Wind-Induced Dynamic Loading and PV Module Frame Fatigue Crack Initiation and Propagation

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Abstract

Key Features

Large-format photovoltaic (PV) modules, while offering cost and efficiency advantages, face significant reliability challenges. A key issue stems from their lack of structural rigidity, leading to mechanical failures. A notable mechanism involves the bottom flange of the module frame tearing away under both extreme and moderate wind conditions.

This bottom flange has been reduced in size with the advent of large-format panels, yet identical failures occur in smaller-format modules, highlighting design and material vulnerabilities. Photographs of failures from Hurricane Beryl illustrate the damage, while finite element analysis (FEA) modeling reveals stress points and tear-away conditions. Evidence of frame cracking before failure suggests fatigue crack initiation and propagation as a precursor to catastrophic damage.

Preliminary findings indicate that flange integrity is compromised by cyclical loading and sudden gusts, with wind-induced vibrations amplifying stress in critical areas. These insights underscore the urgent need for improved design standards and testing protocols to ensure durability across diverse climatic conditions.

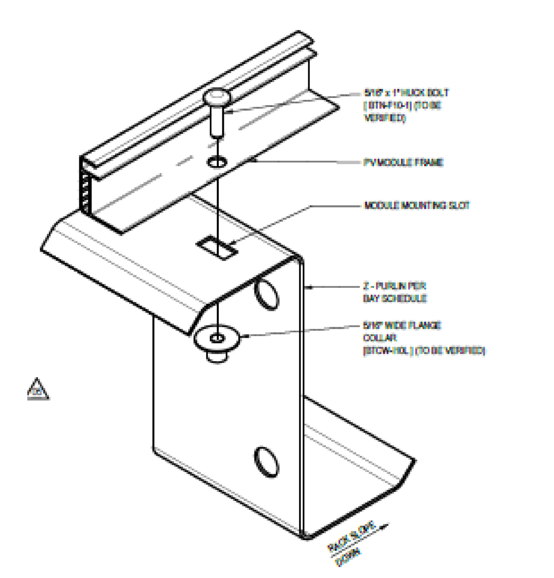
This work has implications for manufacturers, field operators, and policymakers seeking to optimize the reliability and longevity of PV installations. Addressing these reliability concerns will help the industry balance the advantages of large-format modules with the demands of long-term operational resilience.

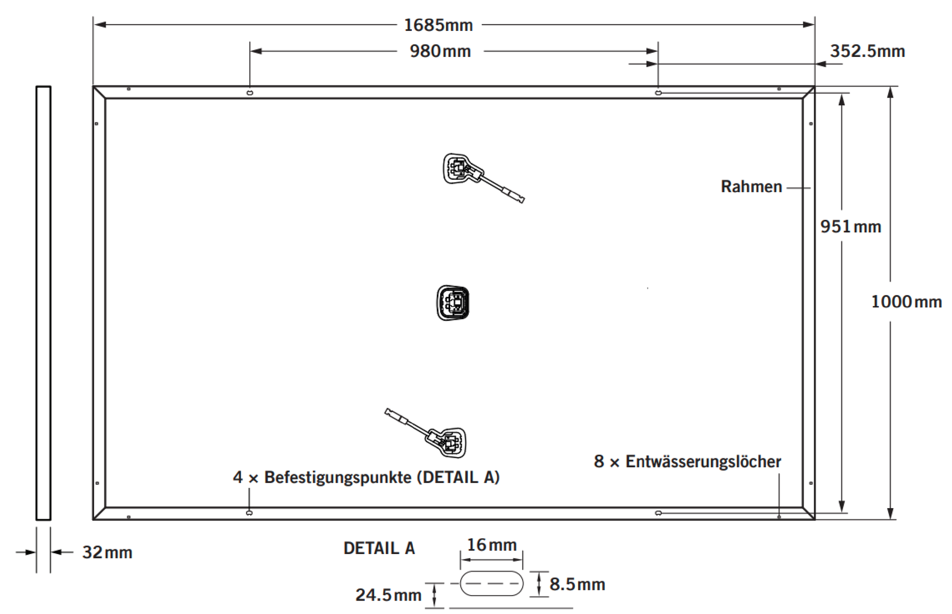
Targeted Audience

- *Project Developers*
- *Engineering, Procurement & Construction (EPC) Companies*
- *Independent Engineering Firms (IE's)*
- *Standards Committees*
- *Insurance Companies*
- *Financiers*
- *Module Manufacturers*
- *Solar Racking Manufacturers*

