IRENA
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Quality infrastructure for **renewables facing extreme weather**

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Disclaimer

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Abbreviations

EU	European Union
FAT	factory assessment test
g	gramme
IEC	International Electrotechnical Commission
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRR	internal rate of return
km	kilometre
km/h	kilometres per hour
kWh	kilowatt hour
m	metre
mm	millimetre
m/s	metres per second
m^2	square metre
NGO	non-governmental organisation
PID	potential induced degradation
PV	photovoltaic
QEERI	Qatar Environment & Energy Research Institute
QI	quality infrastructure
R&D	research and development
s	second
SSP	shared socio-economic pathway
STF	Solar Testing Facility

Executive summary

The increasing frequency and intensity of extreme weather events, driven by climate change, present a critical challenge for renewable energy systems worldwide. From devastating hurricanes to prolonged heatwaves and hailstorms, these phenomena threaten not only the structural integrity of solar photovoltaic (PV) and wind energy installations, but also the stability and reliability of global power systems. Economic impacts are severe, with damage costs rising sharply alongside the growing reliance on renewable energy to meet climate and energy security goals. Against this backdrop, robust quality infrastructure (QI) emerges as a cornerstone for ensuring resilience and reliability in renewable energy systems.

Between 2000 and 2021, the recorded number of major disasters caused by extreme weather events nearly doubled compared with the preceding two decades, fuelled by global warming and intensifying climate variability. Such events have affected billions of people and caused trillions of dollars of damage, emphasising the urgent need for comprehensive mitigation strategies. Climate models project an increase in the frequency, duration and severity of extreme weather, with even regions historically spared now becoming vulnerable. These trends coincide with the rising penetration of renewables in power grids, creating a compounding risk of outages and blackouts unless countered by targeted adaptation measures.

The role of QI is pivotal in this context. Comprising a co-ordinated system of standards, testing, certification, accreditation and metrology, QI underpins the safety, reliability and performance of renewable energy assets. By integrating QI measures throughout the life cycle of renewable projects – from design and construction to operation and maintenance – it is possible to mitigate risks, enhance resilience and minimise financial losses. For instance, international standards such as International Electrotechnical Commission (IEC) 61215 for PV modules and IEC 61400 for wind turbines establish critical performance benchmarks under extreme conditions, while rigorous testing and certification ensure the durability of components in harsh environments.

Climate resilience begins with robust risk assessment. Using historical meteorological data, site-specific measurements and predictive modelling, project developers can identify vulnerabilities and tailor mitigation strategies. For example, the integration of real-time monitoring and predictive maintenance systems enables early detection of threats like component degradation due to high temperatures, salt corrosion or mechanical fatigue from strong winds. Such measures reduce downtime and prevent catastrophic failures, preserving energy yields and extending asset lifespans.

The construction phase is another critical juncture where QI plays a transformative role. Ensuring adherence to international standards in procurement, testing, and assembly processes safeguards the long-term resilience of installations. Factory acceptance tests (FAT) and independent third-party inspections during construction ensure that critical components, from PV panels to wind turbine blades, meet performance specifications. In coastal wind farms, for instance, the application of advanced anti-corrosion coatings and air filters has proven to significantly reduce maintenance costs and operational downtime.

Operational resilience depends on integrating QI practices into ongoing maintenance and monitoring. Predictive technologies, informed by standardised performance benchmarks, enable infrastructure operators to anticipate extreme weather impacts and respond proactively. In cyclone-prone regions, this includes securing wind turbines against rapid wind direction changes and ensuring that auxiliary systems, such as backup power supplies, remain operational during grid outages.

Economic analysis highlights that the costs of implementing extensive QI measures are outweighed by their benefits. Projects incorporating robust risk mitigation consistently achieve higher internal rates of return, driven by reduced repair costs, minimised operational disruption and improved investor confidence. For example, the adoption of NEN 7250 standards in the Netherlands following severe storms has reduced wind farm damage and lowered insurance premiums, demonstrating the financial viability of integrating QI measures.

Policy makers play a vital role in strengthening QI systems by promoting the adoption of advanced standards and establishing national testing facilities. Their efforts should align with international standardisation frameworks, listed in databases as IRENA's INSPIRE platform that categorises over 600 standards dedicated to renewable energy. By mandating the use of QI practices in public tenders, governments can foster widespread adoption of resilience measures, ensuring that renewable projects are future-proofed against escalating climate risks.

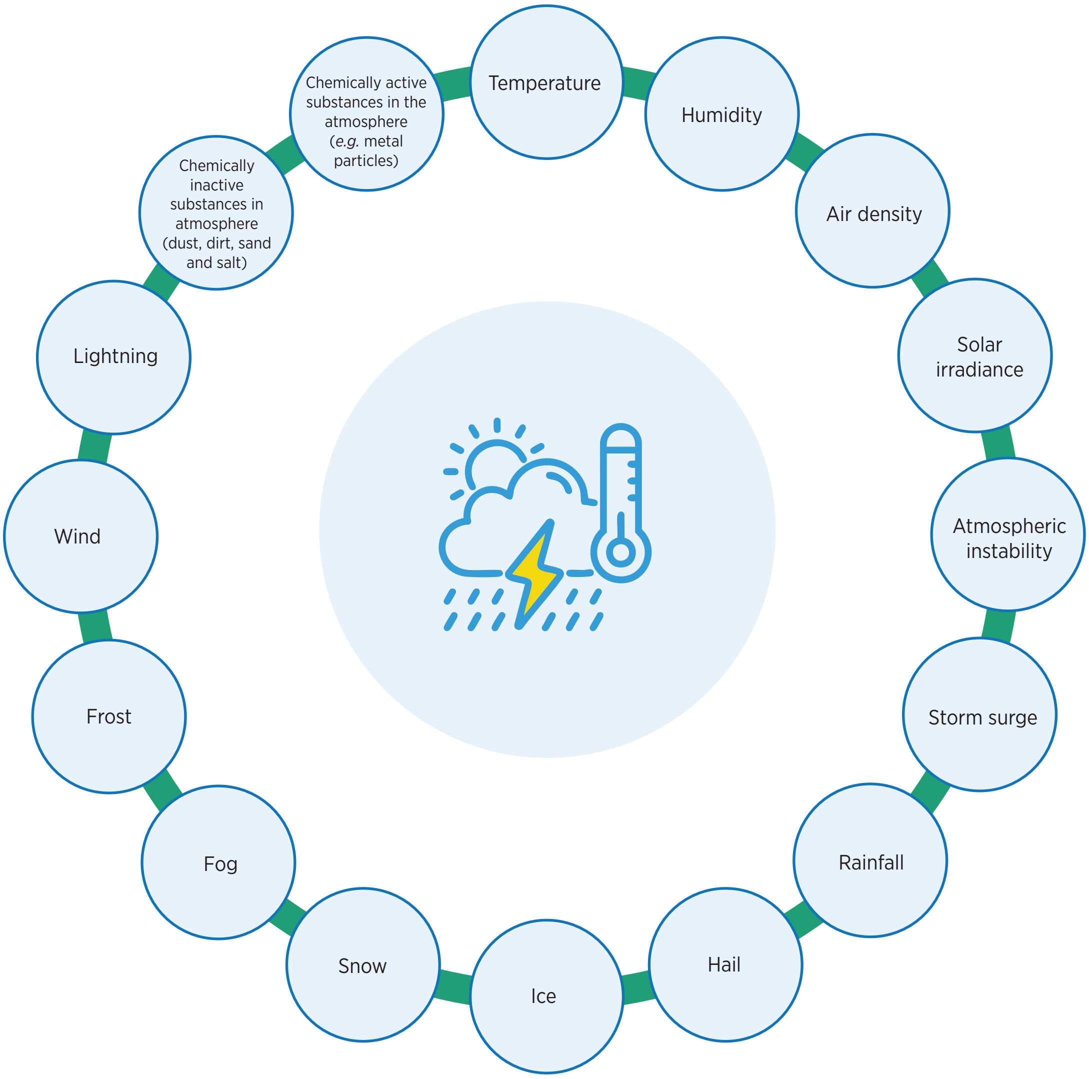
As extreme weather events continue to intensify, the implementation of QI is no longer optional but essential. By embedding resilience at every stage of renewable energy development, stakeholders can safeguard their investments, support grid stability and accelerate the transition to a sustainable, climate-resilient energy future. IRENA's guidance highlights the transformative potential of QI in meeting the dual challenge of scaling renewables and adapting to a changing climate.

1. Introduction

Extreme weather events are a major threat in the coming decades. Fuelled by climate change, 8 179 major disaster events were recorded in the 2000-2021 period, an increase from 4 212 disasters recorded in the 1980-1999 period. These events also have growing impacts due to increasing urbanisation. Hence, it is estimated that 4.2 billion people have been affected by climate disasters between 2000 and 2019, compared with 3.25 billion in the 1980-1999 period. Economically, the impact of extreme events increased from USD 1.63 trillion (1980-1999) to USD 2.97 trillion (2000-2019).

Renewable energy installations are affected by climate conditions and meteorological phenomena in a similar way to all types of infrastructure. Impacts vary according to the technology and type of meteorological event, and can lead to the total destruction of the energy generation facility. In order to analyse the impacts of extreme weather conditions, 16 meteorological factors that can affect renewable energy installations have been identified, including temperature, humidity, rainfall and wind.

Figure 1 Weather conditions that must be considered in a PV or wind generation project



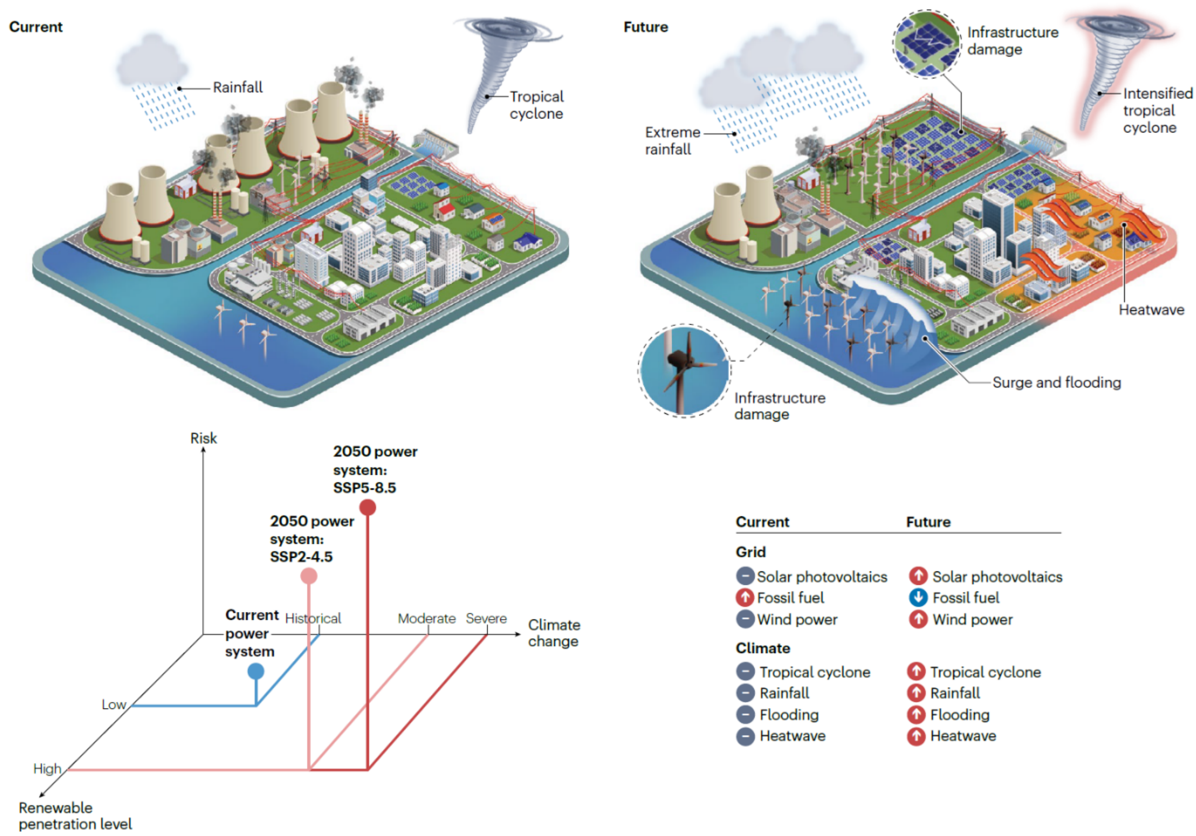
Extreme weather conditions can occur in different ways:

- **Climatic conditions.** These include extreme levels of one or several meteorological factors over long periods (several months). Cold climate, desert, coastal and high-altitude conditions can show persistent metrics of extreme weather. Additionally, regions where these conditions used to have limited duration can become affected for entire seasons, as in the case of desertic conditions fuelled by climate change.
- **Meteorological phenomena.** These include extreme levels of one or several meteorological factors over short or medium-term periods (from hours to days), as well as important variations both in amplitude and frequency (IRENA, 2021). Several extreme meteorological phenomena have been identified, such as cyclones, tornados, severe thunderstorms and sandstorms.

