Technical Memorandum

Best Practices for Hail Stow of Single-Axis Tracker-Mounted Solar Projects

Dr. Peter Bostock, VDE Americas
Ken Elser, Wells Fargo
Jon Previtali, VDE Americas

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Author(s)	Dr. Peter Bostock, VDE Americas | Ken Elser, Wells Fargo Renewable Energy & Environmental Finance | Jon Previtali, VDE Americas
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Background

Hail has proven to be among the largest property damage risks for solar projects in hail-prone regions. Although property insurance and warranties play a crucial role in mitigating these risks, they do not eliminate the perils associated with severe hailstorms. Insurance often does not cover all exposure, and warranties are subject to carve-outs, photovoltaic (PV) module design standard limitations, and burden of proof. Where PV module hail resilience is insufficient on its own to reduce the risk of hail damage to acceptable levels in utility-scale projects deployed using single-axis trackers, project stakeholders must use defensive hail stow procedures to enhance system-level resiliency.

Stowing single-axis tracker-mounted PV modules at a maximum tilt angle mitigates hail damage in two important ways: First, it can reduce the effective area of glass that is exposed to falling hail; second, it reduces the damage potential associated with hail impacts. Horizontally-oriented PV modules (i.e., 0° tilt or flat) are subject to the normal element of kinetic energy associated with falling hail (i.e., direct blows). Rotating PV modules to a tracker's maximum tilt angle (i.e., 50–75°) generally reduces the normal element of kinetic energy associated with falling hail (i.e., indirect or glancing blows), thereby significantly reducing the damage potential of hail impact.

With input from key stakeholders, VDE Americas and Wells Fargo have compiled the following recommendations and best practices for hail alert and defensive stow protocols for single-axis tracker-mounted solar power projects to guide sponsors, insurers, owners, developers, constructors, operators, and technical advisors. Though some project locations will inevitably experience severe hail events, stakeholders can prevent or limit catastrophic hail damages with improved due diligence, technical literacy, and risk mitigation. The measures described in this memo are intended to mitigate hail risk through physical defenses against damage and should be understood as a supplement to hail insurance, PV module warranties, and appropriate equipment selection.

General Considerations

The following elements are foundational to extreme weather stowing procedures. These general considerations also apply specifically to hail stowing procedures.

- Extreme weather events (e.g., high winds, large hailstones, lightning, and so on) can be very hazardous to personnel. *Personnel safety precautions should take precedence over property protection in all cases.*

- Project design details (e.g., pile specification, PV module mounting system, freeboard versus 100-year flood depth, module glass, PV cell technology) should account for severe weather risks—including, wind, flooding, hail, and hurricanes—on a site-specific basis. Likewise, project operational procedures (e.g., tracker controls, severe weather alerts, and so on) should reflect the results of a site-specific severe weather risk assessment.

- Operational procedures should be integrated into the project operations and maintenance (O&M) contract(s). To codify contractual responsibilities, these procedures should cover the remote monitoring scope of work and the on-site operations scope of work. Providing a flowchart or schematic showing the responsibilities for alerts and action—including escalation paths—may further clarify these roles and responsibilities.

- The practices in the following section require that a remote operation control center (ROCC) is available to respond to operational needs on a 24/7 basis as the primary responsible party. On-site personnel may be unavailable during extreme weather events, either due to safety considerations or due to events occurring outside business hours. ROCC staff should be prepared to operate the plant remotely and document steps taken without assistance from on-site staff. If the ROCC fails to initiate stow within a predetermined period following the alert (e.g., 2 minutes), the on-site site manager should have backup responsibility to initiate stow.

- Project-specific procedures should identify the specific points of contact for responsible organizations and service providers. These procedures should identify specific individuals, where possible, and include primary and secondary contact information (e.g., phone number and email). Ensure that the primary ROCC contact number does not divert incoming calls to voicemail or a similar unstaffed option. As a best practice, the ROCC phone number of record should connect to a 24/7 staffed line; any incoming calls to this number that are not answered in a timely manner should automatically redirect to a monitored and staffed secondary number.