Grenadines Project Information

Current Design



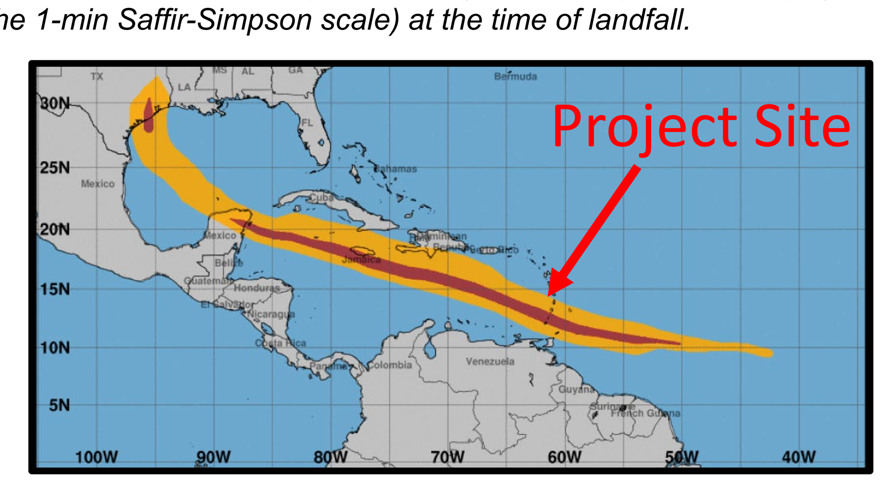


Installation was performed at the four mounting points utilizing direct bolted connections per the installation manual. It was confirmed in the installation manual that the test load (push/pull) is 4000 PA which after applying the IEC61215-2-2016 and UL61730 safety factor of 1.5, provides a **design load (push/pull) of 2670 PA**.

Modules were mounted at a low angle (~5 deg) to nominal but were located on a slope (~15 deg) with the leading edge of the module almost perpendicular to the oncoming wind direction. This is an area for future project design improvement and will be outlined in Solar Under Storm III guidance in May 2025

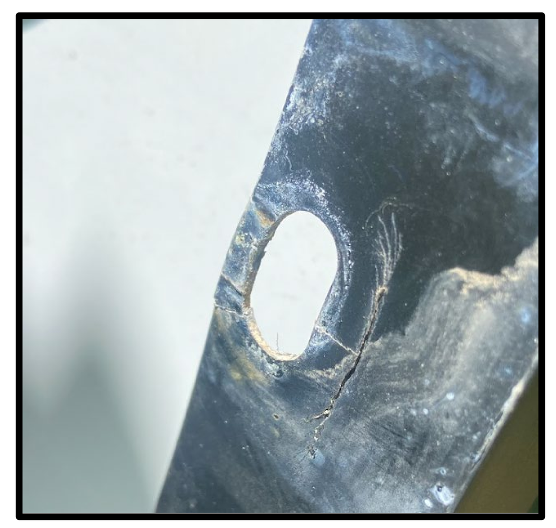
Hurricane Beryl

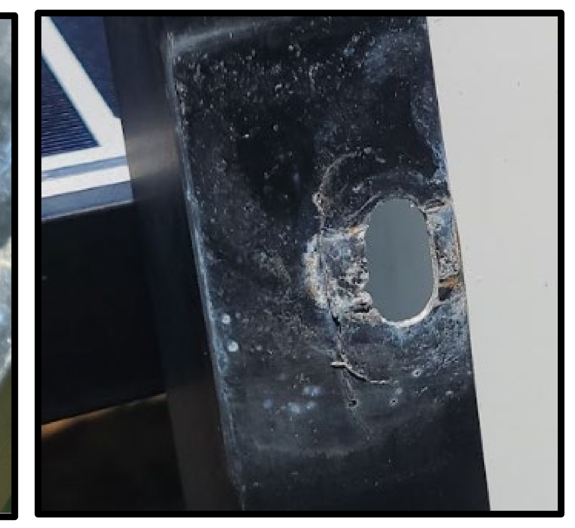
Hurricane Beryl struck the Grenadines on July 2nd, 2024. NOAA estimated peak winds of 140mph categorizing Beryl as a dangerous Category 4 storm (on the 1-min Saffir-Simpson scale) at the time of landfall.

