TROPICAL STORM PREPAREDNESS FOR ONSHORE RENEWABLE ENERGY PROJECTS

AXIS RENEWABLES
IN PARTNERSHIP WITH
rcg Renewables Consulting Group

AXIS

INTRODUCTION

This report is about the recommended steps for preparing onshore wind farms, fixed solar farms and battery storage facilities for hurricanes, cyclones and typhoons, collectively known as tropical storms.

This report aims to highlight the key vulnerabilities of projects to high wind speed events, and provide typical mitigation procedures that can be checked as means of protecting the asset. It covers mitigations at the design, construction and operational phases, each presented as self-standing sections, which flow together to provide a complete story, with the balance of the weight on operations.

The key issues identified are where the key risks lie, and how these may be addressed. Brief descriptions to aid understanding, plus diagrams and checklists, provide the context to the guidelines.

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TROPICAL STORMS OVERVIEW

What is a hurricane/cyclone/typhoon?

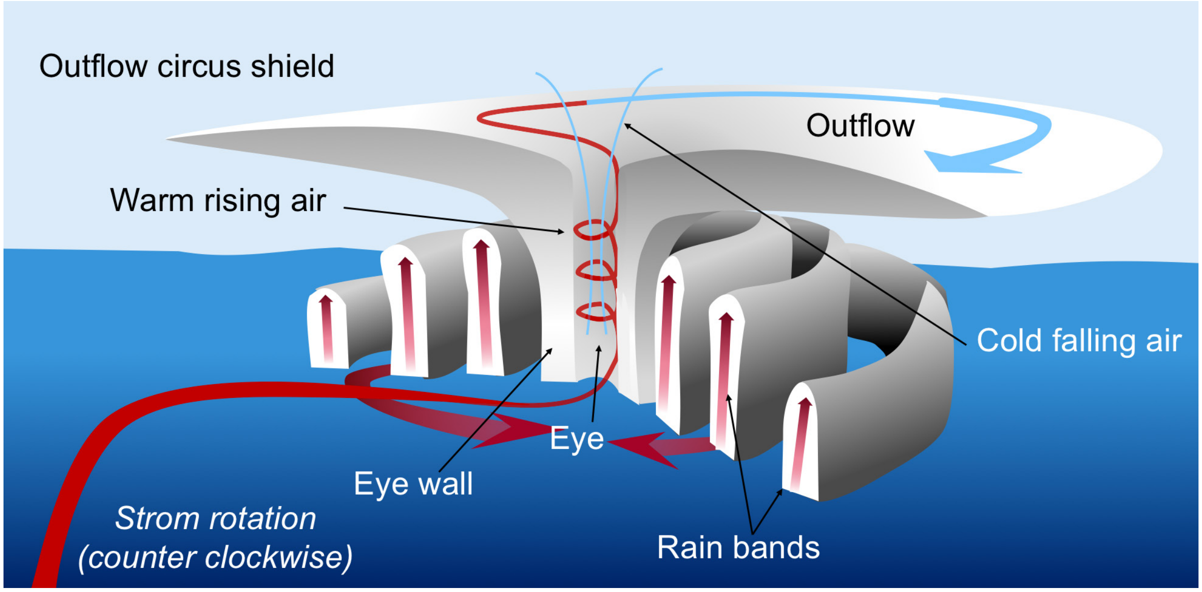
Hurricanes, cyclones and typhoons are all tropical storms, forming in different regions. They are large rotating low-pressure weather systems that bring high winds, heavy rain and often flooding.

These weather events will be referred to as tropical storms, unless they refer to a specific region.

Exhibit 1: Tropical Storm nomenclature

Label	Formed in	Typical Season
Hurricane	Northern Atlantic and north eastern Pacific	June to October
Typhoons	North western Pacific	May to November
Cyclones	South Pacific and Indian Ocean	Northern Hemisphere — May to November; Southern Hemisphere — November to April

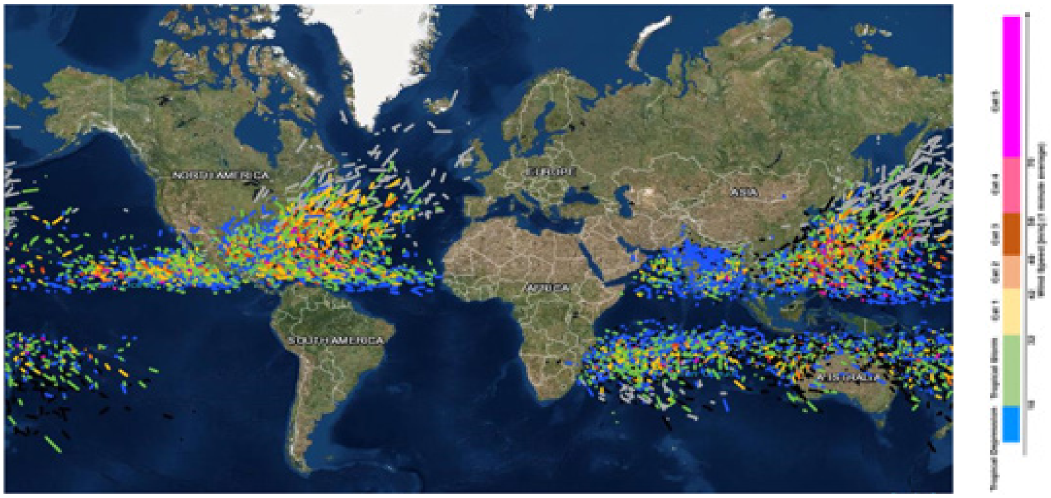
Exhibit 2: Anatomy of a tropical storm



Source: RCG

The anatomy of a tropical storm includes an eye, and eye wall and rain bands. The eye of the storm lies in the middle of the weather system, where winds are generally calm, the eye wall circulates around the eye, bringing thunderstorms with the highest winds and heaviest rainfall; and the rain band stretches out for hundreds of miles from the eye, bringing continuous high winds and rain.

Exhibit 3: *Geographical spread of major storm events over the last 50 years along with an indication of maximum wind speeds, categorised by the Saffir Simpson scale.*



Source: Image from of NOAA: www.nhc.noaa.gov, accessed November 2017

The scale of categories describing the intensity of the storm event is called the Saffir-Simpson Hurricane Scale. It is based on the maximum sustained (for a period of 1 minute) surface windspeed at 10 m above an unobstructed exposure. The wind speed ranges with associated damage profiles are as follows:

Exhibit 1: Saffir-Simpson Hurricane Scale

Scale	Category	Windspeeds	Description of damage
	1	74-95 mph (33–42 m/s)	Very dangerous winds leading to damage
	2	96-110 mph (43–49 m/s)	Extremely dangerous winds leading to extensive damage
	3	111-129 mph (50–57 m/s)	Devasting damage expected
	4	130-156 mph (58–70m/s)	Catastrophic damage expected
	5	above 156 mph (70 m/s)	Extensive catastrophic damage expected

The degree of damage rises by about a factor of four for each category increase[1].