- The project-specific operating procedures should detail the expected stow behavior for the on-site equipment, including stow angle and direction (e.g., east/west), hazard-specific stow responses and priorities (e.g., hail, wind, snow, and flood), potential differences among tracker rows (e.g., perimeter versus interior rows), hazard-specific stow thresholds, order of precedence for automatic and manual stow modes, and so on.

- Operational procedures should clearly convey the requisite urgency (e.g., "Code Red") to O&M staff. Specifically, hail stow response time is of the essence. Severe weather in general—and hail in particular—has extreme damage potential. Due to the highly localized nature of severe weather events, ROCC staff will likely receive a hail alert 30 minutes or less ahead of an advancing storm. Depending on communication procedures and tracker functionality, remote operators may need up to 30 minutes to fully implement defensive hail stow at the site.

- Project operating procedures should require a site inspection after an extreme weather event. This site inspection should assess and report damage in accordance with a prewritten action plan. Methods of assessing damage may include aerial infrared (IR) thermography, drone video, or ground-based visual inspection. The site inspection report should identify the locations of damaged PV modules and the locations of any PV modules flagged for analysis (e.g., electroluminescence testing, I-V curve tracing, and similar methods). To support forensic analyses, insurance claims, and/or warranty claims, archive any data and records relevant to the extreme weather event (e.g., weather service alerts, hail sensor data, on-site observations, operational steps, and so on).

Hail Defense Considerations

For optimal hail resilience, adhere to the following hail defense guidelines and recommendations. Note that best practices in this discipline are rapidly emerging and evolving; the considerations detailed here represent the best opinion available at the time of publication (i.e., the cover page date) but may not reflect the latest lessons learned. Moreover, the tracker manufacturer's wind stow guidelines may take precedence over hail stow optimization, which is the primary focus of this tech memo.

- Conduct an initial hail risk assessment for all projects. The goal of this initial assessment is to generally characterize hail risk (low, moderate, high) on a location-specific basis, as shown in Figure 1. For projects in hail-prone regions, engage a qualified party to conduct a science- and engineering-based hail loss study that covers time periods required by insurers (e.g., 500 years) and within typical investment hold periods (e.g., 10-, 20-, and 40-year hold). This hail loss study should provide probable maximum loss (PML) and average annual loss (AAL) estimates based on site-specific meteorological characteristics (e.g., historical hail event size and frequency) and project-specific technical considerations (e.g., primarily PV module glass thickness and strengthening, tracker maximum stow angle, and PV module size). Sponsors should use the PML and AAL results to inform acceptable insurance terms and conditions (e.g., coverage, sublimits, and similar) for the transaction. Operators should use the results of this hail loss study to inform O&M procedures (such as stow protocols, hail stow alert trigger radius, and other operational criteria).