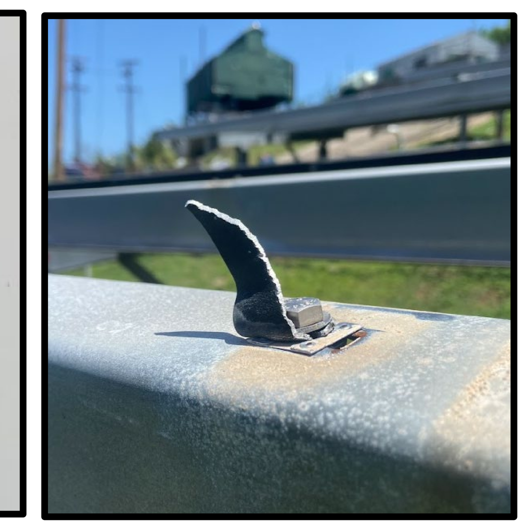


Site Performance & On-Site Findings

- *The project site was modeled after Solar Under Storm 1 recommendations and by all accounts performed admirably. To have a test bed for resiliency improvements hit by a second hurricane is incredibly improbable and an amazing opportunity to find new failure modes.*
- *Racking utilized dual-post foundations and low-angle module mounting, resulting in zero primary failure modes in the racking system.*
- *31% of modules remained visibly undamaged.*
- *No witnessed hardware loosening due to use of Nylock nuts (vibration resistant hardware)*
- *Mild structural corrosion was present - typical of the region and age.*
- *Module frame tear-out was the primary cause of module liberation. Photo below >95% of all module hardware*