Why are tropical storms a risk to projects?

Damage due to tropical storms is becoming increasingly prevalent across the globe. Populations and assets are continually growing, especially in coastal regions—most at risk. In addition, records show more intense tropical storm activity in the past 50 years[2], making projects more at risk[3].

Exhibit 5: Image of the aftermath of the 2018 Atlantic Hurricane Michael

Source: https://illumination.duke-energy.com/articles/hurricane-michael-damage-so-extensive-company-inspecting-with-boats-and-drones. Accessed 27/02/19

In 2018 Hurricane Michael, with winds sustaining 150 mph, caused so much damage that areas had to be assessed with drones, as access to demolished areas was limited.

In 2005, Hurricane Katrina, in the U.S.A., resulted in a death toll in excess of 1,500 and a cost of $100bn in damages.

These are just two examples of many tropical storms experienced in recent years.

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1 https://www.nhc.noaa.gov/pdf/sshws.pdf

2 IPCC AR5 https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

3 N. Ranger and F. Niehorster, "Deep uncertainty in long-term hurricane risk: Scenario generation and implications for future climate experiments" Global Environmental Change, 2012

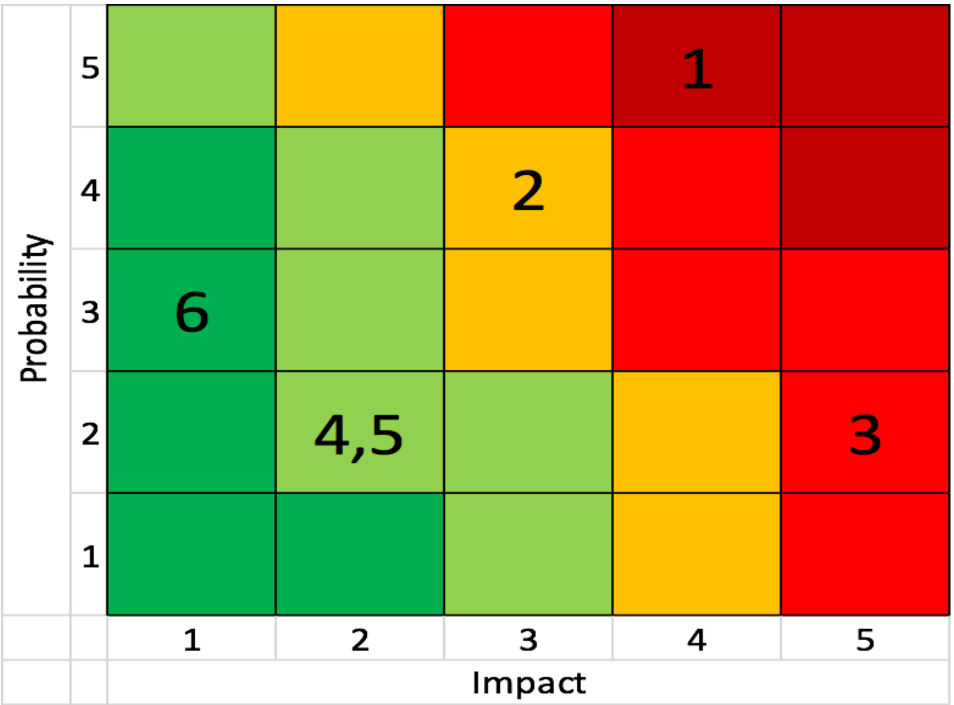
MANAGEMENT SYSTEMS — TECHNOLOGY AGNOSTIC

Standard site design, construction and operational processes and systems need to take account of the fact the site is in a tropical storm region. The key governance documents, under which all activity will be conducted, are as follows;

Risk Assessments, and the Safety File

Risk Assessments (RAs) at every stage need to consider and include tropical storm issues.

Exhibit 6: *Risk Assessment*



Source: *RCG*

- The **Design Risk Assessment (DRA)** needs to include provisions for any additional equipment required, to survive a tropical storm during construction, operations or decommissioning
- The **Construction Risk Assessment** needs to specifically consider temporary situations, as well as permanent operations—for example, equipment storage prior to installation
- The **Operations Risk Assessment** needs to identify any additional measures required through normal operations, and identify and mitigate for risks of the operational site being exposed to a tropical storm
- The **Decommissioning Risk Assessment** can reasonably be assumed to have similar requirements to construction

Construction and Operations and Maintenance (O&M) Plans

Project owners may operate and maintain plants themselves or contract a third party, whilst construction is likely to be contracted. Mitigations identified through the Risk Assessment process must be reflected in contracts and site procedures, making clear who is responsible for issues such as; liability for design and construction and operational systems. Any additional work required as mitigation, whether in supply, construction or routine operational activity, must be included and funded. Specific timing requirements for activity, (e.g. avoiding or in anticipation of, the tropical storm season) must also be made clear, or the responsibility for the decision on suitable timing, with associated liability, made clear.

Emergency Response Plan

All projects under construction, in operations, or in decommissioning, will have an Emergency Response Plan (ERP) to outline their site-specific procedures when faced with potentially dangerous issues that could lead to injury, death and significant financial and/or reputational damage. This will include typical issues relevant to the site and technology, and include such elements as nearest hospital, fire and ambulance services, regulatory and project notification requirements, as well as action steps to address the emergency, including evacuation, damage containment and application of back-up systems. It will include shut-down, and procedures for re-start.

For sites within a tropical storm region, the ERP should reasonably be expected to include the plans for a tropical storm situation. In this event, it is likely that key services will be compromised, including medical and fire services, hospitals and availability of suitable sub-contractors to make safe the site. Therefore, the ERP should also include the following considerations:

- Arrangements (procurement/priority contacting) for back-up diesel generators
- Stockpiling of critical supplies, including fuel for generators and medical supplies
- Sourcing of specialist vehicles and earth moving equipment to gain access to the site in the event of roads being destroyed or flooding

The element of the plan pertaining to tropical storms is expected to include:

Training

All personnel are to be trained in execution of the plan, as well as made familiar with the additional ongoing preparation required for a tropical storm situation.

Prediction

Tropical storm trajectories are continuously monitored and re-forecast. If there is potential for a tropical storm to make landfall on a project, this will be issued as a tropical storm "watch" from the relevant local weather advisory services. The timing of this notification will depend upon the storm and the service, but is typically a few days. If the tropical storm is almost certainly going to affect a project site, a tropical storm "warning" is then issued, which could be multiple hours before the weather system arrives at the site location. This will be continually refined as the storm approaches.

