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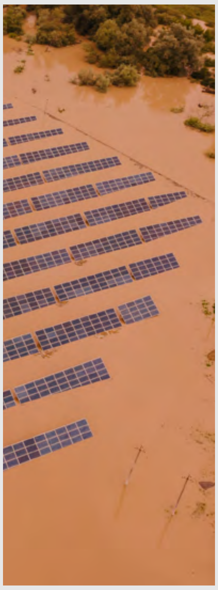

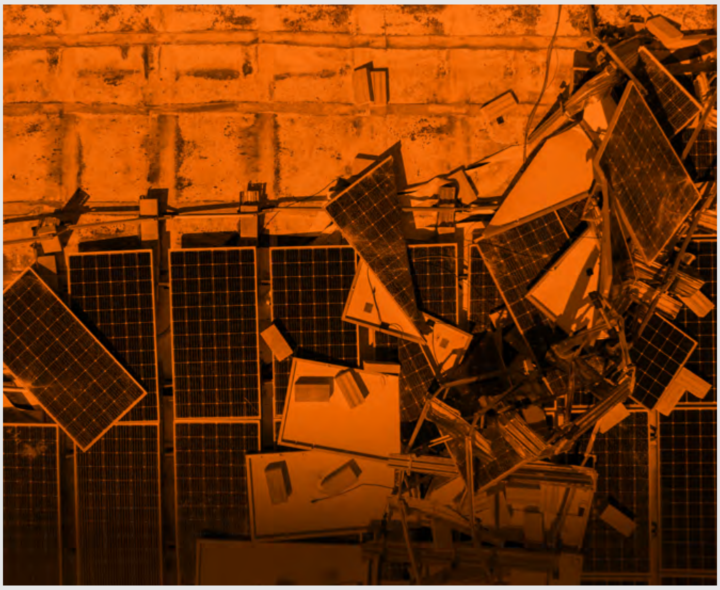


ENHANCING RESILIENCE
CLIMATE-PROOFING POWER INFRASTRUCTURE

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About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international co-operation, a centre of excellence, and a repository of policy, technology, resource, and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity. www.irena.org

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Disclaimer

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ABBREVIATIONS

AI	artificial intelligence
BESS	battery energy storage system
CAES	compressed air energy storage
CBA	cost-benefit analysis
COP	Conference of the Parties (UNFCCC)
DER	distributed energy resources
DOE	Department of Energy
EBRD	European Bank for Reconstruction and Development
ENSO	El Niño Southern Oscillation
ESG	environmental, social and governance
EU	European Union
EV	electric vehicle
FRT	fault ride-through
GW	gigawatt
HILF	high-impact low-frequency
HILP	high-impact low-probability
HVDC	high-voltage direct current
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IPCC	Intergovernmental Panel on Climate Change
km	kilometre
LDC	least developed country
LT-LEDS	long-term low emissions development strategy
MESS	mobile energy storage systems
MREP	Mozambique Renewable Energy Programme
MW	megawatt
NAP	national adaptation plan
NDC	nationally determined contribution
NREL	National Renewable Energy Laboratory
PG&E	Pacific Gas and Electric Company
PPP	public–private partnership
PSH	pumped-storage hydroelectricity
PV	photovoltaic
ROI	return on investment
SAA	Sharm-El-Sheikh Adaptation Agenda
SEFA	Sustainable Energy Africa Fund for Africa
SIDS	small island developing states
SST	sea surface temperatures
TES	thermal energy storage
T&D	transmission and distribution
VRE	variable renewable energy
VSC	voltage source converter

EXECUTIVE SUMMARY

THE NEED FOR POWER SYSTEM RESILIENCE AGAINST EXTREME WEATHER EVENTS

Recent years have seen a surge in the frequency and intensity of extreme weather events globally, causing significant casualties, displacements and economic losses. Global examples vividly illustrate the urgency of bolstering the climate resilience of power systems as a means of mitigating the disruptive impacts of extreme weather events on critical infrastructure. For example, Hurricane Helene's assault on the United States, Mexico and Cuba in September 2024 caused over USD 55 billion of damage, with widespread power outages affecting over 4.7 million people. The frequency, intensity, unpredictability and duration of natural disasters – due to climate change – are projected to keep increasing in the future.

Climate disasters or extreme weather events are considered high-impact low-frequency (HILF) or high-impact low-probability (HILP) events. A HILP event cannot easily be anticipated; it occurs randomly and unexpectedly, and is characterised by having immediate and significant impacts (European Commission, 2022a). Extreme weather events pose a major threat to all segments of the power system and ultimately can cause power outages, *i.e.* the loss of power supply to the end user. These events not only cause power outages and affect assets, but also trigger a chain of consequences, including lost productivity and supply chain collapse. Besides extreme weather events, changes in climate such as prolonged heat waves, cold snaps and droughts also cause harm to power systems.

The escalating impact of climate change has made adaptation a priority in national climate plans (such as nationally determined contributions [NDCs] and long-term low emissions development strategies [LT-LEDS]), particularly for least developed countries (LDCs) and small island developing states (SIDS), which face heightened vulnerability to extreme weather events, with fewer resources to maintain or increase their resilience. However, climate resilience is a global issue. Even regions that are not as adversely affected by events such as hurricanes and storms are often affected by climate change effects such as periods of extreme temperatures. Additionally, vulnerabilities to extreme weather events and climate change are heightened by ageing infrastructure worldwide.

The urgency of addressing the significant impacts that extreme weather events and a changing climate have on power system assets is further increased by the anticipated dependence on power systems: by 2050 electricity is expected to make up more than 52% of total final energy consumption, compared with 23% in 2022, according to IRENA's 1.5°C Scenario (IRENA, 2024).

The current round of NDC updates – NDC 3.0 – as well as NDC implementation plans and National Adaptation Plans (NAPs) present opportunities for countries to make power system resilience against extreme weather events an important adaptation topic, providing a clear message to power system stakeholders that this should be a priority. Enhancing the resilience of power systems is an urgent and critical task. The alternative corrective approach, or "fix it when it breaks", is no longer sufficient in the face of increasing disruptions and their escalating economic and social costs.

BUILDING A RESILIENT POWER SYSTEM

Resilience against extreme climate events focuses on the ability of electrical grids and related infrastructure to withstand, adapt to and recover from extreme events. The different definitions of power system resilience have much in common: they highlight the concept of resilience as the ability of a system to withstand, adapt to, quickly recover from, and learn from extreme events, particularly HILP events, while limiting the duration and severity of the impacts on the system.

Strategic, proactive and long-term power sector plans are needed at a national level to enable and provide the right regulatory and policy environment, and avoid *ad hoc* and autonomous resilience measures at individual asset or utility level. Long-term planning (generation, transmission, distribution) needs to be reformed to consider the impact of a changing climate and the growing prevalence of extreme events.

Novel regulatory frameworks have the potential to stimulate prompt investment in resilience and incentivise utilities to adopt proactive measures. A resilience enhancement framework represents a comprehensive approach to improving resilience at all levels – supporting both the planning for resilience and developing strategies to enable more rapid recovery after disruptive events. A good framework should provide clear steps for assessing risk, analysing vulnerabilities, identifying infrastructure hardening requirements and other resilience measures, and improving information sharing and communication channels.