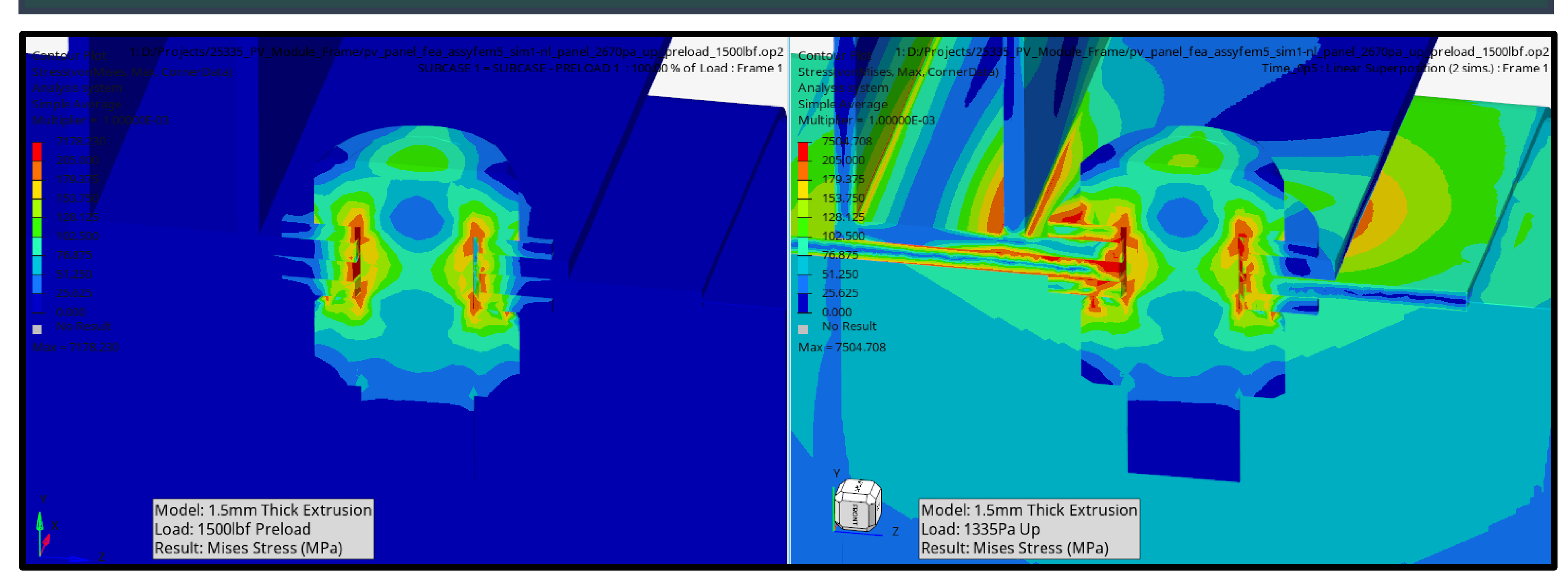




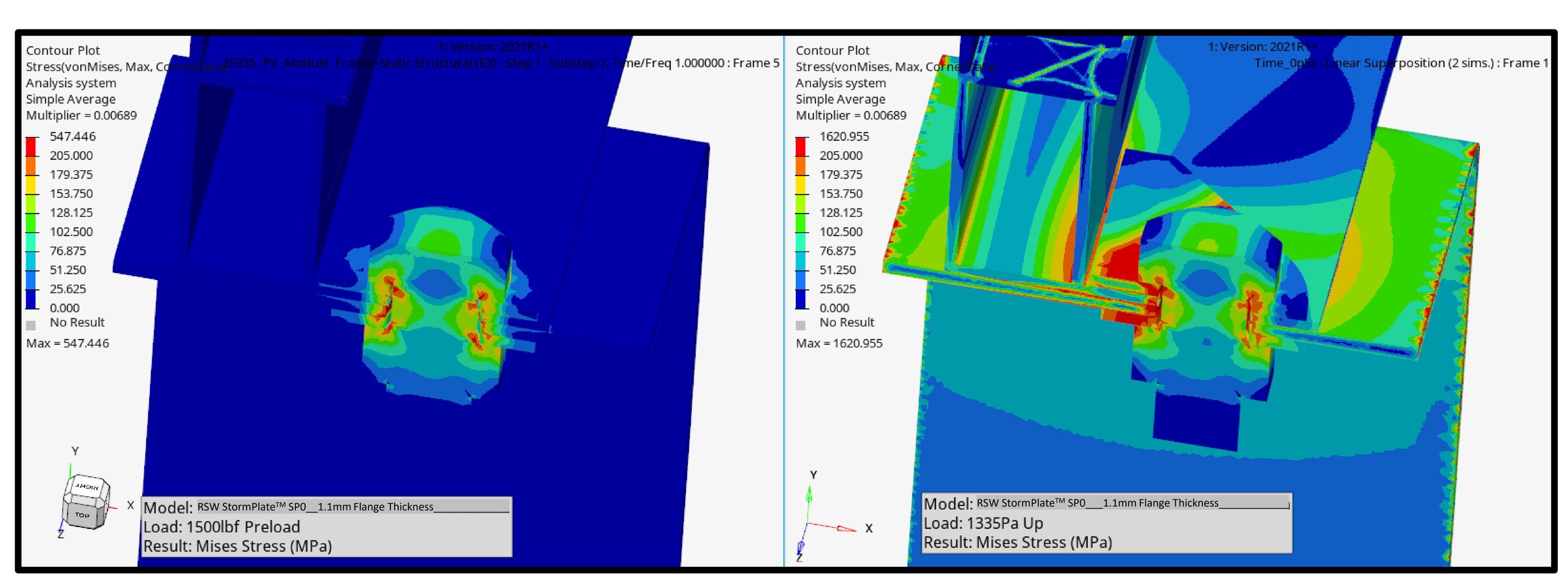


Low-cycle fatigue cracks were found on many remaining modules both on hardware on the low and high-pressure sides of the modules. Propagation led to failures and is the primary failure mode for module liberation.