Pre-storm preparation

Site lock-down and preparation will include generic storm lock-down procedures, as well as technology-specific requirements.

Post-storm assessment and re-normalisation

Depending on the severity of the tropical storm and the local damage, access to a site may be restricted until it is deemed safe by the relevant local authorities, and appropriate permissions have been obtained. Once access to the site is granted, some initial checks can be performed, as identified in the ERP.

Checklist

- Have tropical storms been reviewed on all RAs?
- Have all contracts considered and referenced tropical storms?
- Is there an ERP in place?
- Have personnel been trained in the ERP? And drills held?

There are two levels for each check — (i) confirm the existence; and (ii) confirm the adequacy/comprehensiveness

GENERIC SITE RISKS AND ACTIONS

The following issues may equally be relevant to wind farms, solar plants and battery storage facilities, therefore must be considered in all cases.

Exhibit 7: Generic tropical storm issues — actions on site owner

Item	Design	Construction	Operations
Buildings	Design to withstand tropical storms, including means of "battening down."	Build to design. Preferably schedule construction outside of tropical storm season, to protect both building and contents.	Implement ERP for battening doors and windows, prior to storm and safety and re-mobilisation post-storm.
Flooding & drainage	Design site drainage to accommodate storm flooding where practical, and enable recovery. Consider drainage of road drains, substation and transformer foundations and cabling, as well as primary equipment foundations. Route site roads to avoid landslide risk. Take into account neighbouring towns, rivers and plants. Base design upon a hydrological survey. Drainage systems are key to protecting structures from flood damage. This prevents foundations from being undermined and landslides occurring.	Construct to design, as contracted. Drainage inspection, silt-trap monitoring and clearing are all normal construction practice. This may be enhanced during storm season. Should a storm occur during construction, drainage should be cleared as far as practical prior to the event, and inspected and cleared and repaired following the event. Drainage systems to be inspected and signed off prior to hand-over.	Undertake ongoing inspection & clearing of drainage systems, as defined by the O&M plan, suitably modified to take account of tropical storm season. For a tropical storm, the ERP should include pre and post -storm clearance, and post-storm damage assessment. Area drainage may be required post-storm, including pumping, for which standby pumps (or contracts for these), with a power supply are required. If the flooding affects electrical infrastructure, competent personnel are required for testing and re-energisation, or write-off.
Site infra-structure — electrical systems	Design considering storm potential, for example indoor or contained equipment, raised above flood level.	Construct as per agreed and contracted design. Ensure equipment remains dry prior to energisation.	Undertake, self or via contract, required inspection and maintenance. Ensure appropriately competent personnel are available.
Site infra-structure — roads & hard-standings	Design to withstand expected rainfall, to include balance of construction and maintenance.	Construct as per agreed and contracted design.	Roads and hardstandings (hard ground areas for parking) require regular maintenance. Requirement may be increased in areas of high rainfall, especially if traffic continues after the event.

Item	Design	Construction	Operations
Overhead lines (OHLs)	Design to withstand tropical storms, including means of "battening down."	Build to design. Preferably schedule construction out-with tropical storm season, to protect both building and contents.	Implement ERP for battening doors and windows, prior to storm and safety and re-mobilisation post-storm.
Flooding & drainage	These are likely to be owned and designed by the System Operator.	Construction activity will put up goalposts for access under OHLs. Actions on safety of, these goalposts included within ERP. Post-storm, status of any OHLs needs to be established.	Checks for any downed power lines post-tropical storm need to be carried out if applicable.
Miscella-neous site	Design should recognise the need for rapid turnover of equipment, materials and waste, and make provision during both construction and operations for permanent or rapid safe storage of all loose items. There have been instances of loose cover sheets and tarpaulins impacting on main transformers, causing short circuits leading to significant asset damages	A well managed, tidy site, with suitably designed storage for loose items, should be readily made safe prior to any tropical storm event. The actions to undertake in preparation for, and in response to, the storm will be defined in the ERP, and include • Storing of loose items • Emptying of oil/water bunds • Post-event damage checks	The ERP for operations will be similar to that for construction, however with permanent operations underway there may be permanent storage locations and specific actions for movement of equipment prior to an event.
Security	N/A at design stage	Typically present during construction	Consider security requirements should daily measures fail
Grid contracted obligations	Wind farms, solar farms and battery storage facilities may provide important services to grid networks. Ensuring their ability to tolerate the impact of a tropical storm and return to service may be crucial to the operation of the wider network.	Pre-energisation, no services are provided, therefore N/A.	Notification to grid operators is a crucial contracted requirement.

Contract requirements — all contracts

During design — procurement

- During supplier selection, competence and suitability for the tropical storm situation is to be evaluated.
- Pre-construction, responsibilities are allocated through the Employer's Requirements in the contracts.
- Quality control monitoring has been defined to include tropical-storm-sensitive component inspections.

During construction — quality assurance

- The safety file from the design phase is brought forward, augmented and maintained.
- Minimum standards for construction completion, as should have been set at the contracting stage, need to be checked—for example, bolt tensioning, commissioning of primary and reserve systems, prior to hand-over.

ERP inclusions

For a "Storm Watch" — Site checks should (as applicable) include the availability of essential emergency equipment and supplies, securing and storing of loose items, taping/boarding up of windows, fuelling of back-up generators and on-site vehicles, storing of water and protection/back-up of business records. Staff should be briefed and the status should be monitored for further information, with any changes communicated as appropriate.

For a "Storm Warning" — Proactive actions should be taken to secure the site (where applicable) which includes the protection of vulnerable equipment either through relocation or secure covering, bracing of doors and securing windows, turning off of electricity and evacuating the site from site, ensuring all personnel are clear of the site before the tropical storm arrives.

Minimum requirements post-tropical storm — Checks should be made for damage, for example downed power lines and flooded areas, blocked roads, efficacy of flood proofing measures, risk of falling debris plus potential looting and unsanitary conditions. All issues reported as required to site management.

Checklist

- Have all the relevant generic technical issues been identified, and risks assessed via an RA?
- Do all contracts include liability for, and funding for, generic storm-related issues?
- Does the ERP include the appropriate generic technical requirements?