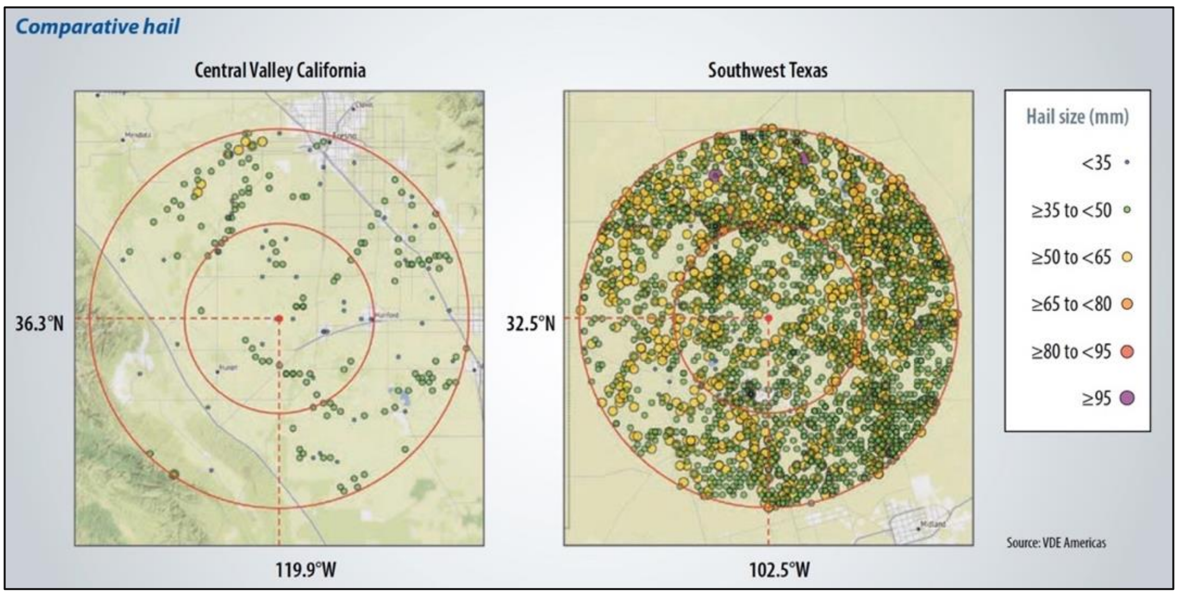

Figure 1. Comparative hail risk assessment for low- and high-risk locations (Source: VDE Americas)

- Automate defensive hail stow for operational projects based on alerts from a reputable weather service provider. This is typically accomplished by automated processing of electronic alerts or linking a frequent call response from an application programming interface (API) to the appropriate stow command via the project's supervisory control and data acquisition (SCADA) system. Tracker manufacturers are starting to offer automated hail stow functionality natively and can typically support this functionality via custom hail alerting service and project SCADA system integration. To meet cybersecurity standards on large projects governed by NERC CIP [critical infrastructure protection], restrict tracker control to NERC-certified entities. While automated hail stow is a best practice, some of the following recommendations assume that no automation is in place, in which case on-site staff or off-site ROCC personnel must manually trigger hail stow after receiving a weather alert.

- Meteorological conditions conducive to severe hail generally coincide with periods of low solar irradiance. A kWh Analytics study[1] suggests that the benefits of improved hail risk reduction outweigh the costs associated with lost revenue. Modeling the performance of a hail-prone site in Texas, kWh Analytics estimates that preemptive hail stow during National Weather Service

[1] "Proactive hail stow programs can reduce property insurance premiums," kWh Analytics, Solar Risk Assessment, 2023.

severe thunderstorm watches, warnings, and advisories would sacrifice only 0.1% of annual revenue. Given the magnitude of potential damage due to hail, this suggests a reasonable approach is to "stow early and stow often" in response to hail risk.

- To optimize response times, projects should enable site-level hail stow functionality rather than stowing on a block-by-block basis. Some original equipment manufacturers may require that the project purchase optional services to enable effective, whole-plant hail stow. For due diligence purposes, technical advisors should confirm that projects have purchased these optional features.

- Where the tracker manufacturer allows, hail stow should take precedence over wind stow. In many cases, severe hail has proved to be more destructive to solar power plants than straight-line winds. The project-specific severe weather response protocol should clarify and resolve any risk that an automated stow response may inadvertently override a hail stow command.

- All else being equal, *the ideal defensive hail stow orientation for PV modules is facing away from the wind at a maximum tilt angle,* as shown in Figure 2. In real-world applications, optimizing for defensive hail stow is not always practicable or advisable. Consult the original equipment manufacturer to determine the risk of wind damage at different wind speeds and factor these equipment-specific wind speed ratings into the project's operational stow protocols. Avoid moving a tracker through a horizontal orientation (e.g., flat, 0° tilt) in advance of a fast-moving storm front without sufficient time to complete the operation, as this could inadvertently increase hail and wind damage.[2] If stowing away from the wind is not practicable (e.g., due to insufficient tracker strength or limited response time), stow PV modules at a maximum tilt angle facing into the wind. Because time is of the essence, a good default hail alert response is to stow PV modules at the nearest maximum tilt angle as quickly as possible.