Mapping vulnerabilities across the power system is key to implementing measures to enhance resilience. However, addressing vulnerabilities needs to be preceded by an exercise to prioritise measures based on the projected climate risks and the cascading impacts of possible asset failure. Socio-economic benefits should also be considered in decision making for power system upgrades.

Resilience enhancement measures are diverse and include targeted infrastructure build-up and operational measures. Utilities identify system vulnerabilities and resilience measures by weighing costs and benefits. Resilience metrics help identify the value of resilience measures. Metrics such as loss of load expectation or loss of service, and economic losses to the community and utility can be weighed against the cost of resilience measures to identify the right measures to be implemented.

Distributed energy resources (DERs) are doubly beneficial as they not only help to increase the share of renewables in the system, but also provide resilience in case of extreme weather events. They can also improve grid reliability and reduce the risk of outages. Grid forming inverter-based resources, able to operate in standalone mode, should also be taken into consideration to increase resilience and allow the continuation of service during or after extreme events. The capability of DERs and grid-forming inverter-based resources can be enhanced by the inclusion of storage systems. Storage, in addition to improving overall system resilience,

helps mitigate the impacts of extreme events. Modular storage, especially batteries, offers the flexibility of deployment at different voltage levels and locations, and restoration of critical systems after major outages through black-start capabilities.

Leveraging the advanced capabilities of smart meters to manage DERs brings many advantages, such as being able to anticipate power demand, supply and grid conditions. The use of weather data can also ensure subsequent actions, including emergency restoration system readiness and efforts, are prepared in advance to mitigate the effects of these events. Smart meters, in addition to aiding optimal energy utilisation and grid management, can also help diagnose faults and aid the utility in responding quickly or restoring service.

The extreme vulnerability of power systems to climatic events has encouraged several countries to adopt a path of evaluating and enhancing resilience through a diverse set of measures. It is also essential that countries' efforts are shared globally through knowledge sharing and peer-to-peer learning opportunities. As resilience enhancement cannot be successfully achieved in silos, there is a clear need for effective stakeholder engagement and cross-sectoral collaboration to resolve sectoral interdependence. Establishing clear institutional roles and responsibilities within organisations will promote accountability and foster a proactive approach to resilience enhancement. Engaging consumers is also a key aspect here, as they need to be involved from the very beginning. This is especially the case for installing microgrids, where it is crucial for them to understand its benefits and how they can support the grid. Skill development is again a crucial aspect, where we need to create a workforce capable of handling the technological advancements being implemented and thereby support a rapid recovery.

Finally, the implementation of resilience measures requires the right financial mechanisms to support them. A comprehensive risk assessment followed by a systemic analysis can provide crucial information on the impacts of climatic events. These need to be followed by an aligned market, adaptive standards and proactive investment. This report highlights several examples of innovative financing mechanisms for resilience measures, such as grants and concessional financing, market-based risk management, private–public partnerships, green and resilience-themed debt instruments and community-driven solutions.

This report demonstrates the impacts that extreme events can have on power systems and the vulnerabilities of their different segments. It discusses proactive strategies and a diverse set of solutions that can enable resilience enhancement, including technology, policy making and financial mechanisms, including examples from a geographically diverse set of countries.

ENHANCING RESILIENCE
10 ACTIONS TO CLIMATE-PROOF POWER INFRASTRUCTURE

ACTION 1 IDENTIFY EXTREME WEATHER EVENTS AND SYSTEM VULNERABILITIES

Conduct detailed assessments with the support of accurate weather and climate modelling to identify likelihood of extreme weather events and to understand how these impact generation, transmission and distribution assets. Map the most critical vulnerabilities.

ACTION 2 IDENTIFY RESILIENCE-ENHANCING MEASURES

Prioritise most crucial vulnerabilities across the different power system assets and assess possible resilience enhancement measures that will mitigate these critical vulnerabilities.

ACTION 3 PERFORM COST-BENEFIT ANALYSIS

Conduct a cost-benefit analysis comparing the long-term economic impact of proactive resilience investments versus the consequences of repeated weather-related outages and repairs. Prioritise resilience measures based on cost vs. benefit.

ACTION 4 ADOPT POLICIES FOR PROACTIVE RESILIENCE

Develop strategic national plans and policies targeting the power sector that incentivise the adoption of proactive resilience measures, preventative investments and the integration of resilience into power system design and operations.

ACTION 5 SECURE INVESTMENT FOR RESILIENCE

Evaluate the return on investment for resilience upgrades. Quantify how targeted spending will reduce losses over time, aiding decision makers in prioritising investments. Explore innovative funding models, highlighting replicable successes within comparable regions.

ACTION 6 HARDEN INFRASTRUCTURE

Protect critical assets with upgrades tailored to local climate threats (flood defences, storm hardening, *etc.*). Selected solutions must match the specific vulnerabilities identified.

ACTION 7 FOSTER DISTRIBUTED ENERGY RESOURCES

Distributed energy (solar, microgrids) lessens reliance on the centralised grid and safeguards critical services. Deploy diverse energy storage options based on local needs. Storage provides backup power, balances supply and demand, and unlocks new revenue streams.

ACTION 8 INTEGRATE GRID-FORMING RENEWABLES

Integrate renewables that provide grid-forming capability as their share of power generation increases. This enhances reliability during disruption and reduces dependence on fossil fuel supply chains.

ACTION 9 IMPLEMENT SMART GRID SOLUTIONS

Predictive analytics, forecasting and smart monitoring enable proactive responses to weather risks. This minimises outages and optimises existing infrastructure, avoiding costly buildouts.

ACTION 10 FACILITATE KNOWLEDGE SHARING

Develop regular capacity-building training for utility staff. Create open platforms to share resilience strategies, case studies and policy frameworks and improve community engagement and communication with power system stakeholders. Encourage R&D by government, private sector and academic institutions. South-South knowledge exchange accelerates learning and adaptation within similar contexts.

INTRODUCTION: ACCELERATING POWER SYSTEM RESILIENCE

In recent decades the effects of climate change on humanity and the earth have become more frequent and severe. Under the Paris Agreement, 197 countries committed to limiting global warming to below 2°C above pre-industrial levels by submitting nationally determined contributions (NDCs) every five years. These documents outline targets and measures to reduce greenhouse gas emissions and strengthen climate adaptation.

Although mitigation has dominated climate discussions, the increasing frequency and severity of extreme weather events due to climate change has shifted the focus towards adaptation. The most recent Conferences of the Parties (COPs) provide evidence of this, where climate-related loss and damage as well as mobilisation of private finance for adaptation and resilience were the centre of important discussions. Despite the progress that has been made, further action is needed to support countries in their fight against the impacts of climate events, especially for least developed countries (LDCs) and small island developing states (SIDS). These countries face heightened vulnerability to extreme weather events, with fewer resources to maintain or increase their resilience to such events. The current round of NDC updates – NDC 3.0 – and upcoming NDC implementation plans offer crucial opportunities for countries to prioritise adaptation planning.

The urgency of addressing the significant impacts that extreme weather events and climate change have on power system assets, often leading to power outages, is reinforced by the world's predicted reliance on power systems. According to IRENA's 1.5°C Scenario, by 2050 electricity will account for more than 52% of total final energy consumption, while in 2022 its share was only 23% (IRENA, 2024). This is why power systems must be climate resilient. Furthermore, with renewable energy having a more prominent role in the power sector, the list of power sector assets is supplemented by storage technologies and other enablers that support the incorporation of variable renewable generation units such as solar PV and wind. Understanding the role of these technologies as enablers and enhancers of power system resilience becomes very important as well.