The risk of outages and blackouts is growing as climate change increases the occurrence and severity of extreme weather events, and power systems increase their reliance on renewable energy sources. This can be countered by solid quality infrastructure (QI) to support the robustness of renewable generation installations. QI is defined as the system of organisations, policies, legal frameworks and practices required to assure that products and services are safe and sustainable. It serves as a fundamental element in the smooth functioning of domestic markets and facilitates international market access (INetQI, 2024). QI includes metrology, standardisation, accreditation, conformity assessment (including testing, certification, verification/validation and inspection) and market surveillance as its components, with technical regulation as a cross-cutting aspect (IRENA, 2024).

A QI-based mitigation strategy for PV and wind assets must complement efforts on grid resilience, maintaining security of supply despite the increased risk of extreme weather. Figure 2 provides a qualitative representation of these risks and impacts, from current power systems and climate to future scenarios with a higher penetration of renewable sources combined with forecasted climate change in two shared socio-economic pathways (SSP2-4.5 and SSP 5-8.5) (Xu *et al.*, 2024).

Figure 2 Superimposed risks for future high-penetration renewable power



Source: (Xu *et al.*, 2024).

2. General strategy for extreme weather impact mitigation

The general strategy to mitigate the risk of extreme weather impacts is shown in Figure 3.

Figure 3 General strategy for extreme weather impact mitigation

At project site

- Identify all possible extreme weather conditions that can occur in a project site
- Assess their probability and impact
- Identify key components of the infrastructure

- Local and national meteorological data
- Global data (*e.g.* NASA, NOAA)
- Climate change scenarios (IPCC, UNFCCC)
- On-site measurements (tempaerature, humidity etc.)
- Site-specific studies (geotechnical, topographical, hydrology etc.)

Mitigation measures design

- Identify measures to mitigate each identified risk to an acceptable level
- Focus on identified key components

- Site protection measures (*e.g.* drainage, lightning rods)
- Standards for components and procedures
- Insurances
- Cost-benefit analysis

Mitigation measures implementation
Construction phase

- Implement identified mitigation measures throughout construction phase

- Procurement documents
- Factory acceptance texts for key elements
- Construction control by independent quality insurance bodies

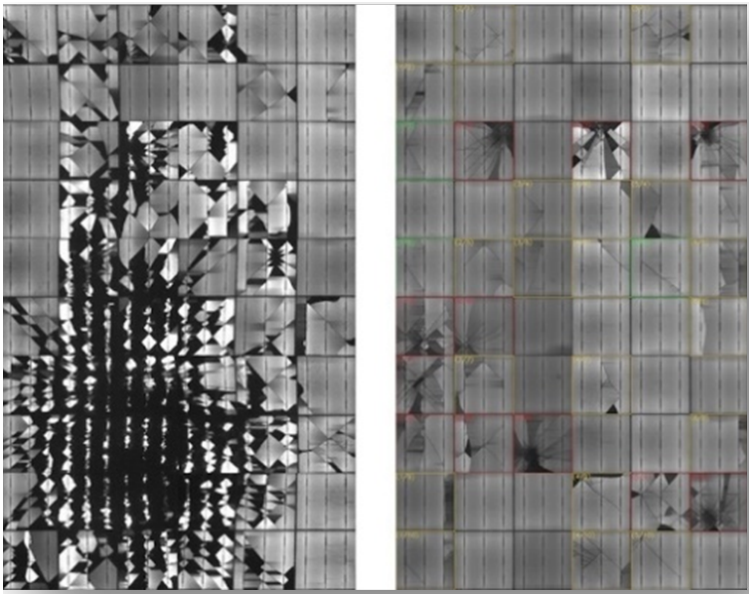
Mitigation measures implementation
Operation phase

- Implement identified mitigation measures throughout operation and maintenance phase

- Preventive maintenance
- Regular performance testing

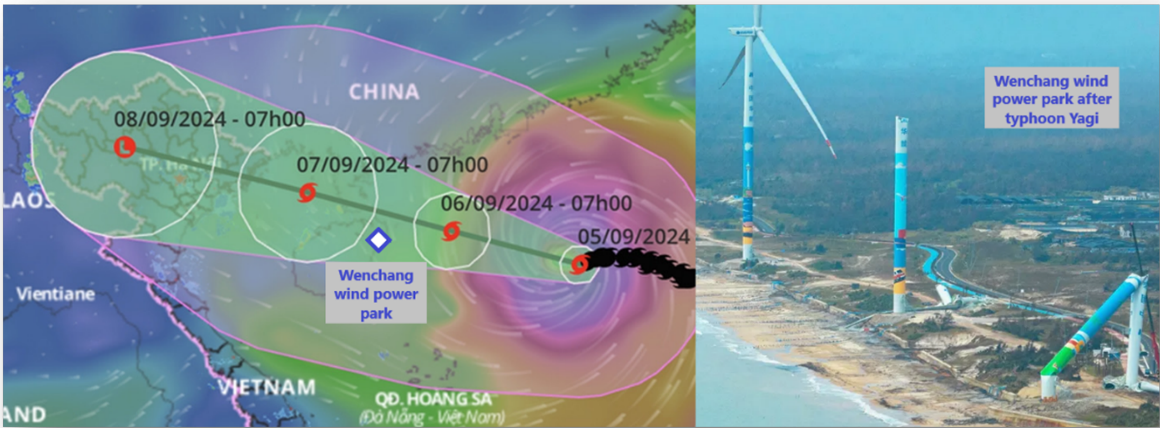
The importance of a mitigation strategy is demonstrated in Figure 4 and Figure 5, showing the potential for extreme weather events to damage PV and wind assets.

Figure 4 X-ray image of a PV panel damaged by hail



Source: Solar Storage Magazine, 2016.

Figure 5 Weather forecast of typhoon Yagi to hit a wind farm in China and aftermath

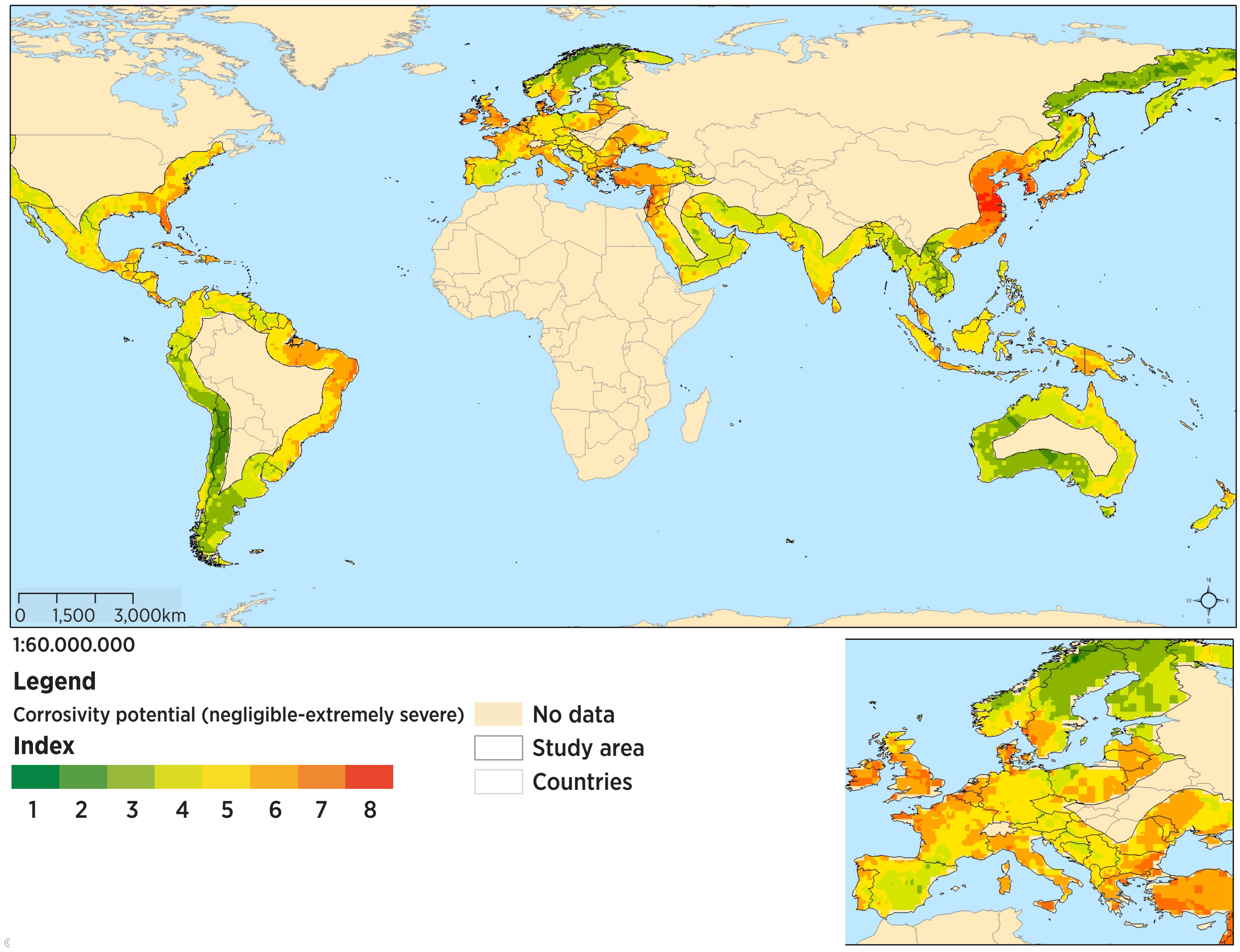


Source: (NCHMF, 2024).

2.1. Risk assessment

Risk is commonly defined as the product of the probability of an event happening and the impact on the infrastructure if the event happens. It helps project developers prioritise the risks that need to be addressed during the project. In the specific case of extreme weather conditions, risk assessment can be a complex task due to the uncertain probability of these phenomena happening and their uncertain strength. Geographical considerations offer a preliminary understanding of the risks to be assessed, as exemplified in Figure 6 and Figure 7 on corrosivity potential and hurricane routes and seasonality.