There are two levels for each check — (i) confirm the inclusion; and (ii) confirm the adequacy/allocation

WIND FARMS

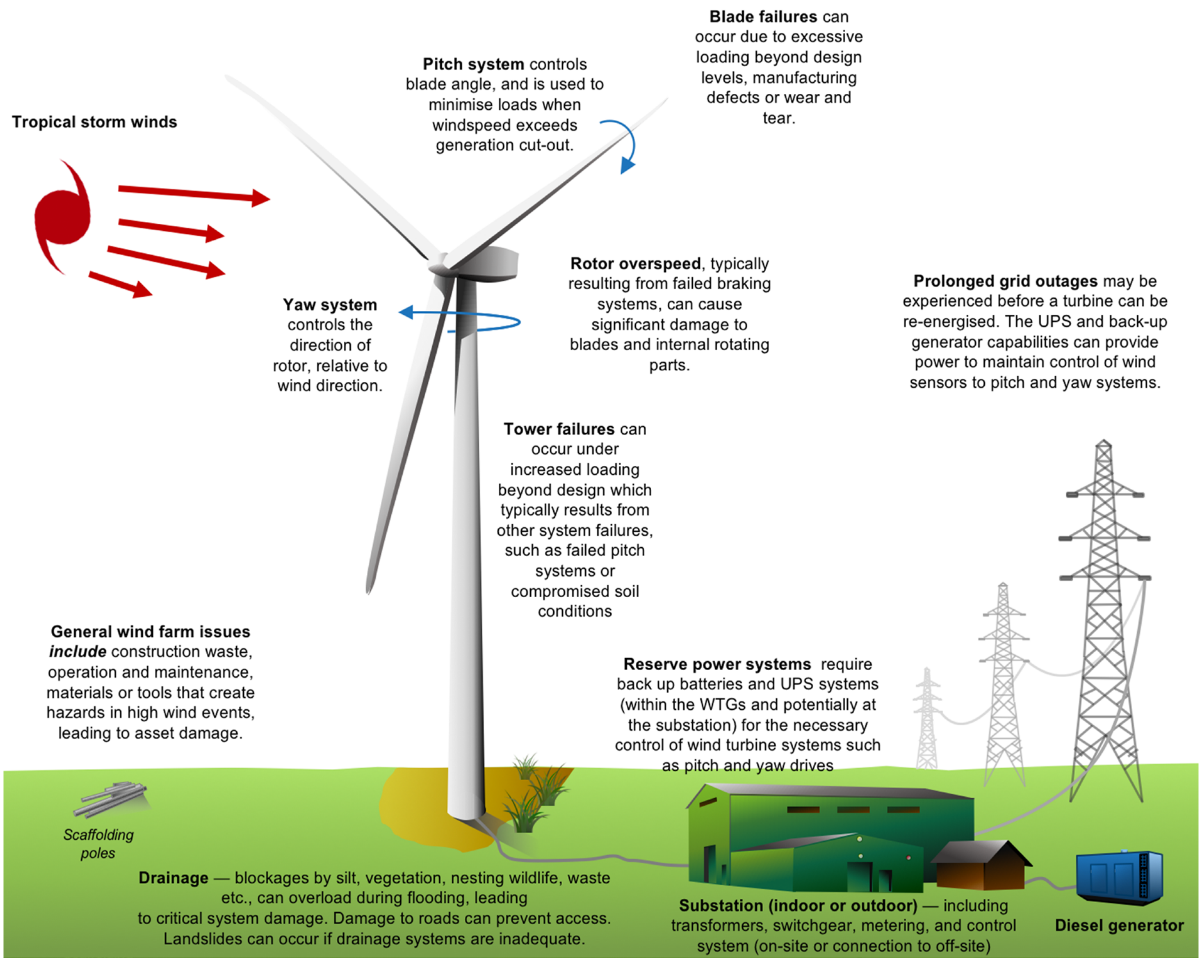
What are the technical risks?

For wind farms, there are several direct and indirect vulnerabilities to extreme wind events such as tropical storms. They may be due to:

- Design assumptions
- Construction quality issues
- Unsatisfactory operational procedures
- Inherent technological vulnerabilities

Wind farms are primarily at risk through the Wind Turbine Generators (WTGs) themselves, as well as risks identified.

Exhibit 1: Overview of the potential risks to a wind farm in the event of a tropical storm



Source: RCG

Wind Turbine Generator (WTG) Design Classification

Exhibit 9: WTG IEC Class Ia

Parameter (windspeeds at hub height)	Class Ia
Mean wind speed (m/s)	10
Extreme Wind Speed (10-min) (m/s)	50
Extreme Wind Speed (3-sec) (m/s)	70
Turbulence Intensity (%)	18
Tropical Storm Category	2–3

Source: IEC 61400-1

WTGs are typically designed to one of three classifications based on their maximum survivable wind conditions, as defined by the International Electrotechnical Commission (IEC). The highest standard class is suitable for lower intensity tropical storms with all category 3 and above tropical storms exceeding WTG design parameters.

There are two additional classifications, these are Class S (site specific, typically applied for normal wind loads rather than extreme winds) and Class T (Typhoon Class introduced in Taiwan in December 2018).

Storms outside the design parameters of the WTG can lead to failures, and would typically be covered by insurance. WTG selection and specification is critical.

The design standard includes specifications for both the structural strength of the wind turbine installation, and the wind turbine internal protection systems, including yaw motors, brakes, blade pitching system, and internal UPS (Uninterruptable Power Supply).

WTG sub-systems — Failure examples

WTG structure — foundations & towers

Failures related to WTG foundations and towers include

- **Complete failure** — Foundation ripped out of the ground. Can be caused by gusts in excess of design, WTG control systems (pitch and yaw) failure, soil liquefaction caused by heavy rain associated with the high winds.
- **Partial failure** — Shearing of tower from the foundation. Can be caused by inadequate design for wind conditions or poor construction.
- **Tower failures** — Tower buckling. Can be caused by bolt failure at a tower joint (which can be caused by under-design or poor maintenance), or as a result of blades hitting the tower when spinning out of control during a high-wind event, causing the tower to buckle.

Exhibit 10: Foundation failure in Germany

Source: *http://www.windfarmbop.com/category/geology-and-geotechnics/*

Exhibit 11: Bolt cage fracture during Typhoon Maemi

Source: *Ishihara and Yamaguchi, 2005*[1]

Exhibit 12: Bolt failure

Source: *https://www.telegraph.co.uk/news/earth/energy/windpower/9837026/Wind-turbinecollapses-in-high-wind.*

[1] Ishihara and Yamaguchi, An Analysis of Damaged Wind Turbines by Typhoon Maemi in 2003. The Sixth Asia-Pacific Conference on Wind Energy, 2005

Exhibit 13: *Tower failure during Typhoon Saomai*

Source: *https://www.telegraph.co.uk/news/earth/earthnews/8998171/Wind-turbine-bladesfly-off-in-storm.html*

WTG blades

Failures related to WTG blades include:

- Buckling due to increased bending stress during high winds, with an increased likelihood if the blade is damaged or the control systems fail to limit rotor speed to within design parameters
- Third party damage, or damage to other components of the wind farm caused by damaged blades disconnecting from the WTG and becoming projectiles.