Resilience is a broad concept that can be applied to the most diverse fields. Although no unanimous definition exists, it is usually described as a given system's level of capability to respond to different stages following a hazardous event. The power sector has long been incorporating resilience into its systems, including both physical and cyber resilience. However, these practices must extend to climate resilience. Although some regions, such as hurricane-prone areas, have already been dealing with this issue for a long time, climate-resilient power systems must become a global topic.

The purpose of this brief is to highlight the importance of enhancing the resilience of power systems to climate change and provide guidance and recommendations for policy makers to develop frameworks with this same objective. The contents of this brief are based on the most recent literature.

The report is organised as follows:

- Chapter 1 addresses the increasing threat of extreme weather events caused by climate change to power system assets and maps vulnerabilities across the power system.
- Chapter 2 presents the definition of resilience and highlights solutions to enhance power system resilience to climate change.
- Chapter 3 describes technological solutions and considerations for enhancing the climate resilience of power systems, including renewables, energy storage and smart grids.
- Chapter 4 focuses on the role of collaboration, risk mitigation and innovative financing when building climate-resilient power systems.

1.

MAPPING SYSTEMIC RISK: THE CASCADING ECONOMIC IMPACT OF POWER SYSTEM VULNERABILITY

1.1 WEATHER EXTREMES: THE NEW NORMAL FOR GRIDS

Recent years have seen a surge in the frequency and intensity of extreme weather events globally, causing significant casualties, displacement and economic losses. The number of extreme weather events[1] has quadrupled over a 50-year period, between the periods 1970-1979 and 2000-2019. Additionally, economic losses due to these events in the same period have increased sevenfold (WMO, 2021). In 2024, the ten most costly climate events resulted in over USD 228 billion in losses and 2 000 fatalities (Christian Aid, 2024). EU countries experienced EUR 738 billion in economic losses of assets due to climate-related events from 1980 to 2023, and more than EUR 162 billion between 2021 and 2023 (European Environment Agency, 2024). In the SIDS, sea level rise, hurricanes and other extreme weather events are driving the displacement of populations, while high temperatures and ocean acidification threaten marine ecosystems that are the cornerstones of their economies.

The World Economic Forum's *Global Risks Report 2024* (WEF, 2024) identifies extreme weather events as the second most severe short-term global risk. Furthermore, this risk was ranked top in likely most severe impacts in the next decade.

Global examples vividly illustrate the urgency of bolstering the climate resilience of power systems as a means of mitigating the disruptive impacts of extreme weather events on critical infrastructure. For instance, Hurricane Helene's assault on the United States, Mexico and Cuba in September 2024 caused over USD 55 billion of damage, with widespread power outages affecting over 4.7 million people (Christian Aid, 2024). Hurricane Maria in 2017 resulted in huge negative impacts in Dominica, with estimations of loss and damage at USD 380 million and USD 931 million, respectively, which corresponds to more than double the 2016 GDP of the country (Government of the Commonwealth of Dominica, 2017). Cyclone Idai wreaked

[1] *The extreme weather events and respective numbers mentioned here refer to the Meteorological, Climatological and Hydrological disaster subgroups as classified by EM-DAT (the international disaster database), which include storms, extreme temperatures, droughts, wildfires, floods and landslides.*

havoc on Mozambique in 2019, leaving over 1.8 million people without electricity. Such disruptions not only jeopardise public safety and welfare, but also inflict substantial economic losses. It is important to note that, besides extreme weather events, changes in climate such as prolonged heat waves, cold snaps and droughts also cause harm to power systems due to these changes not being accounted for in their operational design. The Winter Storm Uri in 2021 caused more than USD 195 billion of damage in Texas, United States (City of Austin, n.d.). All these instances underscore the imperative of taking proactive measures to enhance the resilience of power systems against extreme weather events, encompassing infrastructure reinforcement, adaptive planning and community resilience-building initiatives. Embracing renewable energy integration, grid modernisation and decentralised energy solutions can strengthen power systems against climatic perturbations, fostering sustainable development and climate resilience simultaneously.

The escalating impact of climate change, as exemplified here, has made adaptation a priority in national climate plans (such as nationally determined contributions [NDCs] and long-term low emissions development strategies [LT-LEDS]), particularly for least developed countries (LDCs) and small island developing states (SIDS), which face heightened vulnerability to extreme weather events, with fewer resources to maintain or increase their resilience to such events. However, climate resilience is a global issue. Even regions that are not as affected by events like hurricanes and storms are impacted by climate change effects such as periods of extreme temperatures (*e.g.* heatwaves). Additionally, vulnerability to extreme weather events and climate change is heightened by ageing infrastructure worldwide.

BOX 1 The link between NDCs and NAPs

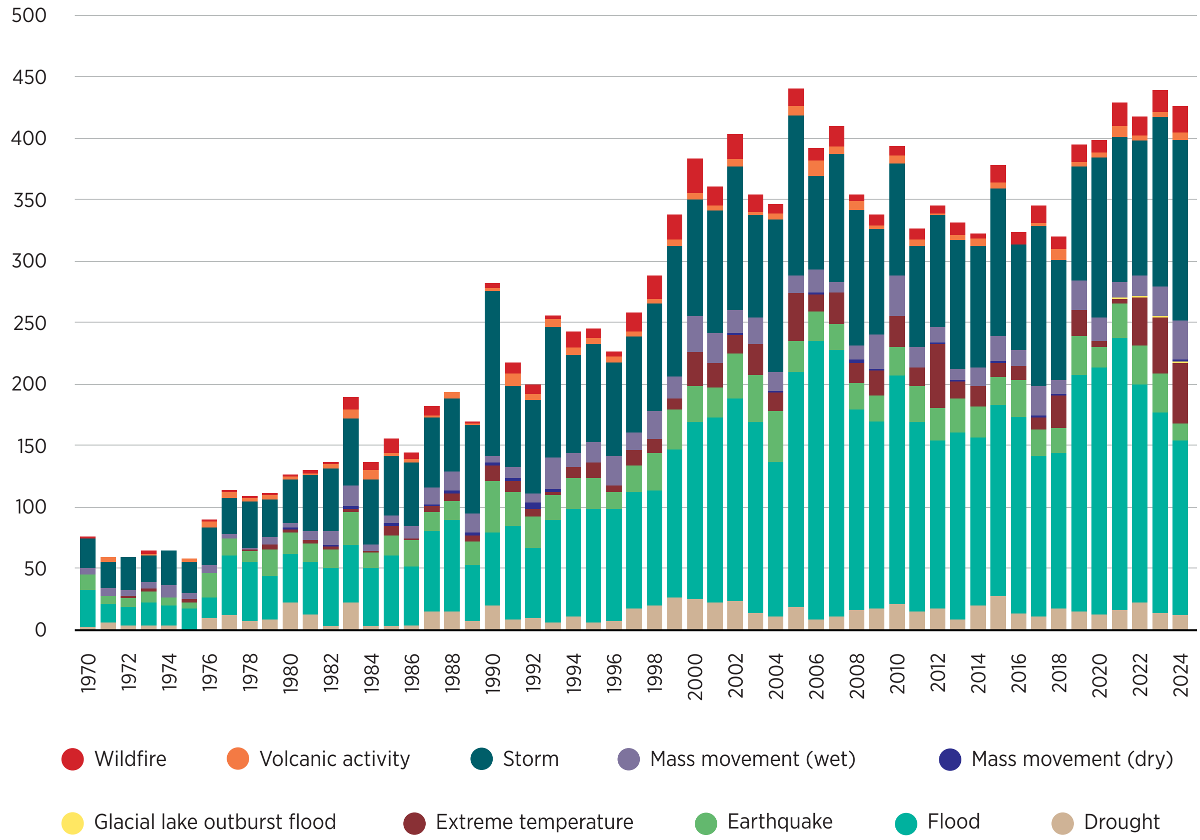
Nationally determined contributions (NDCs) are the backbone of the Paris Agreement. They are climate plans comprising the mitigation and adaptation targets and measures that a party is willing to implement to meet the agreement's objectives.