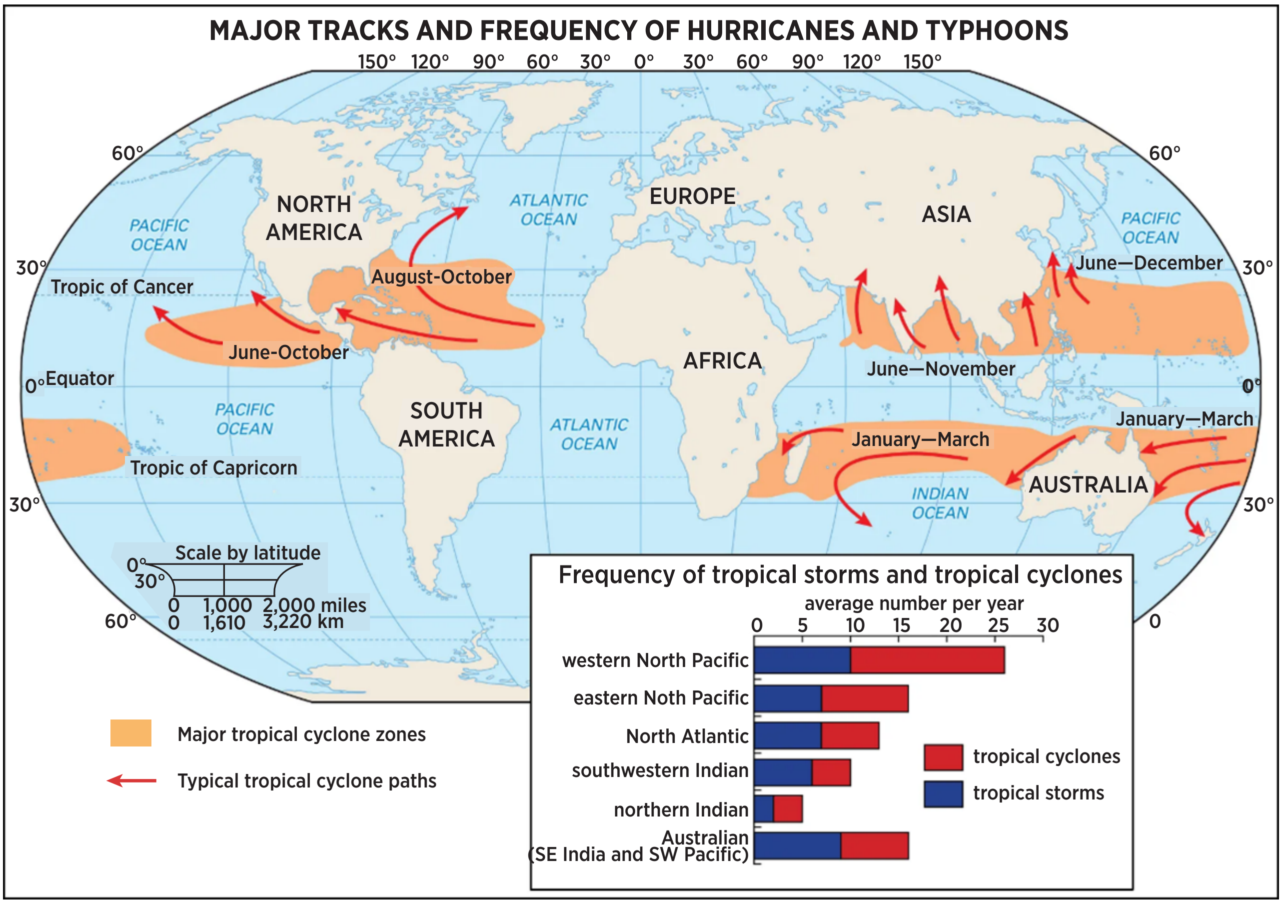
Figure 6 Distribution of atmospheric corrosivity on the global map



Source: (Slamova, 2012).

Notes: Corrosivity reflects a combination of factors, such as temperature, humidity, pollution by sulphur dioxide and airborne salinity, that lead to corrosion; km = kilometre.

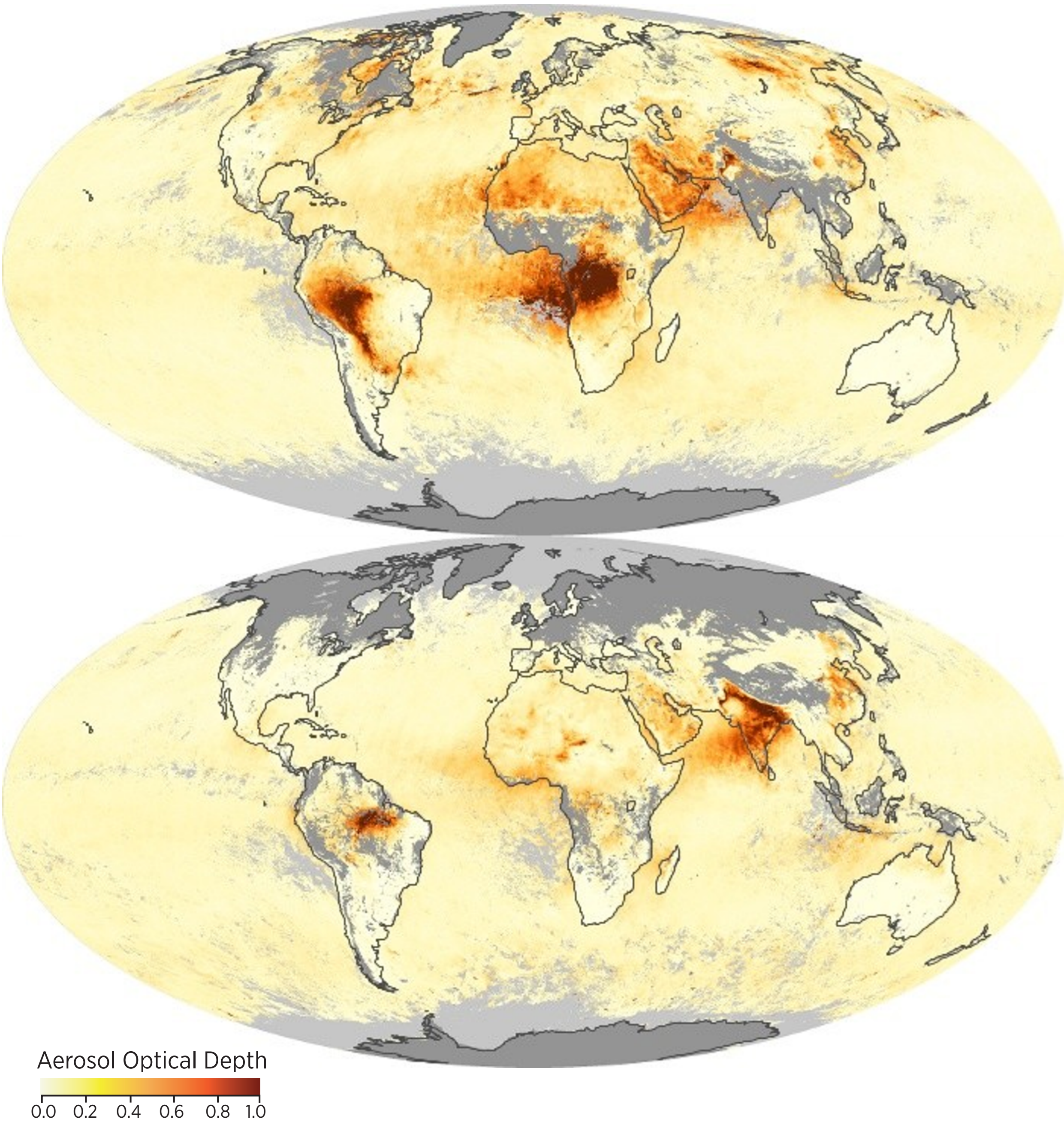
Figure 7 Tracks, seasonality and frequency of hurricanes/typhoons



Source: (Encyclopaedia Britannica, 2024).
Note: km = kilometre.

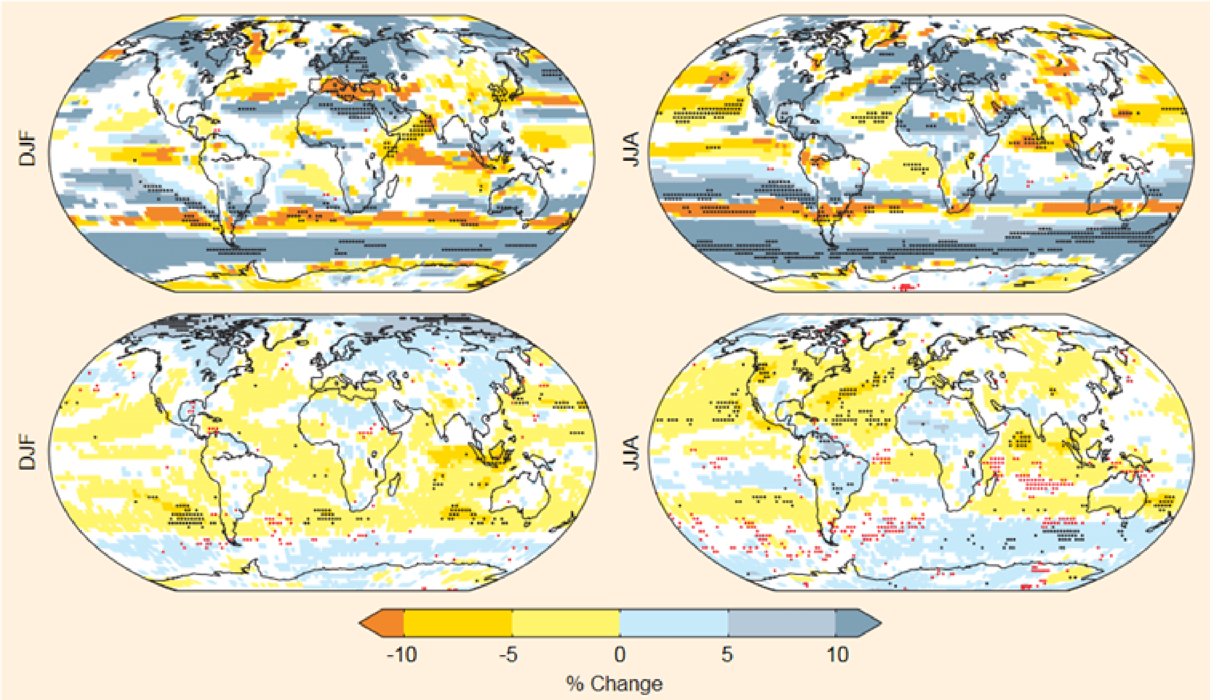
The first step of risk assessment is to analyse in detail the historical data on each meteorological factor that can affect the renewable energy installation, as specific to the site location as possible. These data may be available at the national meteorological institute of the country where the project is being implemented. Depending on the country where the project is planned, dedicated national agencies may also produce *ad hoc* risk maps and analysis for certain meteorological events (such as floods or storm surge). Another useful resource can be global data provided, for example, by NASA, as from its Earth Observatory (NASA, 2024), or the National Oceanic and Atmospheric Administration for specific factors or events. Additionally, assessment reports produced by the Intergovernmental Panel on Climate Change (IPCC) summarise the available literature data, including the evolution of climatic conditions by geographical area for temperature, rainfall and wind. Figure 8 and Figure 9 exemplify high-level mapping of these factors.

Figure 8 Concentration of aerosols measured by NASA in August 2024 (upper) and November 2024 (lower)



Source: (NASA, 2024).

Figure 9 Average changes in the mean daily average 10 m wind speeds (top) and 99th percentile of the daily average 10 m wind speeds (bottom) for the period 2081-2100 for December to February (left) and June to August (right)



Source: (IPCC, 2018).
Note: m = metre.

When the main potential extreme weather conditions have been identified, site-specific measurements of meteorological factors need to be performed in order to have a detailed knowledge adapted to the site conditions and topography. For most meteorological factors, these measurements are relatively easy to take (*e.g.* temperature, humidity, wind force and direction). In the case of sites with a specific rainfall risk, civil works design studies have to put a specific focus on potential floods that can happen on the project site (geotechnical and hydrological studies). Whenever possible, on-site measurements should cover the whole year so as to have exhaustive seasonal data. Three specific resources may be of interest:

- The online platform www.PreventionWeb.net has been developed by the UN Office for Disaster Risk Reduction (UNDRR) under the Sendai Framework for Disaster Risk Reduction 2015-2030. It includes an online knowledge base that features studies, publications, news and training that can be used to assess and mitigate extreme weather condition risks.
- The Copernicus Energy Hub, based on EU Copernicus Earth Observation Programme and implemented by European Centre for Medium-Range Weather Forecasts (ECMWF), facilitates access to key global weather-related information and data of interest to the energy sector, relevant in the risk assessment phase of PV and wind projects.
- The Climate Change Knowledge Portal, provided by the World Bank, presents an extensive database of country profiles that are periodically updated, including historical trends and future climate projections, extreme weather event probabilities and vulnerabilities.

2.2. Mitigation measure design

The objective of risk mitigation is to identify and implement measures to lower each significant risk to an acceptable level in terms of probability and impact without hampering the overall financial profitability of the project. Figure 10 outlines a hierarchy of mitigation measures appropriate for weather-related risks, while Figure 11 sets out the main weather-related risks that apply to PV and wind power generation equipment, with examples of mitigation measures.