Finite Element Analysis

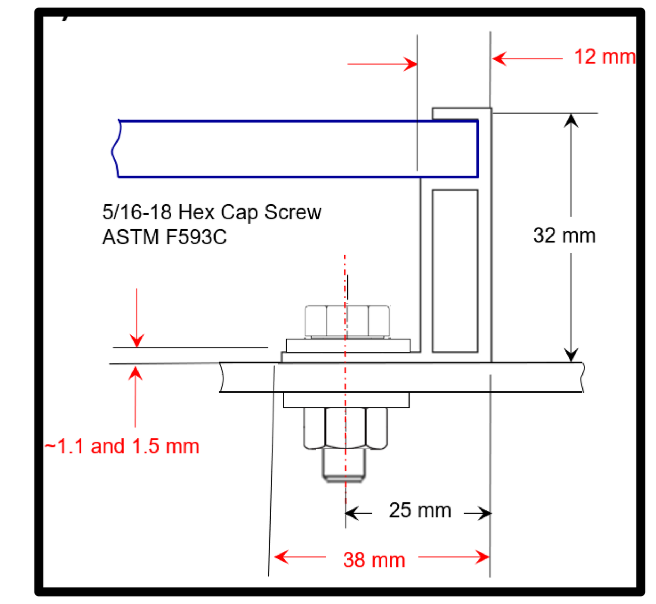


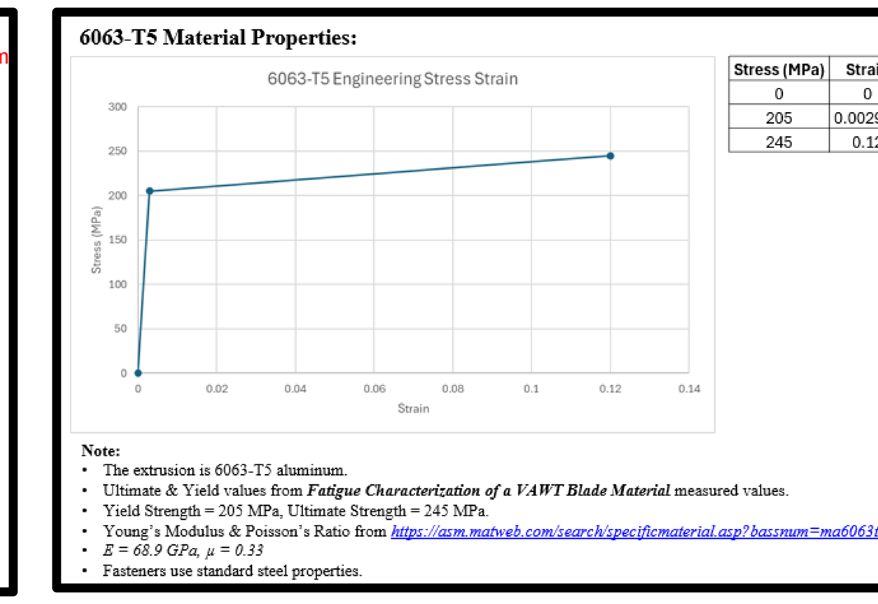
Industry typical 5/16 bolt stack-up utilizing a round washer at 1335Pa of test load (50% of the rated load of this panel) – Failure shows along the interior wall frame which was observed in the field (see photos above)



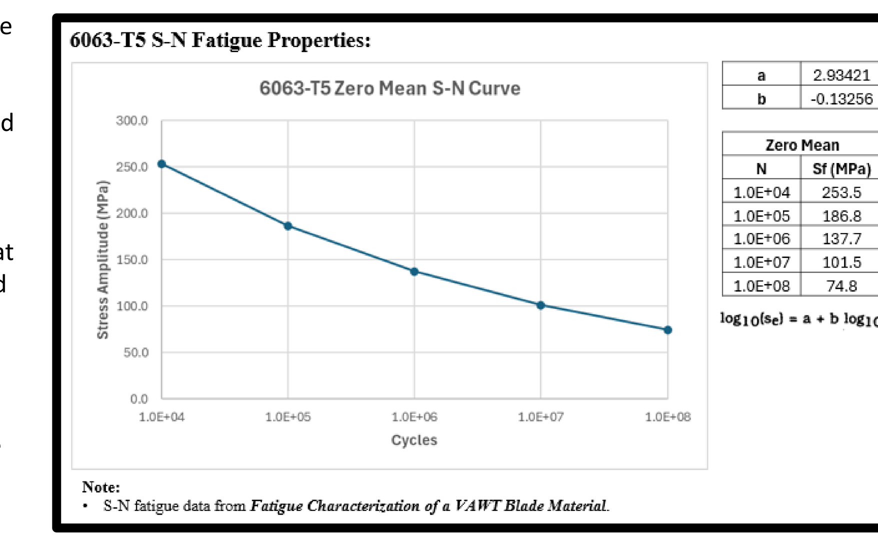
RSW StormPlate™ SP0 design was tested to distribute the load. FEA Static results showed a 33% reduction in peak stress in the AL frame, drastically improving the frame performance and should (with further IEC61215 testing) improve overall module performance if the primary failure mode was frame buckling (which it often is)

FEA Model Setup





- Material properties (6063-T5) and an appropriate S/N fatigue curve for the were selected.
- These properties combined enable non-linear FEA analysis of the fastener, washer selection and frame performance.
- As the frame deforms under load, stresses and forces change. It is important to capture these changes as the static FEA analysis showcased that the vast majority of IEC61215 testing would yield a module frame with permanent plastic deformation, even under 40-60% of the rated static load.
- This in-turn begets the question of "what determines a pass / fail for module performance in IEC 61215?". Electrical continuity considerations are primary in this regard.