National adaptation plans (NAPs) are also a key instrument for parties under the Paris Agreement. They are detailed plans that support the adaptation component of NDCs and provide a clear framework for building resilience. The first Global Stocktake of the Paris Agreement highlighted that 51 parties had submitted NAPs and 62 had submitted adaptation communications (as of 13 December 2023). The first Global Stocktake also recognised the increasing efforts of parties towards adaptation planning and implementation – with the objective of enhancing adaptive capacity, strengthening resilience and reducing vulnerability (UNFCCC, 2023).

The current round of NDC updates – NDC 3.0 – and respective NDC implementation plans present an opportunity for countries to include power system resilience as an important adaptation topic, which can be further addressed under the country's NAP. 73% of Parties that have already submitted an update to their NDC (between 1 January 2024 and 30 September 2025) included a distinct adaptation component in their NDCs (UNFCCC, 2025).

Some international initiatives, such as the Sharm-El-Sheikh Adaptation Agenda (SAA) launched at COP27, are supporting state and non-state actors' adaptation efforts. The SAA aims to rally global action on 30 adaptation outcomes that are needed to address the adaptation gap and achieve a resilient world by 2030. It includes a Taskforce for Energy, which is co-led by IRENA and contains a focus on energy infrastructure and power system climate resilience (Climate Champions, 2024).

Figure 1 Global reported natural disasters by type, 1970–2024



Based on: EM-DAT, CRED, UCL, 2025).

Figure 1 shows an increase in the global annual number of extreme weather events (or natural disasters) in recent decades. Many databases on natural disasters show how this number has been increasing significantly. These include Munich Re's NatCatSERVICE, EM-DAT, Swiss Re Institute's SIGMA, GLIDEnumber and BD Catnat.

The frequency, intensity, unpredictability and duration of natural disasters – due to climate change – are projected to keep increasing in the future (Ebinger and Vergara, 2011; Mideksa and Kallbekken, 2010; Panteli and Mancarella, 2015; Schaeffer *et al.*, 2012) and are expected to be visible in:

- More frequent and severe storm events and wildfires.
- Increasing air and water temperatures.
- Uncertain precipitation patterns and river flows.
- Sea level rise.
- Changes in wind and solar patterns and intensities, making future availability and prediction of renewable resources more uncertain.

Climate disasters or extreme weather events are considered high-impact low-frequency (HILF) or high-impact low-probability (HILP) events. A HILP event cannot be easily anticipated, occurs randomly and unexpectedly, and is characterised by having immediate and significant impacts (European Commission, 2022b). A HILP event has the potential to impact grid operation and includes events such as hurricanes, tornadoes and coastal flooding (Cicilio, Phylicia *et al.*, 2021; Veeramany *et al.*, 2015). Although some natural disasters that are classified as HILP events, such as earthquakes, may not be directly related to climate and extreme weather, and thus not the focus of this report, they still have impacts on the power system and should be accounted for when implementing resilience measures. Table 1 presents different categories of extreme weather events, with examples, whilst Box 2 provides a description of the different stages of the El Nino phenomenon prevalent in the Pacific Ocean.

Table 1 Classification of HILP extreme weather events and examples

HILP	DESCRIPTION	IMPACT	EXAMPLE
Flood	Inundation of land areas due to heavy rainfall, river overflow or coastal storm surge.	Can submerge critical infrastructure, cause short circuits and compromise restoration efforts, creating long-lasting outages.	Rio Grande do Sul Floods, Brazil (2024): Heavy rainfall and river overflow led to widespread flooding, damaging power plants, substations, transmission lines and transformers, causing power outages for hundreds of thousands of homes.
Hurricane	Large rotating storm systems with high winds, heavy rainfall and potential for storm surge.	Can inflict severe damage on coastal infrastructure, compromise power lines, trigger flooding and cause extended power outages.	Hurricane Dorian, The Bahamas (2019): Severe flooding and wind caused damage to several power generation plants and T&D systems, including lines and substations, suffered from wind damage, leaving customers without power.
Ice storm/ hailstorm	Accumulation of freezing rain leading to heavy ice build-up on power lines and structures.	Can cause power line breakage, toppling of transmission towers and widespread outages.	Winter Storm Uri, Texas (2021): A severe ice storm coated power lines with ice, leading to widespread outages across Texas, leaving millions without heat or power during a cold snap.
Tornadoes/ regional storms	Violent rotating columns of air accompanied by destructive winds, often localised in geographic scope.	Can demolish power lines, substations and other grid infrastructure causing outages.	Tornado outbreak, Kentucky, Illinois, Arkansas, Missouri, U.S. (December 2021): A series of tornadoes ripped through several states, causing widespread damage to power lines and infrastructure, leaving hundreds of thousands without power.
Wildfire	Uncontrolled fires in vegetated areas, often fuelled by dry weather conditions.	Can destroy power lines, damage critical infrastructure and hinder access for restoration efforts, leading to extended blackouts.	Portugal wildfires (2017): Wildfires spread across the central and northern regions of the country, damaging power lines and critical infrastructure, leaving many without electricity.
Drought/ heatwaves	Prolonged periods of abnormally low rainfall or extreme heat.	Can strain power system capacity, limit water availability for cooling power plants and potentially cause cascading failures due to overload.	India and Pakistan (2022): Heatwave caused an abnormal increase in power demand, which led to rolling blackouts and long power outages.

Source: (Christian Aid, 2022, 2024; McCurry and Nethercutt, 2022; San-Miguel-Ayanz *et al.*, 2020; NOAA, n.d.).
Notes: This is a non-exhaustive list. T&D = transmission and distribution.

BOX 2 El Niño Southern Oscillation

The El Niño Southern Oscillation (ENSO) is a climate phenomenon characterised by sea surface temperature variability in the central and eastern tropical Pacific Ocean, being the dominant phenomenon to impact weather conditions in this region, and the cause of extreme events such as heavy rains, storms, floods, landslides, heat and cold waves and extreme sea level rise. Although ENSO is not a consequence of climate change, there is growing evidence that global warming has intensified extreme weather events induced by this phenomenon (IPCC, 2022).