Figure 10 Mitigation measures for weather-related risks

Risk suppression

Selecting a site that has a lower risk profile is naturally the best way to mitigate risk. However, in the case of extreme weather conditions, it is often not a possible option once the site has been decided according to multiple other factors, as the risk probability cannot be influenced.

Site protection

Measures protecting the whole installation from a specific risk. This type of protection includes, for example, the construction of dykes or trenches to avoid floods and storm surge as well as the erection of lightning rods connected to the ground to avoid equipment strikes.

Equipment protection

Measures protecting each piece of equipment individually from a specific risk. The use of standardised components and/or construction methods falls into this type of measure. When applied, it guarantees that components have been manufactured, tested and and built to maintain their characteristics under defined conditions and, therefore, constitutes an efficient way to mitigate risks. Standards can be defined at international, regional or national level and, depending on the case, their use can be imposed by local regulation.

Given the specificity and diversity of existing standards, it would not be possible to establish an exhaustive list for every renewable energy technology. To help renewable energy stakeholders quickly identify appropriate standards, IRENA has developed the INSPIRE online database (http://inspire.irena.org), which allows access to the description of more than 600 international, regional and national standards specifically dedicated to renewable energy.

Operating procedures

Foreseen actions for the operation and maintenance of the installation that contribute to reducing the risk level, most often performed by site technicians. For example, this includes the regular cleaning of solar PV modules in a dusty environment. The frequency and characteristics of these maintenance operations is to be defined according to the risk level, especially for important operations that require partial or total interruption of the installation.

Insurance

Once all other steps have been explored and implemented, the last resource to be considered is to take out insurance. This will evidently not physically protect the installation, but will ensure that project finance is not critically affected by climatic events. Insurance is usually used to cover the residual risk that cannot be mitigated by other measures.

Figure 11 Examples of mitigation measures for extreme weather events as they affect PV and wind installations

2.2.1 Mitigation approaches for solar PV parks

Extreme temperatures

High temperatures have a significant impact on the performance of solar PV modules whatever technology is used. As the temperature rises, so the maximum power that a module can output decreases. Furthermore, when adjacent materials have mismatched coefficients of thermal expansion (*e.g.* silicon solar cells and metal busbar ribbons), the interface experiences stress and ages (*i.e.* solder joint fatigue) (IRENA, 2017). Depending on the PV system design, the high temperatures may de-rate the inverter output and can cause an increase in failure rates. This leads to a degradation of the performance of the system, which system modelling typically predicts. Furthermore, both extreme high or low temperatures may cause damage related to the thermal expansion or contraction of mounting structures.

Table 1 PV impacts and mitigation related to extreme temperatures

Climatic conditions favouring the meteorological phenomena	Desertic conditions
Potential impacts	Yield loss
Financial impacts	High
Mitigation measures	• PV module material selection • Mount the PV modules in a way to ensure regular air flow • Water cooling • Salt cooling
Applicable standards	• IEC 61215-1/IEC 61215-2: Terrestrial PV modules – Design qualification and type approval – Part 1: Test requirements/ Part 2: Test procedures • IEC 61730-1/IEC 61730-2: PV module safety qualification – Part 1: Requirements for construction/Part 2: Test requirements • IEC 62892: Extended thermal cycling of PV modules – Test procedure • IEC TS 63126: Guidelines for qualifying PV modules, components and materials for operation at high temperatures
QI gaps	IEC 61215 and IEC 62892 only impose 200 and 500 cycles respectively for Thermal Cycling that may not be sufficient.

Note: IEC = International Electrotechnical Commission; PV = photovoltaic.

Chemically inactive particles (dust, salt)

A common factor limiting the performance of PV installations is dust. In many regions, dust is by far the largest contributing soiling factor for PV modules. Soiling refers to partial shading caused by the settlement of dust and debris on the module surface. By covering the surface, light transmission and energy generation are reduced. Failure to address this issue leads to yield losses and losses in return on investment.

Table 2 PV impacts and mitigation related to chemically inactive particles

Climatic conditions favouring the meteorological phenomena	Desertic conditions, Coastal conditions, Islands
Potential impacts	• Yield loss • Structural damages
Financial impacts	High
Mitigation measures	• Measuring soiling rates • Cleaning (dry if limited water available)
Applicable standards	• IEC 61724-1: Photovoltaic System Performance – Part 1: Monitoring • IEC 61701: Photovoltaic (PV) modules – Salt mist corrosion testing • IEC 61215-1/IEC 61215-2: Terrestrial PV modules – Design qualification and type approval – Part 1: Test requirements/ Part 2: Test procedures
QI gaps	A dedicated standard for coatings could supplement IEC TS 63126:2020

Soiling can cause yield losses of more than 5% within one week. The literature gives ample evidence of PV module soiling (Costa, 2016). The impact of dust on PV installations varies by country and region. The amount of dust that settles on PV modules depends on the rate of dust accumulation and dust removal. Factors such as rainfall, surface coating, wind speeds and mounting structure height affect the accumulation and removal of dust from the surface (IEA, 2017). PV installations in moderate climates with regular rainfall are less prone to soiling. In contrast, soiling can be a substantial issue in arid regions with high dust concentrations.

Box 1 Effects of desertic conditions on PV in Qatar

Desert regions like the Middle East, North Africa, and parts of Asia and the Americas present unique challenges for solar PV systems, such as high temperatures, intense radiation and dust. Individually manageable, these factors combine in desert environments to accelerate wear and reduce efficiency. Establishing national testing facilities aligned with international standards builds confidence among stakeholders and fosters solar market development in such regions.

Located on the Arabian peninsula, Qatar's arid climate features average summer temperatures exceeding 40°C, and minimal rainfall, plus high salinity levels in the atmosphere. These conditions accelerate wear on PV components. However, Qatar's abundant solar resources, with high irradiance and low cloud cover, present significant potential for solar energy. Despite this, uncertainty regarding the combined effects of desertic conditions has hindered large-scale solar PV deployment.

Key risks

1. **Soiling losses**: Dust and sand accumulation on PV modules can reduce energy production by up to 15% monthly. Without regular cleaning, power output can drop significantly over time, particularly during Qatar's dry summer months.
2. **Component degradation**: **Corrosion**: high humidity and salinity accelerate metal oxidation, threatening structures and module frames. **Polymer wear**: elevated temperatures and irradiance degrade cable insulation and other plastic components. **Combined effects**: these factors collectively reduce system lifespan and performance.

As mitigation measures, the **Solar Testing Facility (STF)**, operated by the **Qatar Environment & Energy Research Institute (QEERI)** since 2012, addresses these challenges by:

- **Real-world testing**: Monitoring various PV technologies, including crystalline silicon, thin-film and hybrid modules. Data collected since 2013 show most modules retained production capacity within manufacturers' warranties. Crystalline silicon modules demonstrated the most consistent performance.
- **Optimised cleaning protocols**: Severe soiling necessitates careful cleaning strategies. Instead of fixed schedules, QEERI advocates cleaning based on soiling thresholds to balance operational costs with energy production.

QEERI's studies show that crystalline silicon PV systems can perform reliably in desertic conditions with proper maintenance. Cleaning optimisation and additional monitoring ensure manageable operational costs without compromising energy yield. This supports the viability of solar PV in Qatar, though long-term durability studies are necessary to confirm lifetime performance.

Barriers to QI adoption

1. **Testing duration**: PV modules have a 25-year design life, and some degradation mechanisms only become apparent over extended periods. Long-term testing requires significant resources, deterring commercial investment.
2. **Financial challenges**: High initial costs and perceived risks necessitate government and NGO support to attract private sector involvement.
3. **Confidence building**: Integrating local testing with international standards enhances trust among developers, investors and banks, paving the way for market development.

Qatar's STF demonstrates the potential of solar PV in desertic conditions. While unique challenges like soiling and accelerated degradation exist, strategic maintenance and adherence to international standards can mitigate these risks. With proper support and long-term testing, solar PV systems can thrive in arid regions, unlocking Qatar's solar energy potential.

Hail, snow and frost

Large hailstones can cause cracks in the PV module's glass and cells. The technical inspection association in Germany and Austria (TÜV) reports damage varying according to the hail event, especially hailstone size, hailstone impact, temperature, and the type and mounting of the module (IEA, 2017).

Piled-up snow can cause the PV modules to break and the frames/mounting structures to collapse. A combination of daytime temperatures around 0°C and night-time temperatures below 0°C can cause the snow to compact through melting and freezing. In particular, this prevents the snow from sliding off the PV modules. Over several days, the stacked snowpack became too heavy for the installation. Besides the damage to the solar PV system, snowfall decreases the energy generation (up to zero) by blocking sunlight from the PV surface.

Frost heaves can particularly damage ground-mounted solar PV installations, as water freezing and expansion below the ground leads to movement of the soil. Frost-induced soil uplifting occurs according to the frost susceptibility of the soil, presence of water and temperatures below 0°C (Neely *et al.*, 2017). The direct consequence for PV systems can be structural distortion of the mounting rack due to differential movement of the piles lifted by the frost heave. In severe cases, this can result in deformation and cracking of the PV modules.

Table 3 PV impacts and mitigation related to hail, snow and frost

Climatic conditions favouring the meteorological phenomena	**Desertic conditions, High altitude conditions, Cold climate**
Potential impacts	Damage to the installation
Financial impacts	Low
Mitigation measures	• Measure • Follow strict standards and construction norms
Applicable standards	• IEC 61215-1/IEC 61215-2: Terrestrial photovoltaic (PV) modules – Design qualification and type approval – Part 1: Test requirements/Part 2: Test procedures • Eurocode 1-4: Snow load
QI gaps	Lack of test procedure for hailstones with a diameter superior to 75 mm, weight superior to 203 g, and an impact velocity superior to 39.5 m/s

Notes: g = grammes; mm = millimetres; m/s = metres per second.

High solar UV irradiation

High ultraviolet (UV) irradiation is a key impact factor for PV modules, especially in high-altitude environments, where it is greater. Traditionally, UV-induced degradation was associated with accelerated ageing of module packing materials, leading to encapsulant issues and reduced yield. Although this was progressively solved by the industry, recent high-performance cell technologies are again suffering from the impacts of high UV irradiation, in this case associated with damage to the passivating layer or the silicon of the cell itself, due to its higher sensitivity (Sinha *et al*., 2023). Non-silicon-based panels also show UV-related degradation or stability issues. So far, no standards specifically address UV irradiation due to the time intensity of tests that simulate the module's exposure to UV irradiance over its entire operating life. As the key indicator, the UV dose received by the PV module is the integral of the radiant exposure of UV irradiance over time. In exposure tests, the maximum technically feasible UV-A and UV-B dose is 15 kilowatt hour per square metre per week (kWh/m^2/week). As a consequence, the test time to simulate ten years of exposure at 150 kWh/m^2/year is almost two years, beyond the scope of practically feasible tests at scale. Despite this, for PV system components other than the PV module, the new IEC 62788 series establishes UV tests for the encapsulant and the front sheet (International PV Quality Assurance Task Force, 2019).

Table 4 PV impacts and mitigation related to high solar UV irradiation

Climatic conditions favouring the meteorological phenomena	Desertic conditions, High mountain conditions
Potential impacts	Yield loss
Financial impacts	Medium
Mitigation measures	• Material selection for PV modules • Regular monitoring and replacement of damaged cells
Applicable standards	• IEC 62788 – Measurement procedures for materials used in photovoltaic modules – Part 1-2: Encapsulants – Measurement of volume resistivity of photovoltaic encapsulants and other polymeric materials (not specific for PV module)
QI gaps	Lack of dedicated norm for PV modules

Rainfall and humidity

Humidity can lead to degradation of the PV modules. While temporary exposure to high humidity does not impact the performance of the solar PV modules, especially in their early life, long exposure causes degradation by moisture ingress through the encapsulant (Flowers *et al*., 2016). The datasheets for solar PV modules rarely provide an operating range for relative humidity. The IEC standards provide for module testing to withstand a relative humidity of up to 85%. While this is sufficient for most locations worldwide, coastal regions, such as in India, can face higher levels of humidity over long periods. The degradation of the performance of PV modules is known as potential induced degradation (PID). It describes the power loss that results from the electrical potential differences between the solar cells and other parts of the panel. In operating settings with high humidity and temperatures, this induced electrical field can cause Sodium ions (Na^+) located in the glass to migrate into the solar cells and degrade the semiconductor junction, restricting electron flow. The decelerated electron flow manifests as power degradation. Besides this gradual degradation, high levels of humidity can cause failures in all electronic equipment including inverters, which can undermine system reliability.