Exhibit 14: *Blade failures for wind turbine in the UK in 112 mph winds*

Source: *https://www.telegraph.co.uk/news/earth/earthnews/8998171/Wind-turbine-blades-fly-off-in-storm.html Accessed on 01/03/19*

Exhibit 15: Rotor overspeed blade damage to wind turbine in Canada

***Source:** https://www.wind-watch.org/news/2016/05/07/exelon-mechanical-failure-led-to-turbine-collapse/ Accessed on 01/03/19*

Sub-systems failures

Failures related to yaw and pitch motors, and WTG internal environment, include

- Failure of the yaw motor (which keeps the WTG directed into the wind) leads to hub and blade misalignment and associated stresses, which exposes the WTG to a high risk of overload damage. The yaw system requires electrical power to operate, upon loss of power from the grid it relies on reserve power as long as it remains available. After this time it will fail, causing overload exposure.
- A failure of the pitch system is likely to cause catastrophic blade failure, because the pitch system turns the blades to regulate wind capture and generate power. Failure of the system will cause excess wind capture, leading to overspeed and catastrophic failure. Pitch system failure can be caused by loss of electrical systems, hydraulic leakage and other possible failures.
- WTGs experiencing lengthy power outages are likely to suffer failures of power electronic systems due to moisture ingress when combined with the loss of air-conditioning systems.

Considerations must also be directed towards maintaining the auxiliary systems which supply these motors.

Auxiliary systems

The WTG auxiliary systems may fail because:

- During system shut-down, for maintenance for example, a WTG left in a shut-down state, potentially with physical brakes and Lock-out Tag-out (LOTO) safety systems applied, may not be in a position to apply automated protection systems.
- Reserve power systems, e.g., Uninterruptible Power Supplies (UPSs), are typically designed for a few days at most. A prolonged outage and/or a system not specified with additional capacity to accommodate tropical storm situations, will render electrical supplies unavailable, and all reliant systems (as above) inoperable
- Similarly, a prolonged grid outage will result in depletion of the UPS systems, and without reserve generation will render electrical supplies unavailable and all reliant systems inoperable. This could cause catastrophic failure if it occurs before the tropical storm, or substantial damage as electrical and WTG systems are not kept 'warm' after the event prior to re-energisation.

Considerations to check

Checklist of site actions

At design stage	
Wind farm site	• The DRA has been completed, and design mitigations included, or where excluded risk is quantified and allocated. This is included within the Safety File. • Generic site design requirements, e.g., buildings, flooding, access, landslide risk have all been included within the DRA.
Wind turbines	• Check the WTG is the appropriate design classification, and if not the probability of exposure to events outsidethe design envelope. • The RA should identify how long the WTGs may risk running without electrical power, and size UPS systems, and make connections available for back-up generation, appropriate to the identified need. • Consideration of whether additional redundancy on auxiliary systems would support resilience. • Impact of rain plus wind on foundation integrity to be included within the RA.

At construction stage	
Wind farm site	• The construction RA has been completed, and mitigations included, or where excluded risk is quantified and allocated. This is likely to be undertaken by a combination of the owner, plus contractors, as responsibilities have been allocated through the contracting. • Any high wind events, and lessons learned, experienced through the construction phase are recorded. • The construction RA includes temporary situations, including all tools, equipment and materials storage, including WTG components, temporary structures, fuel-handling equipment and waste. • A construction ERP has been developed, generic technical as well as WTG specific issues included (for example safe stowage of any cranes on site), and personnel have been suitably trained to implement this. • Civil and electrical works are signed off by a competent engineer, based upon the agreed upon design. • Construction materials and temporary compounds and work areas are typically removed from site/ restored upon completion and prior to hand-over. Snagging items, exposed to risk during a tropical storm handed over to operations are to be made clear in the snagging report and passed on RA in the Safety File.
Wind turbines	• WTG factory and site acceptance tests, as defined, should be closely monitored. For tropical storm resilience, particular attention should be paid to bolts and fastenings, and auxiliary systems. • The WTG erection program should consider tropical storm season. WTGs are particularly susceptible to issues during installation, prior to energisation. Typically, installation and testing activities would be scheduled to be completed in advance of the tropical storm season. • The construction RA should include weather monitoring, for tropical storm damage exposure as well as installation lifting windspeeds. If weather windows are not available for an activity, the work should be postponed until it is safe to do so. • If a situation arises where a WTG installation is only partially complete during an extreme weather event, it may not have the adequate control and protections systems in operation to cope with the storm. Construction planning should be designed to avoid this situation.

At operational stage	
Wind farm site — normal operations	• Generic issues are included in the O&M plan and the ERP, which would include the below. • Equipment and staffing to deal with the aftermath of a high wind event, as far as is commercially prudent, is available on standby, on site (owner or maintenance contractor) or through emergency standby contract. Such equipment would reasonably include o portable generators with an adequate fuel supply, typically through a standby contract with a priority allocation and short-notice delivery; o pumps to remove floodwater; o access to suitably electrically qualified personnel for system testing prior to re-energisation; o road and hardstanding repair; o Spill prevention and clean-up. • Roads, drains and electrical systems maintenance should be scheduled with consideration of pending tropical storm seasons, including maintaining clean and empty fuel and chemical bunds.
Wind Turbines — normal operations	• WTGs should be maintained in accordance with the O&M plans and maintenance programs. WTGs not so maintained, irrespective of competence of design and construction, could fail at lower windspeeds than they are designed to tolerate. • Should the WTG supplier identify additional maintenance requirements due to the site situation in a tropical storm region, then this is to be included within the O&M plans and contracts. Otherwise, normal maintenance should be undertaken, with maintenance activity scheduled with consideration of storm season. Specific systems that need to be fully operational prior in pending tropical storm situations include o Back-up power systems o Hydraulic systems o Bolt tensioning and torqueing o Blade inspections • Any faults, particularly in the pitch and yaw systems that are crucial for tropical storm safety protection should be identified and rectified ideally as soon as possible, practically prior to the next storm season. CMS systems, if installed, can be used to identify pending failures, and schedule repairs or replacements to ensure these do not occur during storm season.
WTG specific actions to check included within the operational ERP	• The shut-down procedure will depend upon the WTG model, the location and contracted responsibility of the Operations and Control centre, and the integrity of the SCADA system. When disconnected from the control centre, WTGs operate unilaterally in self-preservation mode. The procedure needs to be clearly set-out, and understood by all staff, for primary and back-up scenarios. • Post-event the ERP needs to define the procedure for declaring the site safe to access, and reinstatement of site and electrical systems, prior to WTG re-energisation. • The ERP must include the protocol for restarting WTGs, which is expected to include o Checking for any structural damage o Checks for blade damage including cracks and lightning strikes o Notification to the Electrical System Operator o Checking of SCADA system o Addressing errors shown, depending on the O&M agreement and manufacturer's handbook, physical inspection may be required of up to 100% of the WTGs on site prior to restarting o Manual or remote re-starting, as possible • WTGs would be returned to operation by the operator, whether that be contracted to the WTG supplier, an independent operations company, or the owner. Each will need to draft its own procedures, using the original WTG procedures are a basis, where these are made available. The responsible party, their obligations and liabilities, and the derivation of the procedures in place, should all be checked.