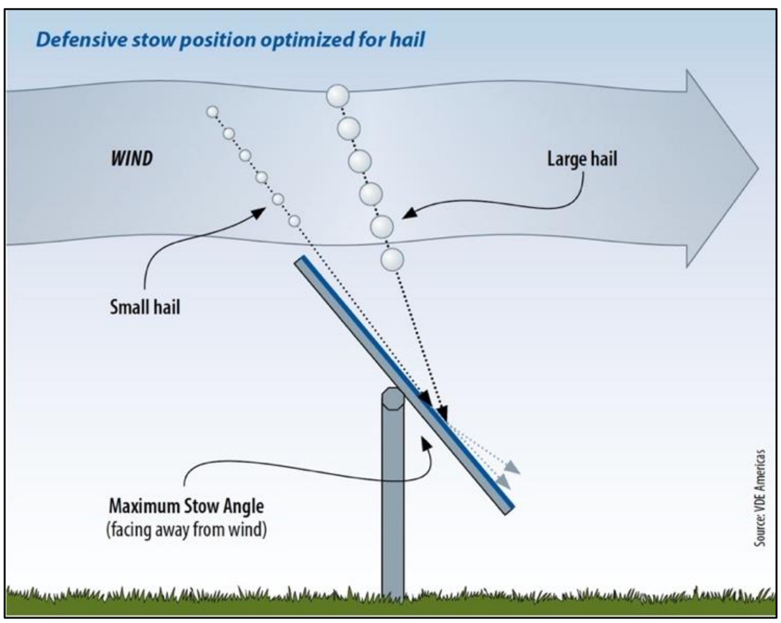

Figure 2. PV modules stowed away from the wind at a maximum tilt angle (Source: VDE Americas)

> A good default hail alert response is to stow PV modules at the nearest maximum tilt angle as quickly as possible.

[2] Though hailstorms in the Continental United States (CONUS) typically approach from the west and predominant winds are from the west, this is a site-specific consideration and wind direction during hail events is subject to significant variability.

- Set trackers to a full hail stow position between dusk and dawn to minimize the overnight risk of hail damage. For trackers capable of withstanding full site wind speeds regardless of wind direction, face PV modules away from the prevailing hailstorm approach direction. Where hailstorms typically approach from the west (e.g., the CONUS), plant operating procedures should face PV modules to the east to minimize overnight hail risk.

- To minimize the risk of hail damage before plant commissioning and energization, set trackers to a full hail stow position as soon as practicable during construction. For trackers capable of withstanding full site wind speeds regardless of wind direction, face PV modules away from the prevailing hailstorm approach direction. Where hailstorms typically approach from the west (e.g., the CONUS) construction contracts should generally call for facing PV modules to the east to minimize hail risk before the commercial operation date (COD).

- In moderate to high hail risk locations, use targeted weather alert services (e.g., AccuWeather, DTN Storm Corridor, DTN Weather Sentry, and so on) to provide site managers and ROCC personnel with proactive email and text alerts based on preset criteria. These alerts should be logged by the SCADA system for record keeping. Because email or text alerts may encounter delays, it is a best practice for the ROCC to automatically monitor relevant weather service alerts (e.g., via minute-by-minute API calls to DTN Storm Corridor.) Though regional weather forecasts are generally inappropriate for making project-level operating decisions, they may be useful for maintaining or heightening site readiness. By monitoring daily forecasts, the site manager and ROCC personnel may be able to identify conditions conducive to severe hail and proactively issue elevated risk alerts.

- PV modules tested to the International Electrotechnical Commission's IEC 61215 product qualification standard must successfully pass ballistic-impact tests conducted using a 1-in. (25-mm) freezer iceball. Because the density of a freezer iceball is greater than the density of naturally occurring hail, PV modules qualified to the IEC 61215 standard have generally demonstrated the ability to withstand 1-in. (25-mm) hail.