Rainfall can have negative and positive effects on the performance of solar PV modules. Direct rainfall on the solar PV module has a cleansing effect and helps to keep performance high by washing off particles that have accumulated on the PV module over time. In contrast, indirect effects of heavy rainfall, such as flooding, can damage the solar PV installation. The Middle East has produced examples of solar PV installations affected by flooding. In particular, flash flooding has occurred in low-lying areas with dry soils that have a low capacity to absorb water (Khan, 2013). Similar to dry soils, saturated soils also have a low capacity to absorb water and are prone to flooding. Fast-running water can carry off debris that can collide with and damage the solar PV installation.

Storm surges, in the form of rising sea levels following tropical cyclones or storms, can lead to coastal seawater flooding with surge heights of up to 7 metres (m). In the case of flooded PV systems, saltwater can damage the equipment.

Table 5 PV impacts and mitigation related to rainfall and humidity

Climatic conditions favouring the meteorological phenomena	Coastal conditions, Islands, High altitude conditions, Cyclones, Typhoons, Thunderstorms
Potential impacts	Damage to the installation and yield loss
Financial impacts	Medium
Mitigation measures	• Measure humidity and rainfall during design phase • Perform geotechnical studies • Follow construction standards • Choose adequate materials
Applicable standards	• IEC TS 62804 PV modules – Test methods for the detection of potential-induced degradation • ISO 1461: Hot dip galvanised coatings on fabricated iron and steel articles • ISO 12944: Paints and varnishes – Corrosion protection of steel structures by protective paint systems
QI gaps	No major gaps identified

Strong winds

Strong winds can damage PV installation, breaking the panels or their mounting structures, in particular where installed on rooftops or during meteorological phenomena such as cyclones, typhoons or severe thunderstorms. In addition, the flying elements can cause additional damage to people, animals or structures in the surroundings.

Table 6 PV impacts and mitigation related to strong wind

Climatic conditions favouring the meteorological phenomena	Coastal conditions, Islands, Cyclones, Typhoons, Thunderstorms
Potential impacts	Damage to the installation
Financial impacts	Medium
Mitigation measures	• Follow international construction standards
Applicable standards	• IEC 61215: Thin-film terrestrial photovoltaic (PV) modules – Design qualification and type approval • UL 1703: Standard for Flat-Plate Photovoltaic Modules and Panels • Eurocode 1: Actions on structures • IEC 62727: Photovoltaic systems – Specifications for solar trackers • IEC 60364: Electrical Installations for Buildings
QI gaps	Standard IEC 62727 has been withdrawn without comparable replacement.

Box 2 Severe winds impacting PV in the Netherlands

While international standards like IEC 62548 regulate PV array design requirements for wind speeds, national codes often deviate on structural design specifics. Dutch building codes, for instance, define wind zones differently, influencing how PV installations are calculated and designed.

The Netherlands, with its 500 kilometre (km) coastline along the North Sea, experiences frequent severe storms. On 18 January 2018 a storm disrupted transport, uprooted trees and caused structural damage to buildings, traffic signs and PV installations. Wind speeds reached 30 m/s (108 kilometre per hour [km/h]) along the coast, with gusts up to 40 m/s (144 km/h), while inland gusts reached 34 m/s (122 km/h). These winds imposed heavy loads on objects, especially elevated rooftop PV systems. Damage ranged from minor issues like lost modules to prolonged de-energisation of systems, leading to financial consequences for stakeholders. This event underscored the need for a national standard, resulting in **NEN 7250**.

Development of NEN 7250: The national standard was developed to standardise rooftop PV installations, addressing gaps in existing practices. It specifies installation methods, supplements Eurocodes for wind loads, and includes requirements for fire safety, noise, moisture and thermal isolation. Previously, unclear installation materials and methods caused problems such as flying modules, water ingress and even roof collapses. The process to develop NEN 7250 took 11 years due to challenges like evolving materials and limited engagement from international manufacturers. Published in 2014, it replaced the pre-norm NVN 7250, which lacked critical wind load specifications.

Cost implications and benefits: Adopting NEN 7250 has reduced risks for PV system owners, installers and developers while lowering insurance costs. It has also boosted acceptance of compliant mounting products. Financial models indicate that addressing extreme weather risks increases returns, as system repair costs after such events can reach 50% of initial investment. Implementing quality improvements adds 10% to costs, but provides a higher return on investment with reduced risks.

Barriers to QI adoption: Adoption of NEN 7250 faced resistance from PV installers due to stricter regulations and limited collaboration from manufacturers. Additionally, as the first country to develop a rooftop PV standard, the Netherlands lacked international benchmarks. Ongoing updates are slowed by limited funding, despite emerging needs, such as special requirements for east/west mounting, which is increasingly popular for flat roofs.

Conclusion

NEN 7250 has gradually gained importance, especially after the 2018 storm. Initially overlooked, it is now incorporated into tenders and on-site inspections, promoting adherence. However, continuous updates and funding are crucial to address evolving practices and ensure its effectiveness in mitigating future risks.

2.2.2 Mitigation approaches for wind parks

Strong winds

Wind turbines are classified according to the fatigue and extreme loads that they can withstand. The extreme wind class is normally defined from the 50-year return period 10-minute mean wind speed (which refers to a 10-minute mean wind speed that, on average, is expected to be exceeded only once in 50 years). Alternatively, the 3-second gust wind speed is used with the gust factor to determine the 10 minute mean wind speed. The annual mean 10-minute wind speed and the turbulence intensity determine the fatigue wind class. Exceedance of the maximum extreme wind speed can cause structural damage to wind turbines within a very short time (*e.g.* tower buckling). Extreme weather events can surpass the mechanical loads that wind turbines are designed to withstand. If small-scale yielding of the turbine structure occurs, fatigue failure can occur subsequently later. Fatigue and extreme loads in excess of the design loads can significantly reduce the wind turbines' lifetime.

In addition to high wind effects, the prevailing wind direction can vary (*e.g.* by 180° in 1.5 hours) and also change rapidly. While turbines can yaw, their yaw speed is low (0.2-0.3°/s) compared with the abrupt changes of the wind direction under cyclone conditions. Yaw systems typically operate according to an 8-10 minute average wind direction; however, typical changes in the wind direction of tropical cyclones are even faster, (*e.g.* 10-30° in 10 s). Therefore, the wind direction can change drastically before the wind turbine yaws.

Table 7 Turbine impacts and mitigation related to strong winds

Climatic conditions favouring the meteorological phenomena	Coastal conditions, Islands, High altitude conditions, Cyclones, Typhoons, Thunderstorms
Potential impacts	Damage to the installation and yield loss
Financial impacts	High
Mitigation measures	• Evaluate occurrence risk of extreme wind • Follow construction standards • Choose adequate materials
Applicable standards	• IEC 61400 – Wind Turbines
QI gaps	Limited availability of data at height of 100+ metres

Box 3 Typhoons impacting wind farms in China

Onshore wind turbines are designed to withstand extreme wind speeds as defined by **IEC 61400-1**. Earlier editions of the standard excluded tropical cyclones, placing the burden of risk on stakeholders. However, **edition 4 (2019)** introduced a special class to address regions prone to tropical cyclones, influenced by local standards like those in Japan. Despite this advancement, most turbines in operation today were certified under older standards (*e.g.* editions 2 and 3). Best practices, including manufacturer engagement and insurance measures, continue to play a critical role in risk management for tropical cyclone-prone areas.

In China, Typhoon Usagi (2013) and Typhoon Dujuan (2003), both category 4 storms, caused significant damage to wind farms. Sustained wind speeds ranged from 58.1 m/s to 69.7 m/s, damaging turbines and components like yaw systems, sensors and rotor blades. In 2013 a tubular tower collapsed and turbine fires occurred. Damage costs reached **USD 16 million** in 2013 and **USD 1.6 million** in 2003, with additional downtime for repairs. Failures were exacerbated by grid outages, which left turbines vulnerable as yaw systems were locked in place.

Risks and mitigation measures: The key risk is structural damage from extreme winds during a typhoon. Wind direction changes can amplify loads on turbines, especially when turbines are locked in an unfavourable position. Mitigation involves:

- **Design adaptations**: Turbines must withstand maximum expected wind speeds, with backup systems ensuring yaw and pitch control during storms.
- **Operational measures**: Backup systems, such as on-site power supplies, should remain operational even during prolonged grid outages.
- **Post-event measures**: Inspections must identify both obvious damage and concealed issues like material fatigue, which could reduce turbine lifespan.

Cost implications of mitigation: Mitigation strategies involve trade-offs between costs and energy yield:

- Smaller rotors and shorter towers reduce forces but lower energy production, affecting financial returns.
- In low annual mean wind speed (AMWS) areas, taller towers and larger rotors are preferred for

energy yield, but these are more susceptible to extreme winds.

- Accurate cost modelling helps optimise turbine design, balancing energy output and structural resilience.

Joint planning and retrofitting

Collaboration among wind farm owners, turbine manufacturers and grid operators is critical. Effective planning ensures timely turbine shutdown, secure positioning and operational safety. Options to retrofit existing turbines are limited unless complete replacement occurs, with mitigation measures focused on survival during storms.

Deploying wind turbines in tropical cyclone-prone regions is feasible with acceptable risk if mitigation is integrated from the development phase. Engagement with manufacturers and utilities ensures turbines can operate in protection mode during cyclones. Insurance typically covers major damage, but minor costs often fall to owners. Reliable backup systems are crucial for minimising storm-related risks.

Barriers to QI adoption

- **Evolving standards**: The latest **IEC 61400-1** addresses tropical cyclones, but many turbines still operate under outdated certifications.
- **Data gaps**: Until recently, wind data were limited to 10 m heights; newer data at 100+ m has informed better standards.
- **Climate change**: Warming temperatures increase cyclone intensity, challenging QI to keep pace with evolving risks.

State-of-the-art wind technology, combined with preventive measures, enables deployment in tropical cyclone regions with manageable financial and operational impacts.

Ice and frost

The main challenges for standard turbines operating in icing environments encompass decreased energy production, increased loads, decreased wind turbine lifetime, increased noise and increased safety issues due to ice throw.

Ice build-up on the blades usually reduces the lift and increases drag, which results in reduced power output and potentially turbine shutdown. Atmospheric icing influences the blades' aerodynamics through the roughness and shape of the blade surface (IEA Wind, 2017).

Also, the security systems installed in the turbines, responsible for feathering the blades above the cut-out wind speed, greatly affect the energy yield, as the control strategy defines under which conditions a turbine continues operation. During icing conditions the sensors freeze, and measuring the wind speeds can become impossible. This can cause problems with the turbine control, shutting it off unnecessarily.

Icing has been shown to have larger interannual variability than average wind speed (Lehtomäki, 2015). It has a larger interannual energy production variability than wind speed.

Additionally, icing increases the noise related to the blades.

Table 8 Turbine impacts and mitigation related to ice and frost

Climatic conditions favouring the meteorological phenomena	**Cold climate**
Potential impacts	Damage to the installation and yield loss
Financial impacts	Medium
Mitigation measures	• Measure ice and frost risks during design phase • Follow construction standards • Choose adequate materials
Applicable standards	• IEC 61400-15 Site energy yield assessment
QI gaps	Lack of specific standards for the design of blade heating systems

Lightning

Depending on the magnitude of the lightning current, mechanical and thermal effects can increase the temperature in the electrical circuits and lead to material melting from arcs. Statistics show that 4-8% of European wind turbines incur lightning-caused damage over their operating life. However, in some areas - including some regions of Japan - the high occurrence of lightning and consequent lightning-caused damage is estimated to be much higher (Djalel. et al., 2014). Such conditions may motivate risk-suppression measures, as part of a broader mitigation strategy.

Lightning damage is the largest cause of unplanned downtime in wind turbines. Lightning can cause damage to the control system, the electronics, the sensors and the blades. If undetected, the damage can shorten the blades' lifetime. The geometrical, electrical and mechanical complexities of wind turbines raise various challenges, especially for modern models that are larger and reinforced with carbon fibre materials.