SOLAR FARMS

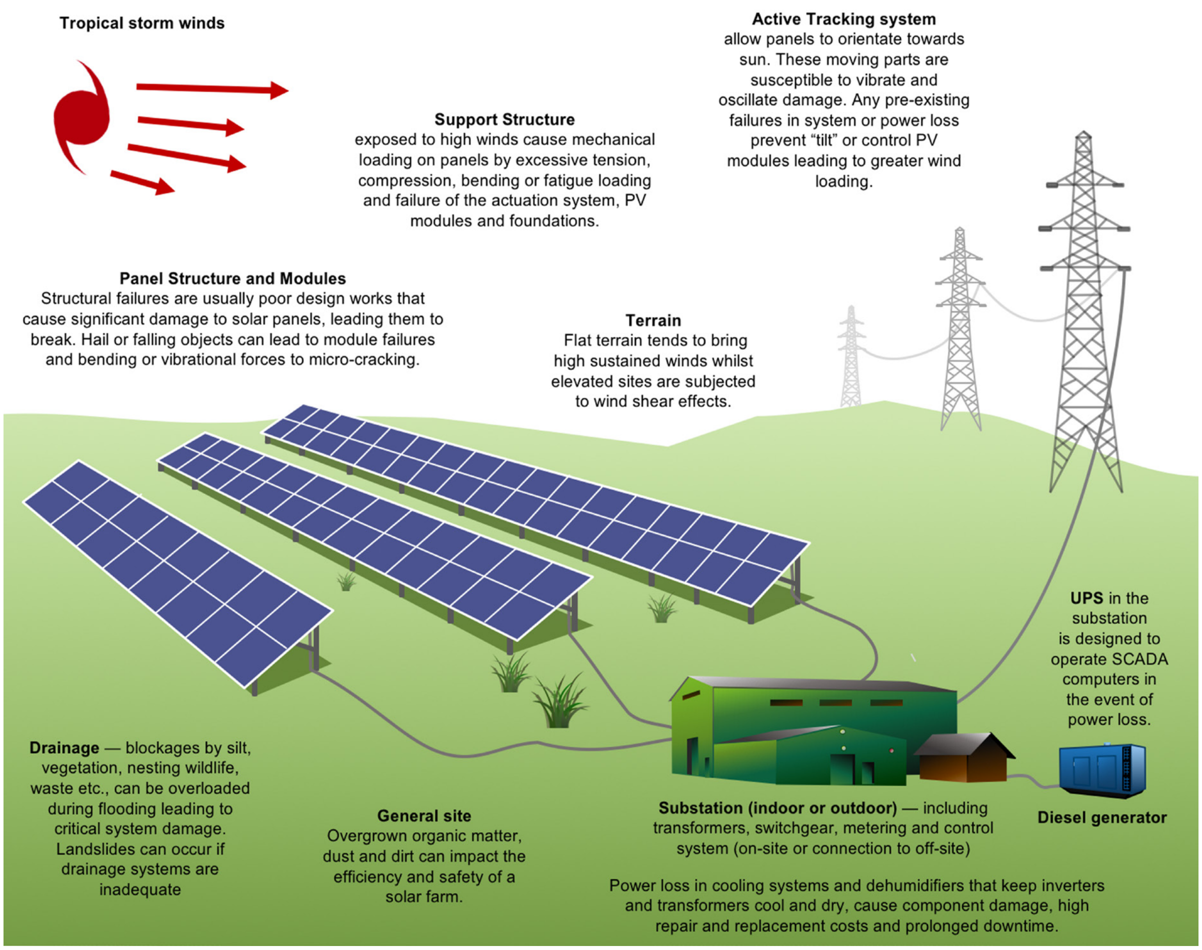
What are the technical risks?

For solar farms, there are several direct and indirect vulnerabilities to tropical storms. They may be due to:

- Design data and assumptions
- Construction quality issues
- Unsatisfactory operational procedures
- An inherent vulnerability of the technology itself

Solar farms are at risk through the solar panels, external impacts upon the panels, and are also potentially exposed to all of the risks previously identified.

Exhibit 16: *Overview of the potential risks to a solar farm in the event of a tropical storm*



Source: *RCG*

Solar farm and panel design

Solar farms with PhotoVoltaic (PV) panels/modules can have various layouts, array numbers and static or dynamic tracking (single axis or bi-axial) systems. Solar PV projects may comprise an electro-mechanical actuation system to rotate the PV panels to maximise energy capture. The project will be connected to the grid or distribution system via direct current to alternating current inverter(s), switchgear and transformers. Modern PV projects also include SCADA systems. PV projects do not have a high number of moving parts and do not have a large mass. PV panels/modules are likely to be subjected to high aerodynamic loading during storm events causing the panels themselves to act as “lifting surfaces.” The probability of PV module damage increases if either bracketing or support structures fail during storm events.

There is no internationally recognised certification system for solar panels and design for survivability and extreme wind depends on appropriate application of local engineering codes and standards. Market and project specific assessment is required to establish the risk to a project in a tropical storm prone area.

Solar farm failure examples

Issues with high wind loading and flooding during tropical storms are proving to be challenging for many solar farms. The photographs below show the destruction of a solar farm in the Virgin Islands due to Hurricane Irma in 2017.

Exhibit 17: *F4.2MW PV system on St. Thomas — before Hurricane Irma*

Source: *https://www.nrel.gov/state-local-tribal/blog/posts/pv-survivability-from-hurricanes-lessons-learned.html. Accessed on 27/02/19*

Exhibit 18: 4.2MW PV system on St. Thomas — after Hurricane Irma

Source: https://www.nrel.gov/state-local-tribal/blog/posts/pv-survivability-from-hurricanes-lessons-learned.html. Accessed on 27/02/19

Panel structure and modules

Structural failures of the modules include:

- **Poor design and selection** — For example poor foundation selections (e.g., screw piles in loose soils).
- **External projectiles** — Damage caused by hail and other debris carried by the storm.
- **Mechanical loading** — Wind generated bending and vibration can lead to micro-cracking.
- **Soil liquefaction** — Excess rain can lead the soil liquefying and failure of the panel-foundation connection.

Active tracking systems

Tracking systems are designed to allow the solar panel to orientate towards the sun as it traverses across the sky. Failures in the tracking system include:

- Wind generated movement of the panels, which at particular frequencies can lead to resonance. This is due to additional flexibility in the linkages of the tracking system and can cause oscillation and damage. This can also affect passive systems.
- Inability to stow (i.e., put the panels into a safe position) when outside design parameters, such as high winds (potentially coinciding with structural or control issues). Therefore mechanical loads exceed the design parameters (as above).
- Excessive wind loading caused by damaged actuators or loss of power, leading to the tracking system being unable to "tilt" or control PV modules.