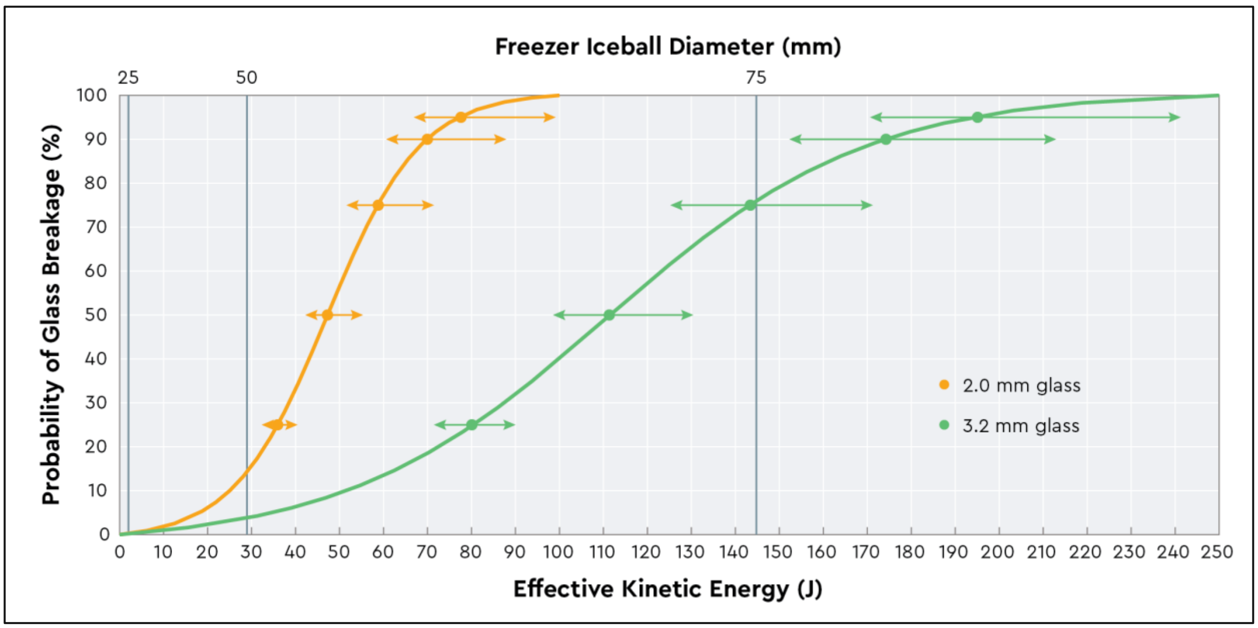

Figure 3. Comparative freezer iceball resiliency curves for common c-Si PV module packages (Source: RETC)

- Since qualification to IEC 61215 represents the industry-typical minimum requirement for product safety, additional hail resiliency, as determined by beyond-qualification testing, may be prudent for projects in hail-prone areas.[3] Figure 4 provides comparative hail resiliency curves for two common crystalline silicon (c-Si) PV module packages: 1) 2.0-mm glass superstrate with a 2.0-mm glass substrate (orange line), and 2) 3.2-mm glass superstrate with a polymer substrate (green line). A technology-specific hail loss study can characterize how comparative product resiliency impacts a project's hail risk profile.

[3] IEC TS 63397 includes a hail test protocol that uses accelerated lifetime testing to help estimate the long-term effect of hail damage.

> A good rule of thumb is to put trackers into hail stow if the National Weather Service predicts a severe thunderstorm.

- According to NOAA, a severe thunderstorm produces wind speeds greater than or equal to 58 mph (25 meters per second) and hail greater than or equal to 1 in. (25 mm) in diameter. A good rule of thumb is to put trackers into hail stow if the National Weather Service predicts a severe thunderstorm for the county where the project is located. When monitoring weather advisories, forecasts, and broadcasts for a given site, note that severe hail can form in a variety of weather phenomena (e.g., supercells, high-precipitation supercells, multicell cluster storms, squall lines, mesoscale convective storms, elevated thunderstorms, and tornadoes).

- Use 1-in. (25-mm) hail events as a minimum remote alerting criterion. This is consistent with DTN's "severe hail" alert setting.[4] If weather service capabilities do not permit hail size differentiation, it may be prudent to use "any hail" (or a similar option) as a remote alerting criterion; this is a conservative posture as it assumes that all hail has damage potential.

- The radius for weather service alerts should be no less than 30 miles (48 km) away from the project perimeter; in some cases, the radius should be up to 60 miles (97 km) away from the project perimeter. To identify the optimal weather alert radius, evaluate the local meteorological conditions, the overall site hail risk, and the tracker response time to reach maximum tilt. A hailstorm can travel as fast as 60 mph (97 km/h) and some trackers take 15 minutes or more to reach hail stow after receipt of the command.