The main risk factors from lightning encompass damage to blades by direct strikes and by indirect strikes to connected devices. Direct effects include burns, erosion and damage to the structure (*e.g.* arc attachment). Indirect effects include the electromagnetic field and associated lightning strikes (Peesapati, 2010). Direct lightning strikes only account for one-third of all lightning faults (Bermudez *et al.*, 2005). Indirect lightning strikes and near-strikes affecting the power and telecommunication networks connected to the turbines account for the other two-thirds of all lightning faults. When a lightning storm passes near a wind turbine, the storm imposes a strong electric field on the turbine and blades. This electric field is amplified near the blade tips, ionising the air by the tip. The ionisation of the air can lead to energetic, high-voltage streamers and leaders — otherwise known as near-strikes (Froese, 2018). Associated problems often remain undetected. Near-strikes cause small faults in the blades' substrate material. If unnoticed, rain seeps in and creates water damage.

Table 9 Turbine impacts and mitigation related to lightning

Climatic conditions favouring the meteorological phenomena	**Coastal conditions, Islands, High altitude conditions, Cyclones, Typhoons, Thunderstorms**
Potential impacts	Damage to the installation
Financial impacts	Medium
Mitigation measures	• Follow construction standards • Install lightning protection systems • Choose adequate materials
Applicable standards	• IEC 61400-24: Lightning Protection of Wind Turbines
QI gaps	No major gaps identified

High humidity

Nacelles have openings, cracks, holes and vents through which air enters continuously during the lifetime of the wind farm. When air is very humid, it condenses. This increases the likelihood of corrosion and may cause electrical faults and increase the prevalence of mould in components inside and outside the nacelle and in the tower and the blades. High humidity (> 95%) thus reduces the service life of individual components and the whole structure. It reduces the availability of the turbine due to failure, the need for replacement parts and maintenance. Electrical failure effects can vary from current leakages to short circuits. In the most extreme cases, these insulation issues can cause fires. Additionally, like air temperature, humidity affects the air density, and therefore the aerodynamics in the blades.

Table 10 Turbine impacts and mitigation related to high humidity

Climatic conditions favouring the meteorological phenomena	**Coastal conditions, Islands**
Potential impacts	Yield loss
Financial impacts	Low
Mitigation measures	• Choice of adapted protection materials
Applicable standards	Not available
QI gaps	Lack of dedicated standards

Box 4 Coastal conditions in wind parks in Brazil

Coastal regions often feature strong winds and proximity to electricity demand centres, making them ideal for wind energy projects. While offshore wind turbines are designed for saline and humid environments, onshore turbines in coastal areas often face similar conditions without proper design adaptations. Corrosion is a significant issue in such environments, particularly in Brazil, where coastal conditions exacerbate degradation.

As an example, a coastal wind farm in Brazil, operational since 2008, faced severe corrosion due to inadequate paint systems on its towers. By 2013 epoxy-based paint with higher corrosion resistance had been applied. Handling damage during the transport of equipment to the site had also worsened corrosivity, prompting the adoption of padded transport methods and coated bolts for better protection.

Another major challenge was the clogging of air-cooled generators with salt, leading to stator failures. Electronic components in cabinets and pitch converters were also affected. To mitigate these issues, air filters were installed to desalinate incoming air, and gearbox oil breathers were replaced more frequently to prevent moisture ingress. However, these retrofits involved high costs, revenue loss and operational downtime.

To address the impacts of coastal conditions, the following mitigation measures were implemented:

- **Protective coatings**: Use of marine anti-corrosive paint for towers and coated bolts to resist corrosion.
- **Air filters**: Installation in cabinets and cooling fan vents to prevent saline air damage.
- **Improved oil breathers**: Frequent replacement with coastal-specific designs to reduce gearbox corrosion.
- **Retrofitting cooling systems**: Upgrades to air-cooled generators to handle saline conditions.

Despite these measures, some issues persist, such as salt-affected generators. Over 10 years, USD 50 million was spent upgrading 180 turbines, demonstrating the importance of early design-phase adaptations to reduce costs and downtime.

This case highlights that **proactive design adaptations** for onshore turbines in coastal conditions – such as corrosion-resistant coatings and filters – are more cost-effective than retrofits. Implementing these measures early has only a slight impact on project internal rate of return (IRR), improving system reliability and reducing repair costs.

Barriers to QI adoption

- No specific standards currently address the combined effects of coastal conditions on onshore turbines.
- Offshore standards such as IEC 61400-3 and ISO 12944-2 provide guidance for salinity and environmental loads, but there is a lack of alignment between onshore and offshore standards.

Mitigating coastal impacts on wind farms requires relatively inexpensive design adaptations during construction. Proactive measures lower maintenance costs and downtime, enhancing overall project viability and long-term profitability. Aligning onshore standards with offshore guidelines can further support the development of coastal wind projects.

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Extreme temperatures

Temperature changes impact the physical properties of wind turbine materials and the can render their operation hazardous. If the ambient temperature falls outside the band for normal conditions (*i.e.* -10°C to +40°C) the wind turbine typically shuts down to idling. In particular, the electronic equipment and circuits installed in the turbine must be designed to operate reliably over the entire temperature range. If the shutdown is controlled appropriately, the impacts are limited to increased downtime and decreased energy yield. However, if the wind turbine is kept operating, the failure of components could lead to more drastic consequences. Besides this, temperature impacts the air density, which directly affects the energy yield.

Table 11 Turbine impacts and mitigation related to extreme temperatures

Climatic conditions favouring the meteorological phenomena	Desertic conditions, Cold
Potential impacts	Damage to the installation and yield loss
Financial impacts	Low
Mitigation measures	Adapt the characteristics of the turbine components
Applicable standards	Not available
QI gaps	Lack of dedicated standards

Box 5 IRENA's forthcoming publication Enhancing resilience: Climate-proofing the power infrastructure

This forthcoming report by IRENA notes that renewable energy generation assets are not the only power system assets affected by extreme weather conditions. All segments of the power grid are highly vulnerable to these extreme events, including generation, transmission and distribution assets. IRENA's publication "Enhancing resilience: Climate-proofing the power infrastructure" highlights the effects of extreme weather events across the different power system segments, and provides recommendations for power system stakeholders and policy makers to identify the vulnerabilities and mitigate the effects of extreme events through power system resilience enhancement measures. The report highlights technological solutions and considerations in addition to providing guidance on the process of implementing resilience enhancement measures across the power infrastructure to mitigate the impacts of extreme weather.

2.3. Cost-benefit analysis of mitigation measures on PV and wind

Cost-benefit analysis is often the critical factor in selecting from the range of potential mitigation measures. The goal is to compare the cost of these measures to the cost of the potential impact of extreme weather events. The adequate evaluation of costs and benefits is highly challenging due to the amount and diversity of parameters that must be considered. For a simplified assessment, this report has focused on (i) investment cost (capital expenditure [CAPEX]), (ii) operation and maintenance cost, and (iii) insurance costs (both operational expenditure [OPEX]), and (iv) energy revenues. In combination, these indicators determine the internal rate of return (IRR) of a project. Cost-benefit analysis was performed for several extreme weather events and their relevant mitigation measures. The results, as shown in Figure 12, demonstrate that implementing extensive measures does not significantly affect the project's IRR, as compared with a scenario assuming no extreme weather condition impacts.

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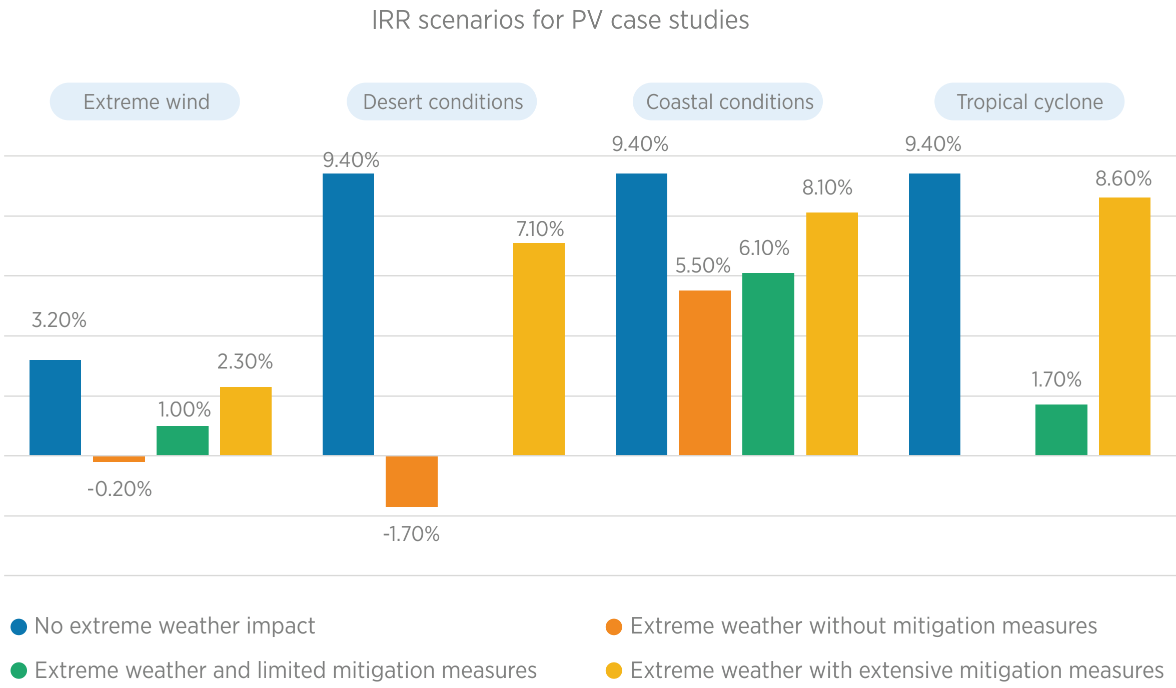
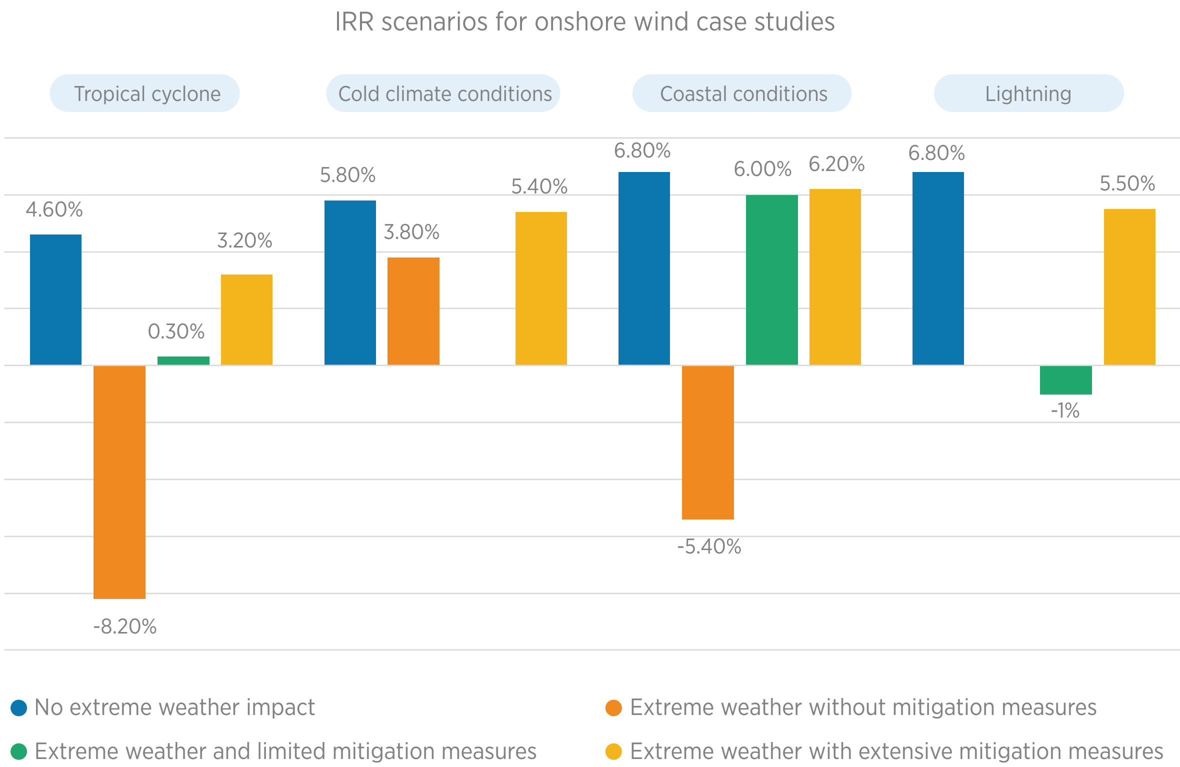
Figure 12 IRR of projects with and without mitigation measures, for different extreme conditions





2.4. Financial implications

Most extreme weather conditions lead to a reduction in the yield of the generation facility. Wind installations can be required to shut down because of high winds or icing of the blades. A real-life example addresses a wind farm of 18 turbines in Scandinavia, for the period from 2008 to 2014 (Figure 13). In this example, energy yield loss refers to both performance loss and downtime, and it illustrates a seasonal loss amounting 14% of total production.