<u>An area for future improvement in IEC 61215 would be to utilize cyclical loading protocols after a static load test to determine an appropriate amount of static load test plastic deformation in the frame.</u>

Results

Fatigue Life 2 Elements from Edge A (Cycles)			
	Applied Load		
Model	1068 Pa 40% Rated	1335 Pa 50% Rated	1602 Pa 60% Rated
1.1mm Thick Extrusion	198,427	14,730	607
1.5mm Thick Extrusion	2,298,817	283,000	38,958
RSW StormPlate™ SP0 1.1mm Thick Extrusion	4,144,299	1,015,000	283,169

The 1.1mm thick frame flange showcased failure at approximately 607 cycles of load at 60% of it's rated load (1602 Pa). <u>Assuming the wind comes from the worst-case direction (rear) this could be achieved in the field in a matter of minutes.</u>

The addition of the RSW StormPlate™ SP0 in the analysis shows a great area of promise.

<u>RSW StormPlate™ SP0 showed a 450x increase in the number of cyclical loads</u> compared to the 1.1mm thick frame utilizing industry-standard hardware stacks.

As modules evolve to become larger and have less rigidity, fastener selection needs to be tailored to the application. RSW StormPlate™ SP0 is one example of how to better support these smaller frames against stress concentrations. Application specific mounting innovation and techniques like load distribution are key to reducing module liberations in the field.

Taking this analysis away from smaller-format modules under extremely high wind events is also alarming. <u>The expected performance of a large format module under the same conditions would yield an expected failure pressure of 1000Pa</u> (rather than 1335Pa) for an expected performance of under 1000 cycles. This is an industry wide problem, driven by module frame evolutions across all module platforms.

<u>Multiple module frame flange thicknesses were assessed utilizing industry standard round washers</u> to showcase the cyclical loading difference in simply increasing frame material. 1.1mm was measured in the field in the Grenadines. 1.5mm would constitute a 36% increase in material, estimated to cost approximately $2.00 a module depending on module size ($0.005/w). 1.5mm brings a meaningful improvement. However, the <u>minimum cycle requirement for 20-year performance (acceptable) is yet to be determined.</u>

The module frame failed following static mechanical load testing at ±1800 Pa and dynamic mechanical load for 1000 cycles at ±1000 Pa. The failure occurred on DML cycle #962.

Thankfully, <u>industry standards already exist for cyclical load test (IEC 62782-1)</u>. Kiwa PVEL (a well-known industry test lab) showcases IEC62782 results as part of it's 2024 Module Reliability Scorecard and notes : ***"…frame fatigue can also be an issue. In this example, the module's mounting hole was ripped out of the frame during tracker-mounted ± 1800 Pa SML and DML. This failure mode could result in modules becoming dismounted from racking during high wind events and is likely due to using a thinner frame flange to save cost. This type of defect is typically not replicated during standalone SML or DML testing but has been seen on multiple BOMs subjected to the PQP's combination of SML and DML."*** The example above shows failure at cycle #962 out of 1000 cycle test, validating that <u>the non-linear FEA model matches both field empirical evidence and lab analytical findings</u>.

More Information

Resources:

- International Electrotechnical Commission. (2016). *IEC 61215:2016 – Crystalline silicon terrestrial photovoltaic modules – Design qualification and type approval*. Geneva, Switzerland: International Electrotechnical Commission.
- International Electrotechnical Commission. (2021). *IEC 62782-1:2021 – Photovoltaic (PV) modules - Cyclic (dynamic) mechanical load testing* Geneva, Switzerland: International Electrotechnical Commission.
- Kiwa PVEL. (2024). *2024 Module Reliability Scorecard*. Kiwa PVEL.

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