Electrical systems

Failures in inverters, transformers and UPSs include:

- Damage if grid power and UPS support is lost, due to loss of cooling systems and resultant moisture damage.
- Loss of control through loss of the SCADA, caused by UPS running out during a lengthy grid outage.

General site and terrain

In addition to the general technical issues, solar panels are particularly susceptible to impact from dust and dirt. These primarily impact the efficiency of a solar farm and are addressed through regular panel cleaning.

Preparedness checklist

Checklist of site actions

At operational stage	
General site and terrain	• The generic site issues are to be included in the DRA • Additionally for a solar site, the local soil conditions, foliage and rocks should be reviewed, such that the design can tolerate the dirt, debris and potential storm damage that may arise from these. • Meteorological conditions for storms in general should consider probability of hail, size and frequency. • Presence of nearby trees and vegetation on the site fences, which serve to reduce the wind speed limit at which the fences will collapse.
PV modules, support structures and active tracking	• Determine the codes and standards used for design, and any gap between this and potential wind loading as may be experienced in the region. Such a gap may be closed through increased design, or insurance, subject to agreement of exposure levels and risk. • Check design and equipment selection is suitable for the site conditions. • Check that the design considers the fastening technologies for the panels and support structure, safe stowing practices and having suitable back-power supplies available to the site. • Large panels (usually associated to tracking platforms) should be designed to accommodate high winds, being flexible and aligning to the prevailing wind direction in storm events.

At construction stage	
General site and terrain	• The generic considerations, applicable to all project types, need to be included with the RAs and the ERP.
PV modules, support structures and active tracking	• For solar farms, the competence of the installation contractor is a key check. • Quality inspections, testing and hand-over as per the generic requirements

At operational stage	
General site — normal operations	• Follow the generic technical requirements for most issues, as responsibility has been allocated • For solar farms check particular attention is given to debris, and surrounding vegetation.
Modules, support structures and active tracking — normal operations	• Routine maintenance will include bolt tightening, panel cleaning, panel integrity checks. Check the O&M plan includes all activities necessary to maintain the system as it was designed. Identify if any additional activities, or specific timing of activities, has been planned to accommodate tropical storm season, and check these amendments are being adhered to. • Ensure the additional O&M requirements of active over passive systems have been included where applicable.
Solar farm specific actions to check included within the operational ERP	• The shut-down procedure for a solar farm is likely to be mostly automated where SCADA is in place. Check SCADA existence, and ability to report storm damage. Check manual system where SCADA is not in place. • Check system is in place to put plant in stowage, and emergency back-up systems particularly power supplies, are available. • Shut-down may also include physical intervention, including placing of equipment coverings. • Determine whether failure of auxiliary power systems, through water ingress, lack of insulation, high humidity will raise an alarm flag, and whether remote reset is possible, or extended loss of earnings, in part or in full, is indicated. Similarly, a main grid fault will cause loss of export capability, even if the site is operational. • Check that the re-start procedure includes o **Accessing the site** — In addition to the generic safe site access considerations, check specifically for solar farms that consideration is given to further falling debris including panel parts o **Error clearing and restarting** — Manually or remotely, including full inspection (looking for cracking, delamination, structural deformation and evident damage) and testing regime. Stowage angles should be checked for evidence of forced movements. Extent of testing will depend upon the extent of the storm, plus the time the site has been disconnected, and whether back-up power has been made available, or the site has been fully cold. A phased restart may be used for safety and to maximise production o **Reconnection** — Which may be undertaken when technical compliance has been demonstrated to the System Operator, and may also be undertaken as a phased exercise

BATTERY STORAGE

With the continued increase of distributed and variable energy generation installations on power grids, energy storage systems are becoming more prevalent. Energy storage systems can provide much needed power system services. Developers are co-locating large battery systems with renewable energy facilities, to offset grid upgrade costs, to take advantage of site and connection availability and to provide support services.

Exhibit 19: *AES Laurel Mountain, 32MW grid energy storage facility in West Virginia*

Source: *http://energystorage.org/energy-storage/case-studies/frequency-regulation-services-and-firm-wind-product-aes-energy-storage. Accessed on 01/03/2019*

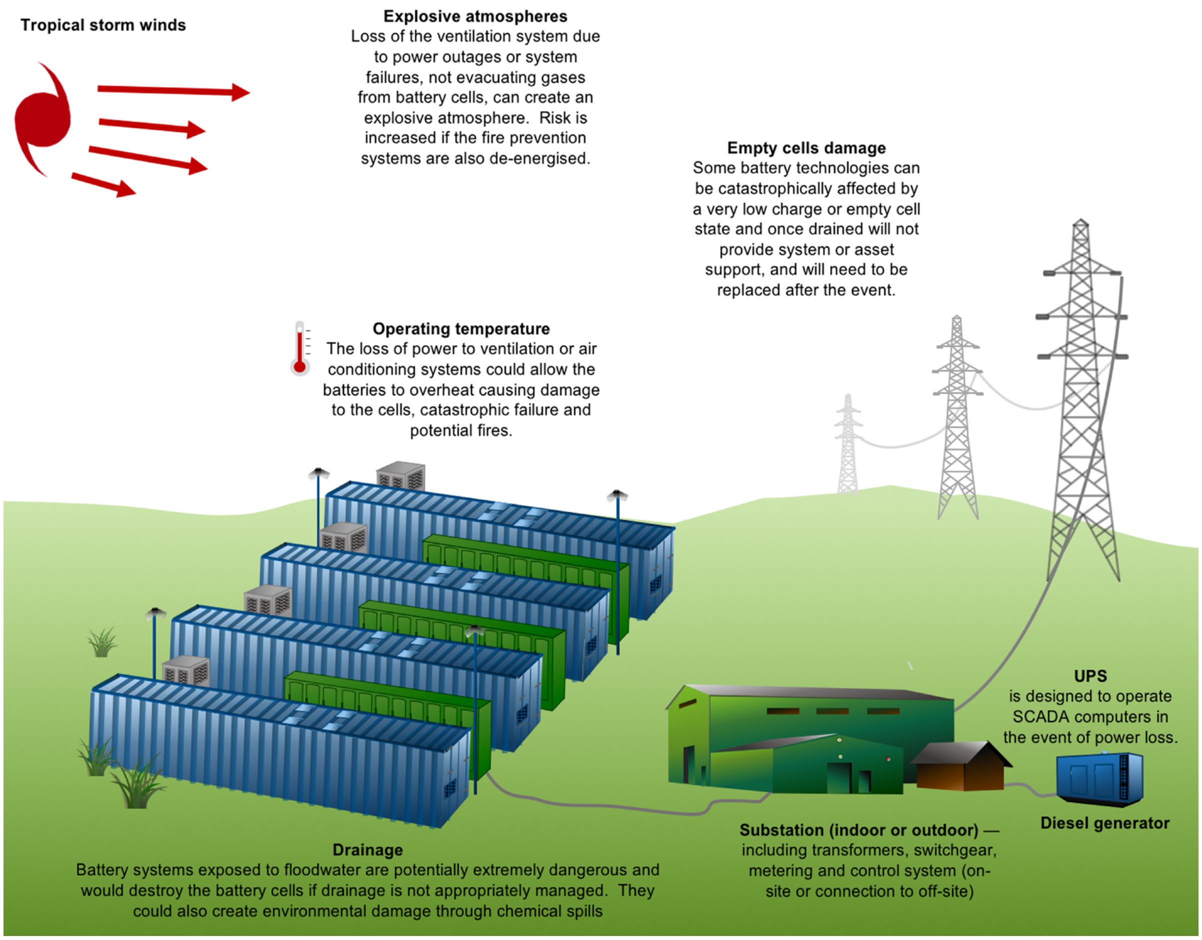
Small batteries are traditionally used within high voltage electrical switchgear, and within UPSs within WTGs for example, to support critical systems through short grid outages. Tropical storms can cause lengthy grid outages, and larger battery systems used for grid support could be used as mid-term support for asset critical systems. During or following longer grid outages, large auxiliary services battery systems will also require external power. All batteries will need time to recharge and become available following a full discharge event.