ENSO has three phases: El Niño, La Niña and Neutral, which can be summarily described as follows (L'Heureux, 2014):

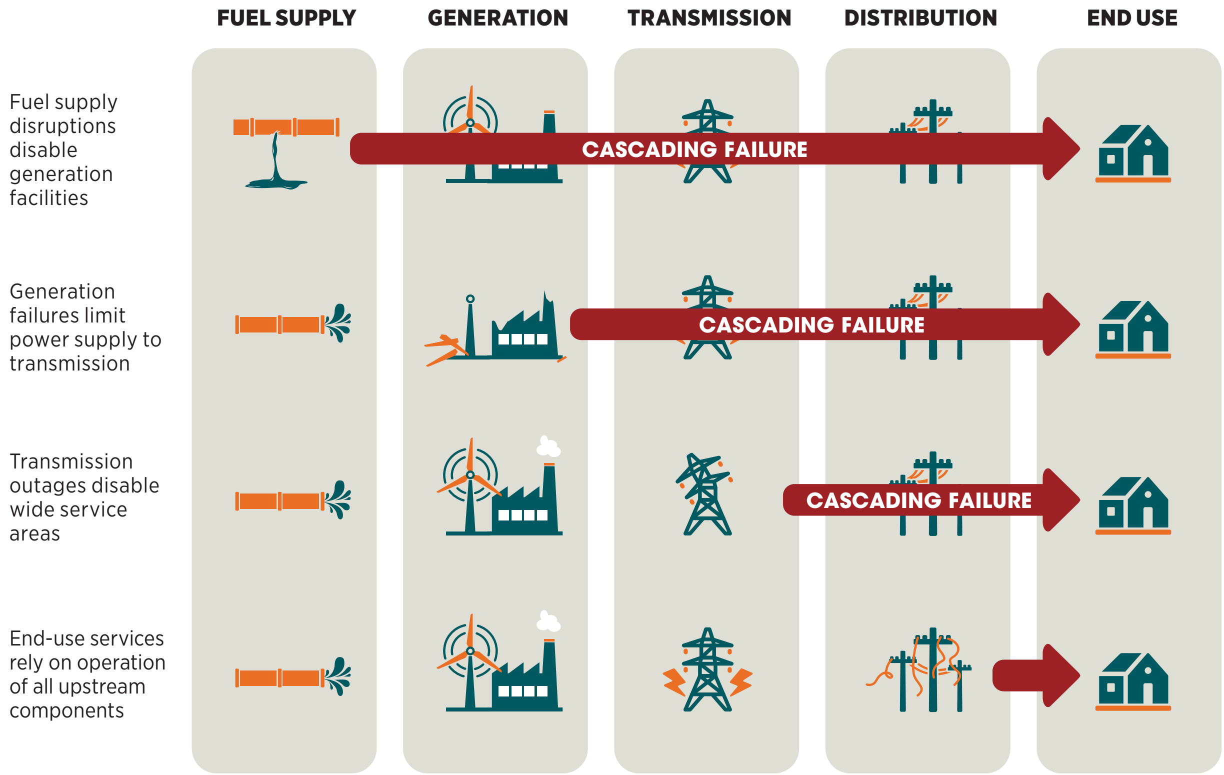
- **El Niño** involves warming sea surface temperatures (SST) in the central and eastern tropical Pacific Ocean, increased rainfall in this region and reduced rainfall in Indonesia, and weakening of the normal easterly winds (from east to west).
- **La Niña** is the opposite, with cooling SST, stronger easterly winds, increased rainfall in Indonesia, and reduced rainfall in the central Pacific Ocean.
- The **Neutral** phase is when SSTs are close to average.

Reports by the Intergovernmental Panel on Climate Change (IPCC) state some of the potential impacts of climate change on this phenomenon, such as that it is very likely that rainfall variability related to ENSO will be amplified significantly by the second half of this century under different IPCC scenarios (IPCC, 2022). This variability and resulting extreme weather events would have significant implications for the power systems of the affected regions.

For example, in 2015-2016 El Niño induced the second strongest drought in the history of Colombia. Colombia is highly dependent on hydropower and, therefore, its power system suffered major impacts from ENSO, including significantly reduced water levels in dams, increased cooling and refrigeration demand and a fire incident at the largest hydroelectric plant in the country. In April 2016, a power shortage of 200 megawatts (MW) occurred (Sustainable Water & Energy Solutions Network, n.d.).

Extreme weather events pose a major threat to all segments of the power system and can ultimately cause power outages, *i.e.* the loss of power supply to end users. Figure 2 highlights the cascading impacts of failures on the different components of the power system. Any disruption to one segment of the power system – whether it is fuel supply, generation, transmission or distribution – can have cascading effects in the other segments downstream, ultimately impacting end-use consumers as well.

Figure 2 Grid architecture and vulnerabilities associated with each component of the grid value chain



Based on: (Dyson and Li, 2020).

These events not only cause power outages and affect assets, but also trigger a chain reaction of consequences, including lost productivity and supply chain collapse. For instance, Hurricane Katrina resulted in significant economic losses in the affected regions, namely the Caribbean and the United States (Swiss Re Institute, 2025). Similarly, the drought that affected multiple countries in Southern Africa in 2024 resulted in critical shortages of food and reduced harvests, as well as reduced access to clean water and higher risk of waterborne diseases (Christian Aid, 2024). Hurricane Sandy led to widespread disruption to supply chains, causing delays and loss of productivity in the United States (Yuzuka Kashiwagi *et al.*, 2021). These examples underscore the urgency of comprehensive resilience strategies and investment in climate-resilient infrastructure to mitigate the multifaceted challenges posed by extreme weather events.

1.2 MAPPING VULNERABILITIES: WHERE THE GRID BREAKS DOWN

All functions of modern society rely on electricity, meaning that power system failure affects transport systems, industry, healthcare, water supply, education and communication. Interruption of the power supply and other impacts on the power system result in substantial economic losses and hinder socio-economic development. In many countries, especially in LDCs and SIDS, the challenge of maintaining and/or enhancing power system resilience is heightened by the presence of ageing infrastructure and their limited capacity and resources to effectively plan for and manage natural disaster risks.

Mapping vulnerabilities across the power system is key to being able to implement measures to enhance resilience. Different events affect the various assets differently. However, addressing vulnerabilities needs to be preceded by an exercise to prioritise measures based on the projected risks of extreme weather events, and the cascading impacts of potential asset failure. Given that capital is limited and not all upgrades and enhancement measures have the same impact on increasing power system resilience, decision making on power system upgrades should be driven by an analysis of the return on investment (ROI) and socio-economic benefits of addressing power system vulnerabilities with these upgrades.

This section explores how extreme weather events can affect different segments of the power system, providing clear examples.

1.2.1 Generation facilities

The impact of natural hazards or extreme weather events on generation facilities is dependent on the type of facility and also its geographical location. Fossil fuel-fired power plants (conventional power plants), for example, and even diesel backup generators, are highly dependent on the transport of fuel, which consequently is a common point of failure. Oil and gas supply chains are highly vulnerable to extreme events, potentially exacerbated by the inability to store fuel on site (Schweikert *et al.*, 2019). Fuel storage facilities can also suffer from extreme weather events, depending on geographical location. For example, flooding of storage facilities can lead to leaks and spills of crude oil and refined products. Changes in climate, such as increasing ambient temperatures, can lead to degradation of stored fuel quality. Below are two examples where the operation of conventional power plants was affected by vulnerabilities in the fuel supply chain and over-reliance on these types of power plants.

