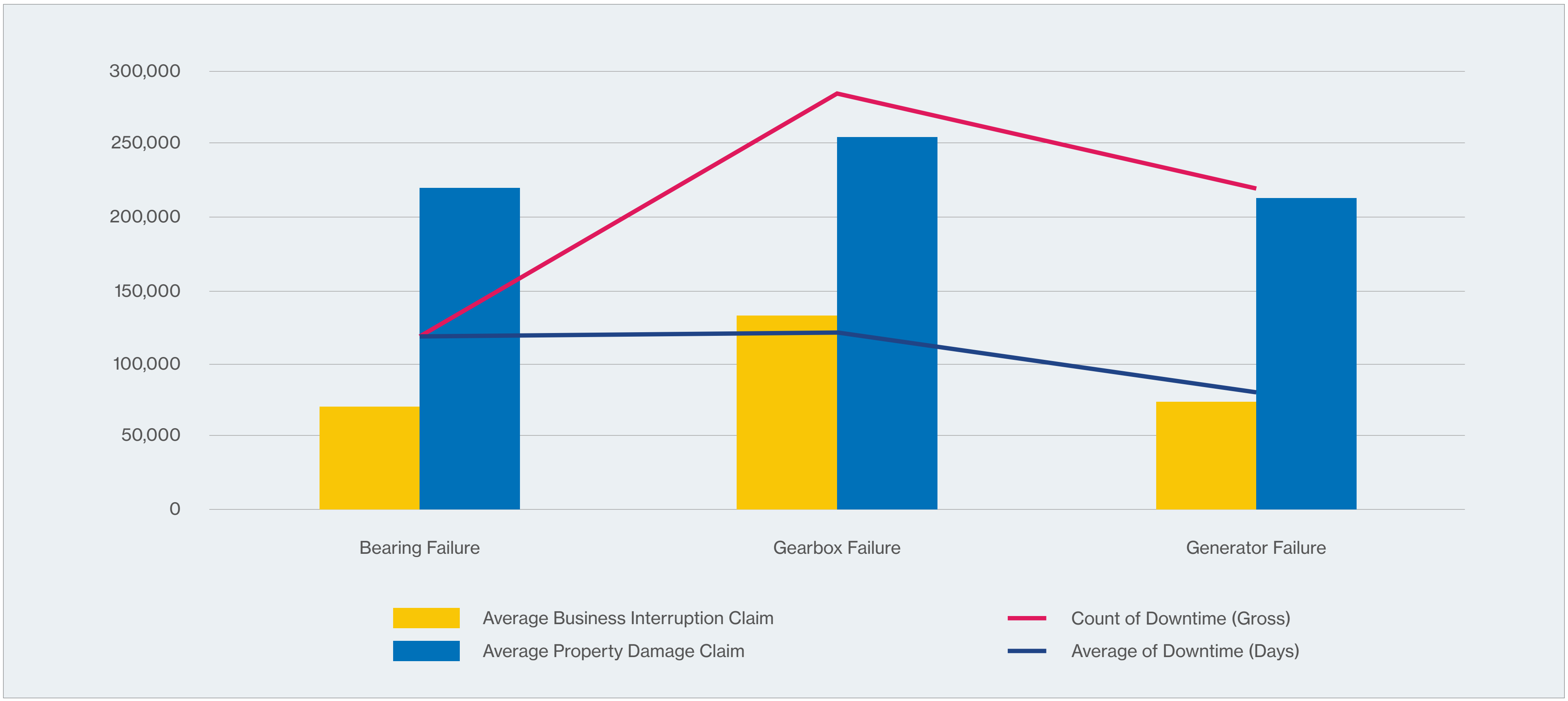

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