Figure 13 Energy yield loss from ice on wind turbines, Scandinavia, 2008-2014

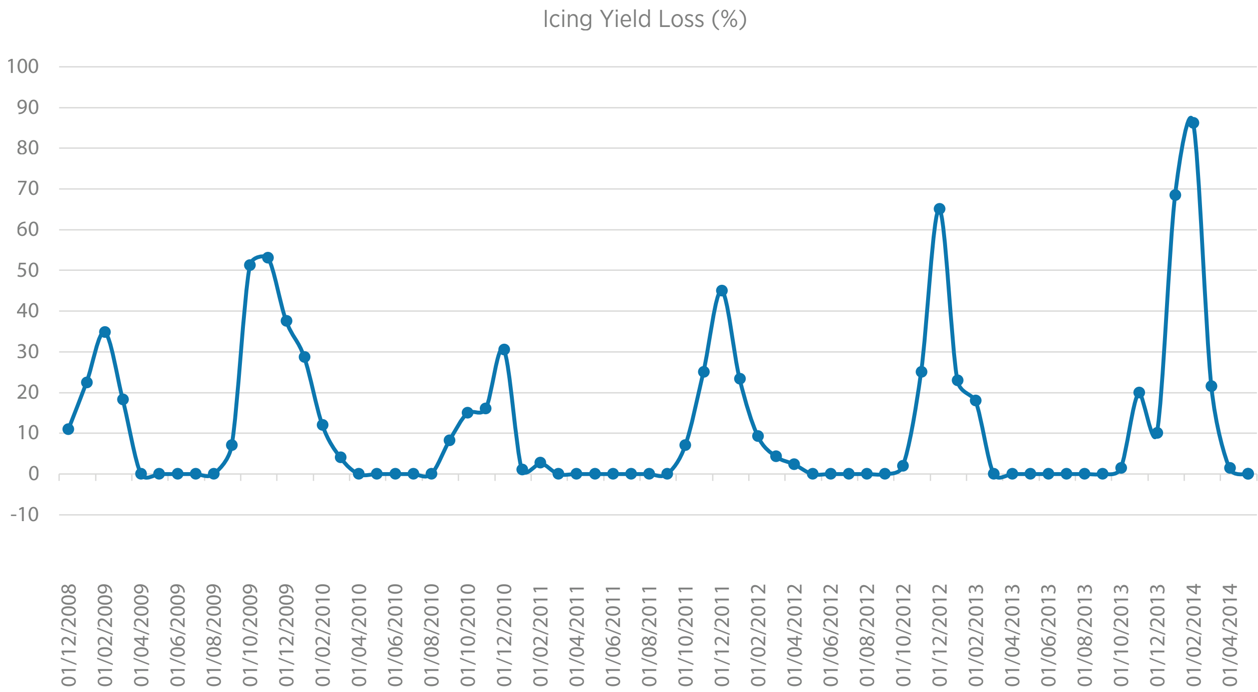
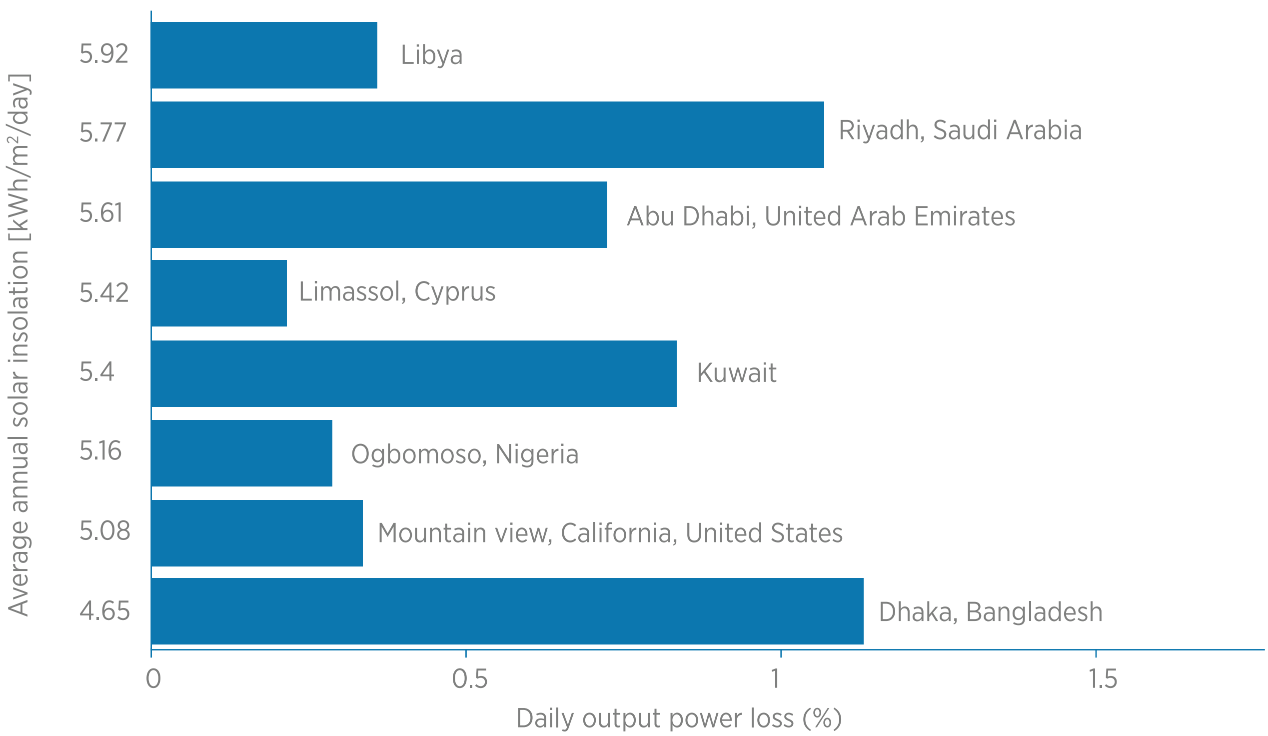


Figure 14 Energy yield loss by dust deposition on PV panels



Source: (Al-Waeli *et al.*, 2019).

Impacts on PV also range from a complete replacement of the PV installation (*e.g.* following a storm surge) to the replacement of individual components (*e.g.* following a direct lightning strike). They can also relate to additional costs for operation and maintenance. Figure 14 displays the direct losses due to dust deposition in regions where desertic conditions are usual.

Other aspects with cost implications are:

- Shortened lifetime due to components being exposed to increased fatigue levels. For example, due to high wind events (tropical cyclones).
- Damaged components in wind turbines/panels, foundation, overhead lines, substation, network and roads during lightning, high wind events, storm surge, heavy or infrequent rainfall in arid sites, hail and snow.
- Damage to main components (fatal event) due to mechanical or electrical destruction or fire triggered by the meteorological condition.

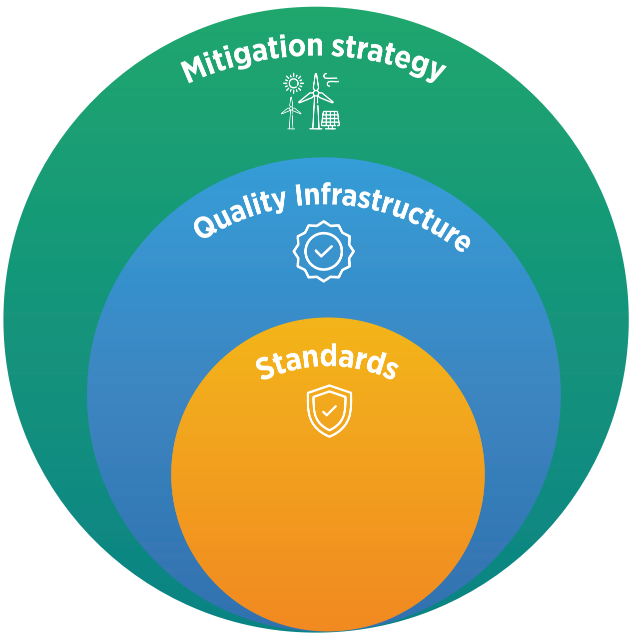
Unmitigated impact results in a yield loss, driven by a set of factors as diverse as:

- Shutdown under ice conditions or when operating out of temperature range.
- Temporal reduction of energy due to changes in wind blade aerodynamic characteristics, or PV irradiation during episodes of ice, frost or dust/sand. Recovery after episode has passed or after cleaning or maintenance.
- Incremental reduction of energy due to permanent change of blade aerodynamic characteristics or permanent damage to the cells due to dust/sand and hail impact.
- Downtime while repairing components, maintaining or cleaning.
- Downtime due to access restriction to the plant, for safety reasons such as during event outside range of design conditions (high wind, temperature, etc.).

2.5. Implementation of mitigation strategy

The implementation of a mitigating strategy can be challenging as all stakeholders must adhere to it and contribute to ensuring its efficiency. The guidelines and standards to be used during the construction and operation phases of renewable energy installation are intended to constitute solid QI that ensures the efficient implementation of the mitigation strategy.

Figure 15 Mitigation strategy based on QI



2.5.1 Construction phase

The construction phase is critical in the building of QI that is able to withstand extreme weather conditions. Poorly built installations are more likely to be significantly affected by extreme weather, leading to increased maintenance costs and service interruptions. Furthermore, this phase involves **multiple actors** (final client, engineering, procurement and construction companies, manufacturers, subcontractors etc.), which makes the implementation of the risk mitigation measures challenging.

The interface between the different stakeholders during construction is often determined by the procurement arrangements, which constitute a key point in the quality assurance process. Indeed, if **procurement documents** are not properly written, significant differences may emerge between the risk mitigation measures designed and those actually implemented.

In particular, tenderers might be inclined to optimise their financial offer by adjusting the quality of the components and procedures used. It is therefore necessary to include all relevant **risk mitigation measures in the procurement process,** especially identifying the **standards** for components and the procedures that need to be used during the construction phase. This will ensure that knowledge is adequately shared between all stakeholders and that QI procedures and materials are part of contractual clauses.

Once construction has begun, another important step is to ensure that the actual key components that will form the plant – identified during the risk assessment phase – conform to the **specifications** given by the manufacturers. In this view, project developers need to ensure that the original equipment manufacturer conducts factory acceptance tests (FAT). A FAT is the comprehensive evaluation of equipment or a system conducted at the manufacturer's facility before delivery to ensure it meets the customer's specifications, ideally also involving representatives from the organisation that will be in charge of operation and maintenance. FAT procedures should be carefully designed, with external assistance if needed, to ensure that every specification of the installation's key components is adequately checked.

The overall QI and its ability to withstand extreme weather conditions are also strongly determined by the quality of the component assembly process. In particular, the link between components and the environment in which it is applied is often a weak point in the overall solidity of the structure. It should be ensured that **independent** quality assurance bodies provide dedicated, wide-ranging **verification** of the infrastructure that covers various risks, including electrical safety (where lightning risk has been identified), mechanical resistance (for extreme wind induced risks) and so on.

Consequently, these independent verifications constitute an efficient tool to ensure the overall capacity of the infrastructure to withstand extreme weather conditions.