What are the technical risks?

The primary risks associated with batteries, which could be initiated by a tropical storm, are;

- Fire caused by overheating, when damage to the power control system results in excessive charge current.
- Battery and environmental (chemical pollution) damage caused by excessive humidity and/or heat resulting from auxiliary power being lost to air conditioning systems inside the container.
- Flooding of battery containers due to inadequate storm drainage or insufficient elevation of the foundations above the flood water level.
- Loss of container ventilation and associated gaseous build-up with explosion risk.
- Battery damage due to excessive discharge during extended event, requiring complete replacement.

Exhibit 20: *Overview of the potential risks to an energy storage facility in the event of a tropical storm*



Source: RCG

Considerations to check

At operational stage	
Generic	• RAs and ERPs have been developed for all stages, and all included actions incorporated • Checklist of generic site actions to be included, with particular focus on flooding
Design stage	• Battery system design and selection to be appropriate to the site conditions • Wider system design should consider battery use hierarchy, when battery is providing power support • Battery management system and power control may include survival mode requirements in the event of an extended outage, during a tropical storm event, and include mitigations (e.g., additional redundancy, safe shut-off at safe holding charge, external actions such as back-up diesel)
Construction stage	• To date, battery systems are typically small and modular, they could reasonably be constructed outside of tropical storm season
Operations stage	• Normal maintenance regimes should be followed, any deviation from normal O&M plan to accommodate tropical storm readiness should be included within the site O&M plan, e.g., fresh batteries • The operational ERP should describe automatic and manual actions for the battery to provide power support initially, and then shut down if there is a prolonged disconnection • Site reactivation needs to be carefully controlled as advised by the manufacturer. Where the battery is co-located with other plant, the priority reactivation sequence is to be set out as far as practical

SUMMARY

This document has summarised the actions of tropical storms, and the actions of site owners in consideration of such storms. These actions run through from the design, construction to operations and decommissioning phases, and are governed by a series of documents and processes that follow through these phases.

Major weather events are becoming more intense, and as more sites are installed, the probability of tropical storm meeting renewable power plant increases, thus elevating the focus placed upon this topic.

it is important to set out the balance of responsibility between site owner, supplier, contractor(s) and insurers. Each party must be comfortable with any additional or amended obligations placed upon them to accommodate tropical storm preparedness, and allow for the costs associated with such obligations, pricing services accordingly. Each project will find its own appropriate technical and commercial mitigation strategy.

Some suggested "do's and don'ts" for tropical storm preparedness are listed here.

Do’s and Don’ts for tropical storm preparedness

DO	DON’T
Ensure all management protocols are in place • RAs at all stages, • ERPs through construction and operations, • Adapted O&M plans	Use previous protocols for sites that are not in a tropical storm zone, or those that are, without amendment
Be clear in contracts • What degree of mitigation spend versus risk is acceptable, • Which contracted parties are undertaking mitigation works, and the compensation for such undertaking • Limits of warranties and insurances — ensure any gaps are closed through further mitigation or insurance	Assume standard contracts & exclusions are coherent throughout the contracting chain, and inclusive
Consider generic site issues, alongside the technology-specific considerations, for example • Drainage design and maintenance • Back-up service contracts, specifically generators • Additional UPS sizing and other redundancy safety features • Site security for post-event protection • Miscellaneous site activity and storage (e.g., for additional auxiliary generators and fuel)	Neglect generic site issues in favour of technology-specific issues. Generic issues tend to cause the technology specific elements to fail.
Consider technology-specific mitigations, appropriate to the technology of the site under consideration, as described in the relevant sections of this report	Assume that technology providers have provided all the answers, especially if limited site condition data was provided to OEMs to inform the design.
Design in tropical-storm proofing where economically appropriate to do so	Use standard designs for non tropical storm sites.
Develop a construction specific ERP, and include construction specific considerations, for example large component storage. Consider construction schedule versus storm season	Use standard construction plans and protocols, for a non tropical storm site, without amendment.
Amend O&M plans if required, including maintenance scheduling considering construction season. Ensure the operational ERP includes hurricane preparedness, automatic and manual steps for shut-down, re-accessing and regeneration, and that all site personnel are familiar with and trained on required protocols.	Use standard operational plans and protocols, for a non tropical storm site, without amendment.
Get comfortable with the obligations and risks associated with renewable plant in tropical storm regions. There are additional considerations, however renewable energy plant is a global requirement, and there are physical and commercial solutions to all issues.	Avoid sites in tropical storm regions, check the site is understood, mitigations are in place, and choose those that have addressed adequately

ACRONYMS AND ABBREVIATIONS

The following acronyms and abbreviations are used throughout this report:

BoP	Balance of Plant
CMS	Condition Monitoring System
DRA	Design Risk Assessment
ERP	Emergency Response Plan
IEC	International Electrotechnical Commission
LOTO	Lock-out tag-out
MTR	Minimum Technical Requirements
OHL	Overhead line
O&M	Operations and Maintenance
PCS	Power Control System
PREPA	Public Readiness and Emergency Preparedness Act
RA	Risk Assessment
RCG	The Renewables Consulting Group LLC
SCADA	Supervisory Control And Data Acquisition
UPS	Uninterruptible Power Supply
WTG	Wind Turbine Generator