Ports were closed for 11 days in Puerto Rico in 2017 following Hurricanes Irma and Maria due to damage to infrastructure, resulting in a lack of imports which translated into estimated losses of 1.2 million barrels of oil per day. This disruption not only affected the immediate availability of fuel for power generation, but also highlighted the critical dependence of conventional power plants on the fuel supply chain. It is important to note that, in this case, the major generation plants relied on imported fuel (Schweikert *et al.*, 2019).

In Indonesia, strong winds disrupted the sea-shipped coal supply, often leading to reductions in power generation and even shutdowns. In 2007 a coal-fired power plant had to be shut down for days and was substituted by costlier oil-fired power generation, leading to additional costs of USD 1.6 million per day (Handayani *et al.*, 2019).

Renewable generation assets are also affected by weather events such as extreme temperatures, storms and variable precipitation. Hydropower specifically is affected by low water availability, and this impact is greater in plants with lower or no water storage capacity, such as “run of the river” facilities (EPRI, 2023).

In 2021, freezing temperatures in Texas affected gas power plants, which suffered fuel shortages and freezing of equipment, wind farms, which suffered from icing over of wind turbine blades, and nuclear power plants, which went offline due to frozen water pumps (Busby, 2021). The grid operator, as a preventive action, had to cut off supply to customers, as demand could exacerbate the impending blackout. This was also exacerbated by limited interconnections, which restricted the importation of electricity, and by the fact that some plants were scheduled for maintenance (University of Texas, 2021). The failure to weatherise power infrastructure, coupled with grid design limitations and inadequate maintenance scheduling, resulted in widespread power outages and direct and indirect economic losses estimated at USD 80-130 billion (Golding *et al.*, 2021). This highlights the importance of proactive measures to enhance resilience, not only to mitigate immediate impacts, but also to safeguard against long-term economic and societal disruption.

BOX 3 Quality infrastructure for renewables facing extreme weather

Power systems are becoming more dependent on the capability of PV and wind generation assets to withstand extreme weather events.

IRENA has produced an analysis on mitigating the impact of extreme weather conditions on them, which emphasises the importance of robust quality infrastructure. Accurate risk assessments and mitigation strategies need the involvement of all the stakeholders in the value chain, from policy makers and standardisation bodies, to manufacturers, project developers and investors.

Quality Infrastructure is not just about technical performance, it is also about financial security; systems built to be resilient experience higher yields, fewer outages, lower maintenance costs and greater investor confidence. By embedding quality infrastructure across the life cycle of renewable projects, from planning and design to construction and operation, countries can significantly reduce weather-related risks.

Read IRENA's (2025) report, *Quality infrastructure for renewables facing extreme weather*, for more information.

Source: (IRENA, 2025).

1.2.2 Transmission and distribution assets

T&D systems are the most susceptible and frequently affected component of the electricity system. The damage to T&D towers and overhead lines are usually the most visible (Handayani *et al.*, 2019; Nicolas *et al.*, 2019; Schweikert *et al.*, 2019). Consequently, a large majority of outages are caused by T&D system failures, with storm events being the primary cause of damage, whether from flying debris, falling trees or the combination of high wind speeds and ice causing the lines to break.

The lifespan of these assets extends over decades and installing new assets can take several years. T&D systems typically have a longer restoration time compared to generation facilities, since they usually depend on other infrastructure, such as on manufacturing facilities working on custom production requests and transport to bring equipment and material for repairs to each site. Structures designed for today's seasonal patterns have to cope with weather changes that may forthcoming in several years' time.

- Between 1992 and 2010, around 78% of major disruptions to the power distribution system in the United States were caused by weather-related events (Campbell, 2012) and 90% of faults were due to natural disasters affecting distribution systems (Najafi *et al.*, 2019). For instance, the 2017 Hurricane Maria in Puerto Rico resulted in extensive damage to T&D infrastructure, with costs estimated at USD 90 billion (Nishant Kishore, M.P.H. *et al.*, 2018). Inaction in bolstering T&D resilience rendered the consequences devastating, amplifying economic losses and hindering recovery efforts.
- Hurricane Irma, with wind speeds up to 360 km/h, hit the northern Caribbean islands in 2017 and destroyed almost 90% of the infrastructure in Antigua and Barbuda, including roads, electrical systems, communications and water systems. An estimated 50% of the population lost their homes. This was followed by Hurricane Maria, which affected the island of Antigua. Total infrastructure damage was estimated to be around USD 136.1 million, with a recovery needs assessment of around USD 8.2 million (ACP-EU, 2018). The event caused damage to generation and distribution assets and loss of transmission lines. Undergrounding the distribution system and a much more resilient renewable energy component were recommended.

- Cyclone Idai in 2019 significantly damaged distribution networks, including damage to substations and broken poles bringing down power lines in Mozambique. Further information on this case study can be found in Section 4.1.

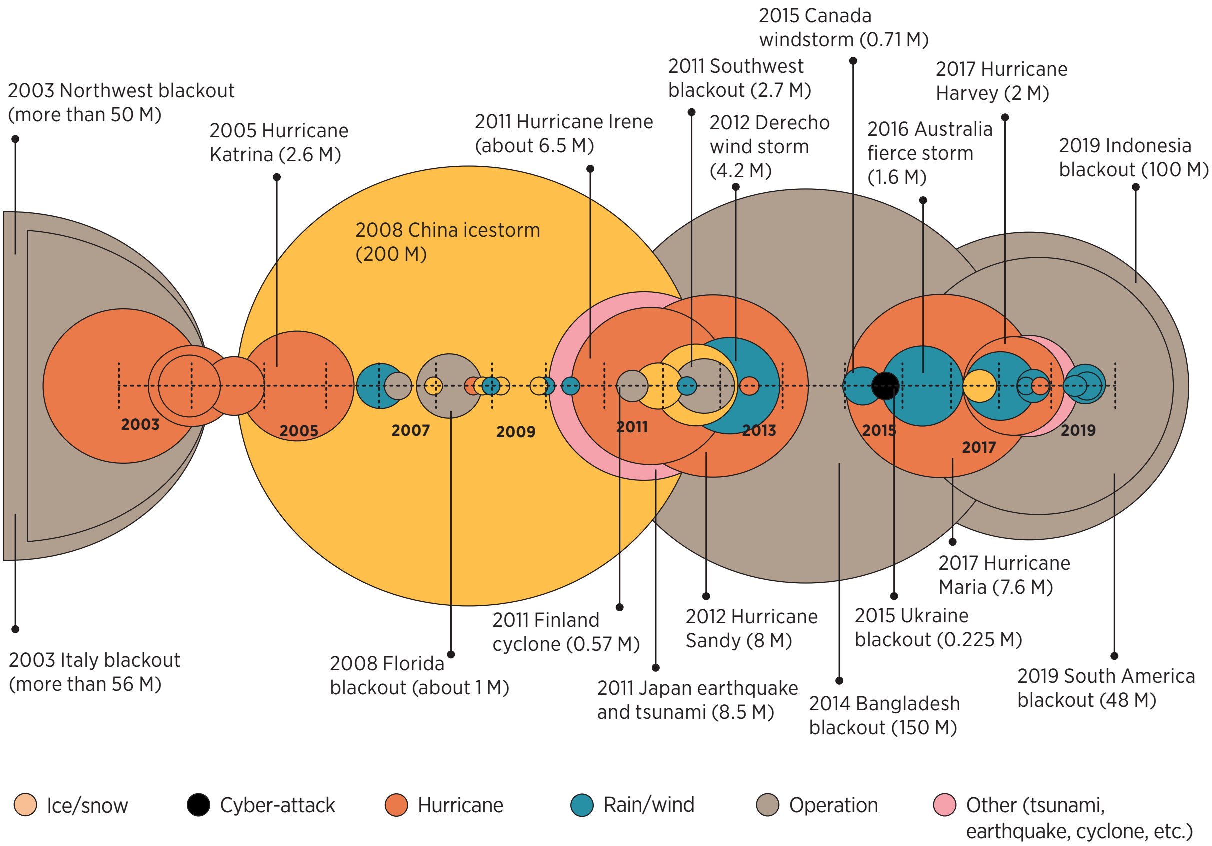
These examples underscore the imperative for proactive measures to fortify T&D infrastructure against the mounting threats posed by extreme weather events.