- Both the ROCC personnel and the on-site manager must receive sufficient training, documentation, permissions, and SCADA access to quickly put trackers into a defensive hail stow position. As part of these measures, ensure that the operational stowing procedures documentation includes the appropriate login information (e.g., SCADA or tracker control system) and hazard-specific operating instructions.

- If the site manager and ROCC are communicating by phone when the hail stow command is issued, these parties should remain on the line until it is confirmed that the trackers have stowed successfully. The site manager or ROCC should identify and document any trackers not responding to the hail stow command and flag defective trackers for troubleshooting and repair.

- The site manager or ROCC staff should thoroughly document hail (or other severe weather) stow events. Valuable documentary evidence for the purposes of substantiating warranty and/or insurance claims includes hail alert notification (e.g., email, screenshot, and so on), stow-initiation time, final stow angle, stow-completion time, general meteorological conditions in the area, event-specific on-site sensor data (with time stamps where available), and so forth.

- The project-specific operating procedures should delineate the process of restoring normal operations after a hail stow event. Operational protocols should identify the party responsible for issuing an all-clear notification and detail the decision-making criteria. As an example, the all-clear criteria might be based on the absence of a continued hail alert from the designated weather service alert provider, provided that a period not less than 30 minutes has elapsed since the last predicted hail impact time. Following plant restoration, the site manager should provide the ROCC with confirmation that the trackers are working as expected or provide an initial hail damage estimate.

- For projects in moderate- to high-hail risk locations, permanently install hail sensors or systems to supplement the on-site meteorological measurements and weather alert services. The primary purpose of these on-site hail sensors or systems is to document site conditions during hail events for warranty and/or insurance claims; secondarily, these sensors are useful to assess the accuracy of weather alert services. Using on-site hail sensors to trigger an automated hail stow response is advisable only as a measure of last resort, as PV modules will already be incurring hail strikes by the time an on-site sensor triggers a

[4] Note that in 2010 the National Weather Service changed its severe hail definition from 0.75 in. [19 mm] to 1 in. [25 mm].

We suggest deploying one hail sensor or system for each square kilometer with spatial coverage across the full project footprint.

defensive stow operation. As a baseline, we suggest deploying one hail sensor or system for each square kilometer with spatial coverage across the full project footprint. Integrate sensors into the SCADA system to log evidence and data regarding hail (e.g., time stamp, hail size estimate, kinetic energy, frequency, and so on). Note that hail sensors measure kinetic energy and do not provide a precise characterization of hail diameter.

- For projects using parametric insurance, where payouts are indexed to hailstone diameter, consider using hail pads for corroboration purposes. A hail pad is a device used to obtain data on hailstone size distribution and mass. A hail pad usually consists of a Styrofoam panel covered by aluminum foil. Hail that strikes the pad leaves dents, as shown in Figure 5. A forensics expert can analyze these dents to characterize hailstone size and mass. For best results, consult with a qualified party to determine size and spatial distribution of hail pads, and mount the hail pads where they will not be damaged by O&M activities.

Figure 4. Dents in a hail pad after a severe hail event (Source: CoCoRaHS)

- New market entrants are starting to introduce physical hail defense systems (e.g., nets, protective plastic sheets, etc.) intended for integration with utility-scale solar projects. When evaluating these unproven technologies, project stakeholders should request independent third-party validation regarding mechanical stress, wind tunnel, material durability, and field performance testing. These test data should evaluate the additional mechanical stresses placed on the module glass, frames, and cells (where applicable), as well as the performance effects associated with additional self- and inter-row shading. Ensure that the project production estimate and pro forma financial model are backed by long-term in-field performance testing data and verify that the physical hail defense hardware is compatible with the module manufacturer's listed installation instructions and its published warranty terms and conditions.

- Project stakeholders should review and test the complete hail alerting and stow procedure prior to substantial completion. As a best practice, schedule a functional hail stow test prior to the start of the project location’s hail season(s). For continued readiness, review hail protocols and test defensive hail stow capabilities on a biannual basis at a minimum.

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2033 Gateway Place, Suite 500 | San Jose, California 95110 | vdeamericas.com

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