Operational and Economic Impacts of Extreme Weather on Photovoltaic Power Plants

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Executive Summary

In an anthropocentric world increasingly defined by changes in atmospheric chemistry, two clear trends have emerged. One is the increase in the frequency and severity of extreme and anomalous weather events, the latter driven by rising temperatures and changing patterns of humidity and precipitation; the other is the rapid acceleration of photovoltaic (PV) capacity worldwide, reaching 2 TW in 2024 on course for the expected 8 TW by 2030.

To ensure the further growth and development of PV systems worldwide, however, requires attention to both trends and especially to opportunities for designing PV systems to withstand specific storm threats. Although there are many examples of solar technologies being deployed without consideration for their storm resilience per se, design optimization is gaining attention as solar energy continues to proliferate across almost all climate zones.

This report provides a comprehensive look at changing weather patterns and their anticipated impact on the reliability and performance of PV systems worldwide. Broken down by storm category, the report covers extreme weather events of greatest significance to PV power plants: tropical cyclones, convective storms, snowstorms, dust storms, heat waves, floods and wildfires. For each category, an overview of the threat landscape is provided, along with best practices for design and procurement, mitigation strategies, post-storm assessment and follow-on O&M.

The report also considers damages to PV systems that can be 1) catastrophic, as in, the total destruction of modules, strings or entire systems: modules unravel from their mounts, racks collapse, and glass

shatters; e.g., tropical cyclones, convective storms (including hail), and flooding (see Table 1 below); and/or 2) sub-catastrophic, as in, visual inspection results in no detectable damage, even though internal damage may have occurred to the solar cells or other module components; e.g., snow, dust storms, heatwaves, and wildfires (see Table 1 below). Detectable only with costly imaging techniques, such as infrared or electroluminescent imaging, undiagnosed damage may deteriorate over time, resulting in accelerated performance degradation or the accelerated senescence of module components, such as backsheets and encapsulants.

In addition, the report acknowledges the rapid pace of technological innovation in the solar industry, including the proliferation of new materials and components, the long-term reliability of which is largely unknown, especially under extreme-weather conditions where modules and other components are subjected to combined and cyclic forces not captured by accelerated testing. The resilience of a PV system during extreme weather depends heavily on the unique characteristics of each storm — including the number and types of stressors, how these stressors interact in unpredictable ways, and how such interactions affect the system's components.

Even so, certain generalizations around best practices can be made: 1) site planning should always include a review of weather threats at that particular site; and 2) design and procurement decisions should be based on the threat landscape. In hail-prone regions, for example, modules with thicker front glass are preferred; in snowy regions, frameless outperform framed modules; in regions where tropical cyclones are the primary risk, consideration must be paid not only to the module architecture but even more to the fasteners and other hardware that hold the system together. Stow algorithms for single-axis trackers should also be validated via track records of damage prevention. In addition, each site must have a set of protocols and response strategies specific to the weather threat and be prepared to follow them on short notice. And last, but not least, the operational status of a plant must be considered. Sites under construction are more prone to erosion because ground cover is lacking, to wind damages because modules may not be properly fastened and are susceptible to flying debris, and to electrical damages, if cable and connectors are exposed to moisture.

Weather Event	Duration		Predictability Window	
Tropical Cyclones	†	1 – 2 days	‡	2 – 3 days in advance
Hailstorms	†	1 – 2 days	‡	< 24 hours in advance
Snowfalls		3 – 6 months	‡	(heavy case) several days in advance
Dust Sandstorms		several days – 1 month	‡	≤ 5 days in advance
Heat Waves		1 – 6 months		
Floods	†	several days	‡	1 day in advance
Wildfires		1 day – several months		

Table 1: General aspects of extreme weather events:
Dagger marks (†) in the Duration column indicate temporary events, and the double dagger marks (‡) in the Predictability Window column denote events that can be forecasted within the specified time frame.

If proper attention is paid to the above, the resilience of PV systems to extreme storms will increase significantly.

Key Takeaways

1. Most PV plants can survive most extreme weather events, if appropriately sited, designed and maintained.
2. This report considers weather events that 1) have short-term impacts and occur sporadically, e.g., tropical cyclones, convective storms (including hail) and 2) those that have longer-term impacts and tend to be repetitive, e.g., snow, dust storms, heatwaves, and wildfires. From an impact perspective, two types of damage can be identified in PV systems: acute and chronic. Risk assessment for PV plants in the first category is a critical first step, whereas design optimization for plants in the second is the priority. From a resilience and mitigation standpoint, **site planning** is essential. Risk assessment based on a review of historical weather data and the probability of future extreme weather events for each location is crucial and must be addressed in the design phase. Once the threat landscape has been properly assessed, project developers, and owners must make informed **design and procurement** choices. All materials and structural components must be code-compliant; module architecture also matters, as in, modules specifically designed for hail resilience. In addition, review of the racking/tracking design, including hardware, by an independent engineer is strongly encouraged. In addition, architects should pay close attention to the terrain and geological conditions at the proposed site. For example, when installing a PV system on sloped ground, the foundation should include features to prevent landslides triggered by tropical cyclones or flooding.
3. Site owners and operators should keep relevant **commissioning** documents, particularly those related to energy production in order to have a baseline against which future performance can be compared. Similarly, any electroluminescent (EL) and infrared (IR) images, along with records of visual inspections and I-V measurements, should be preserved.
4. **Electrical performance data** are essential for evaluating the effects of extreme weather events and any resulting acceleration in system degradation. When combined with weather data-such as temperature, solar irradiation, and wind speed-this information forms time-series data that can help detect weather-related damage. Awareness among site owners and maintenance teams needs to increase regarding the importance of collecting and preserving these data.
5. Robust **operation and maintenance** (O&M) protocols are essential. Defects left unresolved after storm exposure may worsen over time when exposed to additional environmental stressors like heat, wind, and moisture. Continuous monitoring of power output from restored PV systems is therefore critical to ensure their performance and reliability. If a significant drop in power generation is detected, the collected data will help the owner make informed decisions about further actions, such as system refurbishment.
6. **Proactive maintenance** is equally important and should be tailored to the probability of risk. Before a tropical cyclone, for example, tasks such as checking the t tightness of fasteners and clearing debris, which could become airborne-should be carried out in advance.
7. If damage from extreme weather does occur, **corrective maintenance** should be implemented as soon as possible. Immediate steps include 1) ensuring the safety of the site by disconnecting it from the grid and opening all breakers; and 2) conducting electrical and mechanical inspections of the affected PV system. Damaged equipment should be left in situ, pending insurance or other claim-related inspections but all damaged PV modules and electrical components must be replaced prior to re-energization.