1.2.3 Consumers

The vulnerabilities of the power sector translate into vulnerabilities in critical infrastructure such as communication, healthcare and other emergency services, which have a significant impact on end users. Figure 3 presents several examples of extreme events and the corresponding number of customers without power.

Power systems' vulnerabilities to natural hazards, their economy-wide impacts and the fact that these impacts are expected to increase in the future, reveal the increasing need for more resilient power systems.

Figure 3 Examples of extreme events, and respective number of customers without power (millions)



Source: (Bhusal *et al.*, 2020).

Notes: Size of circle denotes number of customers affected. Labels identify selected events. M = million.

The impact of climate change is also seen in the extreme hot and cold temperatures increasing the need for cooling and heating, respectively. Since much heating and cooling equipment relies on electricity, peak demand sees a commensurate increase, which requires a corresponding increase in electricity generation (ONRL, 2019). Higher electricity demand caused by extreme temperatures for long periods of time may result in stress on the grid and can lead to system failure, combined with the impacts that these temperatures have on other components of the system: for example, high temperatures result in reduced wind generation, reduced solar PV output, reduced capacity and efficiency of gas turbines, increased losses in transmission lines and increased failure in distribution assets.

1.3 ANTICIPATING THE FUTURE: CLIMATE AND WEATHER DATA MODELLING FOR GRID PLANNING

One of the crucial steps in building resilience and finding solutions is to identify the type of threats the system may be subject to – including threats caused by weather and man-made threats. Current grid planning practices use climate conditions to specify designs, but projected climate variations will introduce challenges to the physical infrastructure and operation of the grid. Climate models and weather forecasts are interrelated, but with some important differences. Climate models refer to the long term, in the range of months to years, whereas weather forecasts are applicable in the short term, varying from a few days up to two weeks. Climate change impact can be on a small scale, affecting only a few assets, or lead to cascading events. Precipitation and temperature variations can affect the efficiency and operation of assets, cause physical damage and impact demand profiles. This affects the way grids are planned, designed and operated.

Climate and weather data allow us to evaluate the risks associated with variations in the environment and natural resource conditions. Effective solar and wind siting and effective integration of these renewable resources are possible with climate data integration. Variations in individual climate variables, such as heat and drought, can act together to affect power system operations. With higher shares of renewable such as wind and solar being added to the system, more clarity on the climate variables impacting these sources of generation are becoming increasingly important. Solar power generation is dependent on several factors, in particular temperature, wind speed and irradiation levels, which in turn depend on the geographical location. Changes in solar irradiation, cloud cover, wind speed and precipitation affect power production from solar panels. Higher temperatures arising from climate change or wildfires could affect the efficiency of the panel and therefore its power generation capacity. Hydropower generation depends solely on water for its fuel supply, which makes it highly vulnerable to changes in water availability. The impact of rising temperatures, leading to higher demand for water and rivers drying up, is going to be more impactful in regions with a high share of hydropower generation, such as Africa.

Historical data serve as a cornerstone for understanding past occurrences, yet their limitations in forecasting future climatic hazards and extreme weather events are evident. Improving the overall resilience and reliability of the power system needs the latest information on seasonal weather variations.

Emphasising the need for climate and weather modelling downscaled to island level, coupled with localised asset risk mapping, underscores the imperative for a finer resolution than continental grids, enabling tailored interventions to mitigate vulnerabilities. Policy makers must integrate climate and weather modelling insights into strategic planning frameworks. In charting a course forward, it is essential to leverage the insights gleaned from climate and weather modelling to steer power systems towards resilience.

Climate projections therefore offer invaluable foresight, providing policy makers with the tools needed to proactively strengthen power systems against looming challenges. By discerning trends and patterns in climate and weather data, stakeholders can devise actionable strategies, directing investment toward resilient infrastructure and adaptive measures. In the quest to enhance resilience against extreme weather events, a multidimensional approach to modelling extreme events and failures is essential, coupled with an accurate representation of existing resilience measures. Furthermore, recognising the interdependencies between power grids and communication systems underscores the need for co-ordinated restoration efforts during outages to ensure seamless operation and data continuity (Liu, X., *et al.*, 2020). By combining complementary approaches and addressing the weaknesses inherent in relying solely on historical data, policy makers can navigate the complexities of climate change and foster sustainable energy ecosystems resilient to its vagaries.

BOX 4 Enhancing resilience using climate data: Case study from California

One example of how climate data have been included as an integral part of planning processes is California, where the Pacific Gas and Electric Company (PG&E) has improved its planning practices to include climate data or derivatives thereof in identifying vulnerabilities and physical risks (PG&E, 2022). PG&E's infrastructure spans more than 70 000 square miles and is facing a number of physical hazards such as heatwaves, storms, wildfires, drought, subsidence and rising sea levels. These hazards have become more frequent and extreme due to climate change, and they have compounding and cascading effects. PG&E uses the best available climate science and data to evaluate risks to businesses and incorporate climate risk projections into planning for the energy system. This has helped the company to implement several solutions that will reduce the duration of outages and the number of people who are affected by outages. Along with safeguarding substations and surrounding communities from flooding caused by sea level rise, this also included an improved vegetation management programme to lower the risk of wildfire and undergrounding roughly 10 000 miles of power lines in high-risk areas. Additionally, PG&E improved power line safety settings by modifying the sensitivity settings on certain circuits in high-risk areas so that they quickly and automatically cut off power if the system detects an issue. To inform future planning, the company evaluated the projected change in wildfire acreage that would be burnt in 2050 relative to present-day areas designated as having high fire threat, and also began replacing ageing equipment with assets rated for future temperature conditions. An extended period of drought and increasing temperatures have resulted in an increase in wildfire risk and a longer wildfire season. With the understanding that average temperatures will continue to rise and extreme heat events will be more frequent in the near future, the utility is also making a climate-informed decision to upgrade the grid for future temperature conditions.

Using climate and weather modelling, interpreting these data, including their limitations, and considering them in grid planning to make informed decisions are paramount for enhancing the resilience of power systems in the face of escalating climate risks. Power system practices need to evolve to consider the impact of climate as part of the regular data intake and decision-making process. These techniques can help in assessing the potential impacts on infrastructure and system operations through the development of climate scenarios. They can support the designing and retrofitting of infrastructure such as reinforced power lines and elevated substations. Furthermore, they can support the quantification of component degradation and failure by helping to evaluate the impact of wind speed on transmission systems, how ambient temperatures affect the capacity of combined-cycle plants, and the impact of higher risks of wildfire exposure on T&D systems.