2.5.2 Operating phase

The operating phase represents both the longest phase of the lifetime of the infrastructure and the time when extreme weather conditions are most damaging. It is therefore crucial to carefully implement all the mitigation measures identified during the conception phase, such as monitoring and preventive maintenance.

Monitoring encompasses all testing and measurement that allows evaluation of the health of the infrastructure and its components. In the case of extreme weather conditions, it includes the measurement of potentially extreme meteorological factors (humidity, temperature, salinity etc.) as well as the performance of the installation. Appropriate alert thresholds and associated measures need to be defined.

Complementary to monitoring, **preventive maintenance** is aimed at repairing and replacing components before the performance and resistance of the installation are significantly affected.

3. Conclusions

Ensuring the resilience of PV and wind plants to extreme weather conditions needs constant attention throughout the lifetime of the installation, from its conception to the end-of-life phase.

Among the steps described for the risk mitigation process, the risk identification is both important and extremely complex. Indeed, all the mitigation measures and cost-benefit analyses are based on the risk assessment of extreme weather events. Risk identification is generally based on a combination of site measurements and the history of the region.

With the intensification of both the probability and intensity of extreme weather events triggered by the effects of global climate change, it is necessary to study in depth multiple scenarios that cover the whole lifetime of the installation. Project developers have limited resources to dedicate to site measurements, often covering parameters that are insufficient to accurately foresee the risk of extreme weather events. Therefore, a range of data sources need to be used to assess the level of risk. For example, IPCC regional scenarios for extreme weather should be carefully analysed and the safety margins in the design of the installation should be appropriately adapted. Other sources of information could be national projections by authorities on the evolution of various risks in the short or medium term.

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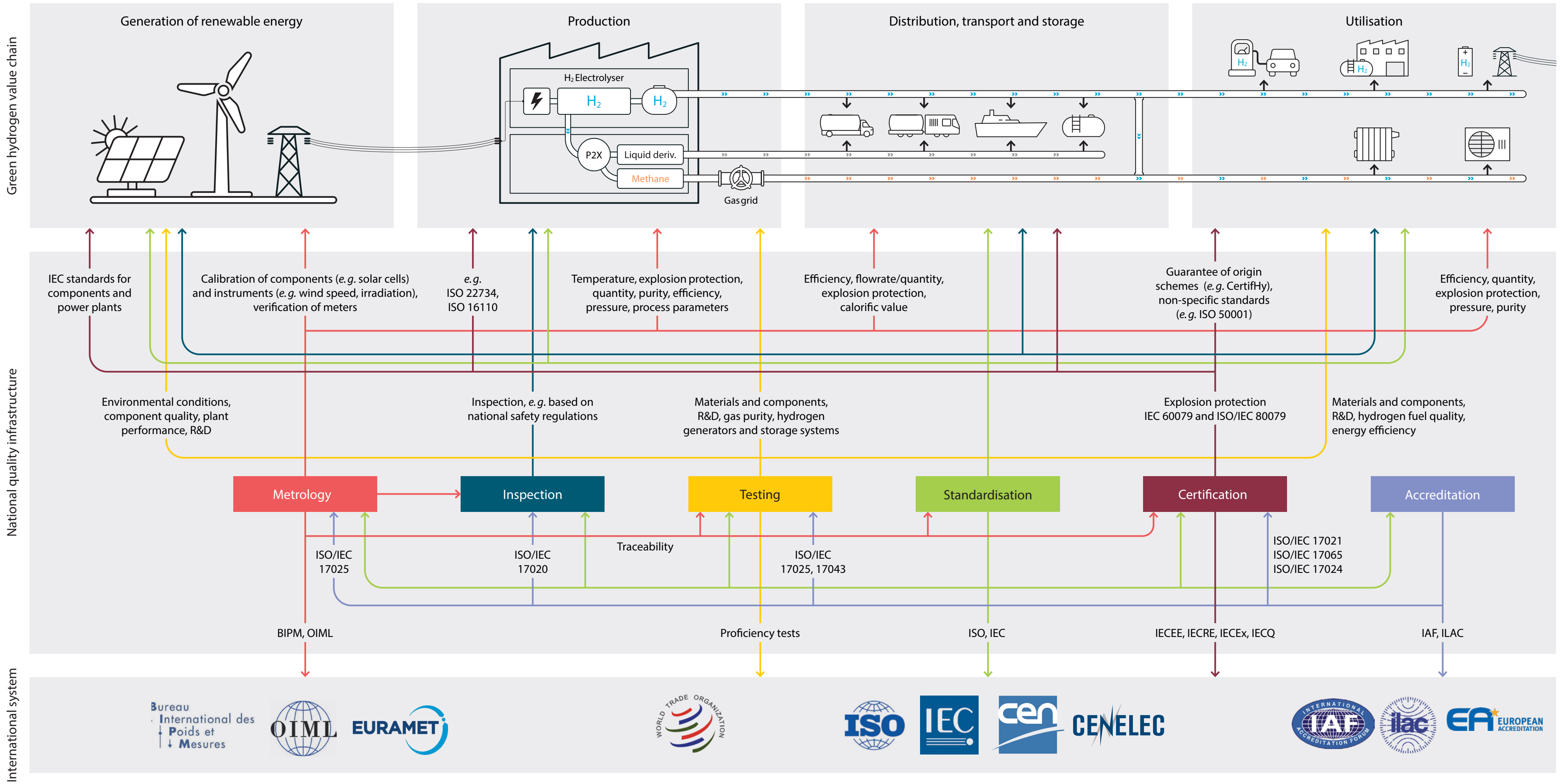
Figure 16 The role of each stakeholder in the QI system



Renewable energy project developers have the leading role regarding the resilience of their installations to extreme weather conditions. They need to ensure that risks are properly assessed, and mitigation measures adequately designed and implemented, both during the construction and the operation phases.

Policy makers have an important role to play in setting the certification, accreditation and standardisation processes at the national level, creating the adequate network of testing laboratories, inspection bodies and metrology institutes to ensure that project developers have the necessary tools at hand to implement an efficient strategy to mitigate extreme weather impacts. Additionally, policy makers could also stipulate the use of relevant standards directly in procurement documents, making their application mandatory.

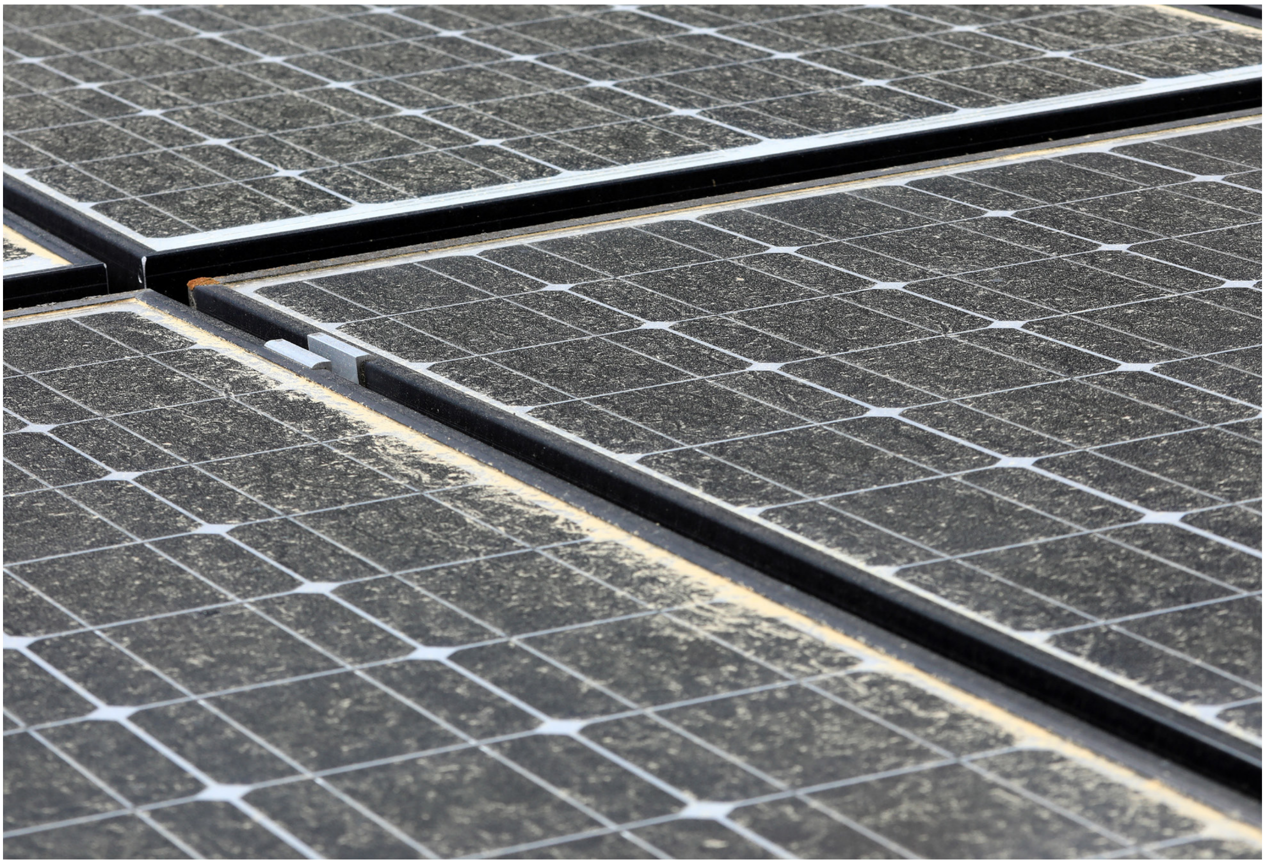
Other stakeholders also have important roles to play. Most notably, component manufacturers should implement the most recent and relevant standards in their products and increase research and development (R&D) efforts to adapt key components to extreme weather conditions and events (see Figure 16 above).

Investors and financial institutions should carefully take extreme weather risks into account in their own investment procedures and due diligence operations, and favour projects that plan the necessary measures to mitigate the risk even though it may require a small reduction in the IRR.

The importance of cost-benefit analysis

For project developers and investors, cost-benefit analysis will ultimately determine the mitigation measures that are ultimately implemented. Different case studies, with conclusions that are included in this report, show that applying extensive mitigation measures systematically gives a higher IRR than applying limited measures. They also show that the degradation of the IRR, due to the cost of these measures, is limited if the comparison is made with a hypothetical situation where no extreme event happens.

Considering the increased likelihood of extreme weather events in the short and medium term due to climate change, cost-benefit analysis can show evidence that adopting extensive mitigating measures is often the most financially attractive option over the lifetime of the installations.



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4. Recommendations

- **Project developers** can mitigate extreme weather damage to their solar PV and wind projects with an appropriate mitigation strategy. This exercise must start with a sound assessment of the risk of extreme weather events and their impact on the installation, and continue with the design and implementation of a mitigation strategy that encompasses measures in (i) the planning and development phase, (ii) the design, engineering and construction phase, and (iii) the operation and maintenance phase. The inclusion of standardised components and procedures favours the effectiveness of the whole mitigation strategy and serves as a baseline from which the dedicated location-based measures can be improved.
- **Standardisation bodies** should increase the minimal requirements in their standards to ensure the resilience of the installations in regard to extreme weather. This is especially relevant considering the effects of climate change on the occurrence and severity of extreme weather conditions, as well as the increasing reliance of power systems on these renewable energy installations.
- **Manufacturers** are encouraged to increase R&D efforts to develop components and procedures that can withstand extreme weather events. Collaboration with standardisation bodies improves the adequacy and future readiness of standards. Additionally, in a context of increased occurrence of extreme weather events, manufacturers that adopt the related standards early can benefit from a competitive advantage while contributing to global resilience.
- **Policy makers** could consider:
  - Developing the necessary QI to ensure that standards are adequately designed, updated and implemented.
  - Evaluating the probability and the severity of extreme weather events on their respective territories, taking into account various scenarios of climate change.
  - Balancing the allocation of extreme weather-related risks in public–private partnerships to foster investment in renewables by the consequent reduction in insurance costs.
  - Including the use of weather-related standards and norms in the various procurement requirements for new renewable energy plants.
- **Investors** can benefit from including extreme weather event risks and the need for mitigation measures, including dedicated insurance, in their financial analysis of projects.

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