2.

BUILDING A RESILIENT POWER SYSTEM: PROACTIVE STRATEGIES

2.1 BEYOND RECOVERY: THE RESILIENCE IMPERATIVE

Resilience is a broad concept that can be applied to the most diverse fields. Although no unanimous definition exists, it is usually described as a given system's level of capability to respond to different stages following a hazardous event. The IPCC defines resilience as: "The ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner, including by ensuring the preservation, restoration, or improvement of its essential basic structures and functions." Resilience in the context of power systems is becoming increasingly important due to changes in the power system landscape. The increasing number of extreme climate events and their growing intensity – due to climate change – has brought attention to this important topic. Additionally, the transition towards a greener energy sector, which relies heavily on the electrification of end-use sectors, makes power system resilience a critical consideration. According to IRENA's 1.5°C Scenario, electricity will account for over 52% of total final energy consumption by 2050, while its share in 2022 was 23% (IRENA, 2024).

Building resilience against extreme climate events means focusing on the ability of electrical grids and related infrastructure to withstand, adapt to and recover from extreme events. It differs from building resilient power systems by designing them to be robust against a wide range of potential disruptions, such as operational failure and supply chain disruption, which are non-weather related. Resilient systems are designed to be more flexible and adaptable, with greater modularity, adaptive planning and continuous monitoring to counter different types of disruption. In this report, the focus is on resilience against climate change and extreme weather events.

Power systems are among the most complex man-made systems as they keep evolving to include new asset types, including generation units, transmission and distribution assets and other equipment to aid system operation. The main aim of the power system is to provide reliable power to end-use customers. The power system planning process determines the least-cost evolution of the system, covering generation, transmission and distribution, so that it can adequately supply the forecast load within a set of constraints, including renewable energy targets. This process includes evaluating how the power system will behave under expected and unexpected conditions to ensure secure, stable and reliable operation. Traditionally, the power system is designed and operated to withstand a set of eventualities referred to as normative incidents or contingencies (*e.g.* N-1 or N-2 criteria), which are selected on the basis of their significant likelihood of occurrence. A typical contingency could be the outage of a single system element at a time, the so-called N-1 criterion.

Building the resilience of the energy sector, especially the power sector, is a key step in climate adaptation. Extreme weather events lead to physical damage to infrastructure and large-scale power outages including multiple assets and cascading blackouts. Therefore, having cleaner power systems that contribute to net zero is no longer enough; instead, the goal should be to create power systems that can withstand a range of impacts, including climate catastrophes and cyberattacks. Having backup systems, reducing dependency on a single source of energy, implementing energy storage solutions and retrofitting or upgrading existing infrastructure are critical. By building, maintaining and ensuring sustained investment in resilient infrastructure, countries can contribute to climate change adaptation and ensure security of energy.

Several organisations and authors have attempted to define resilience in the context of power systems. CIGRE (2019) defines power system resilience as "the ability to limit the extent, severity, and duration of system degradation following an extreme event" (Ciapessoni *et al.*, 2019). Although different, the various definitions of power system resilience present high commonalities: they highlight the concept of resilience as the ability of a system to withstand, adapt to, quickly recover from, and learn from extreme events, particularly, HILP events, while limiting the duration and severity of the impacts on the system. Resilient systems reduce the impact of events and the recovery time after failure. One important aspect of resilience is that it is unique to the power system or power system component in question, as it depends on the design and operation of the system (Willis and Loa, 2015).

Enhancing the resilience of power systems is an urgent and critical task. The alternative corrective approach, or "fix it when it breaks", is no longer sufficient in the face of increasing disruptions and their escalating economic and social costs. These costs include direct losses from disrupted production and services, as well as indirect losses from the ripple effects on the economy (Schmidthaler and Reichl, 2016). The impact of extreme weather events on power infrastructure can have cascading effects on industrial production. For example, during the severe winter storm in Texas in 2021, widespread power outages caused disruption to semiconductor manufacturing, leading to delays in the production of electronic devices and financial losses. It was reported that state's economy lost an estimated USD 130 billion due to this (Converge, 2025). By adopting proactive resilience enhancement strategies, we can ensure the reliability of our power systems, safeguard our economies, and protect the well-being of our communities. The industry is now reinforcing facilities, making sure backup power supplies are installed and functioning, and also co-ordinating with the local authorities to closely monitor the weather situation. The dependence of modern society on electricity for a multitude of functions renders power system failures detrimental in domains such as education, communication, transport, industry, healthcare and water supply. The occurrence of power system events that disrupt supply and cause further consequences result in significant economic detriment and impede socio-economic progress. The 2012 Superstorm Sandy wreaked havoc on the northeastern United States, causing extensive damage to power infrastructure and resulting in prolonged power outages. Power utilities were able to minimise damage through pre-emptive steps due to early warning. This included preparedness of the outage repair teams and trimming of trees. It has been estimated that 8 million customers lost power and some remained without power for 10 days. In addition, 50 deaths were attributed to the lack of electricity due to hypothermia and improperly operated generators, and the cost of outages has been estimated at between USD 14 billion and USD 26 billion (National Academies of Sciences, Engineering, and Medicine, 2017).

2.2 PROACTIVE RESILIENCE: THE ROLE OF POLICY MAKING

A strategic, proactive and long-term power sector plan is needed at a national level to provide the right regulatory and policy environment and avoid *ad hoc* and autonomous resilience measures at individual asset or utility level. Long-term planning for generation, transmission and distribution needs to be reformed to consider the impact of a changing climate and the prevalence of extreme events. In addition, effective policies are equally important to ensure technologies and solutions are put in place. Integrating resilience into national policies, strategies and plans sends strong signals to different power system stakeholders and investors that resilience is a national priority. Policy instruments should be ambitious while simultaneously based on evidence, such as financial risk metrics and historical data from previous weather-related events and national loss and damage data (CDRI, 2023).

Policy making should focus on making resilience an essential part of power system design, planning and operations (IET, 2021). And this needs to begin with identifying a key organisation responsible for prioritising resilience, setting a standard definition for resilience to allow the development of metrics for resilience, identifying the value of resilience measures, and thereby easing the decision-making process on resilience measures and related investment. This should be done in consultation with stakeholders from other sectors, addressing the complexity and interdependency on other infrastructure.

Policies should also reflect the need for sustainable supply chains to facilitate the procurement of components that need regular replacement and make the system more easily repairable. Frameworks should be put in place that insist on maintaining critical inventory to maintain service continuity and an effective spare parts management strategy that can help eliminate costly and reactive situations. It should encourage continuous discussions to review previous outages and response measures, identification of system-specific solutions to improve on failures of the past, and dissemination of best practices.

Conventional regulatory frameworks might fail to sufficiently consider the intricacies and unpredictability that are inherent in climate change and other emerging hazards (IEA, 2022). Power system planning processes generally do not include climate change and extreme weather as important factors. As a result, a regulatory transformation is required to encourage innovative solutions and mandate investments based on risk. This may entail the implementation of novel policy and regulatory methodologies that harmonise investment strategies with factors pertaining to enhancing power system resilience (Robinson, 2014).

Novel regulatory frameworks have the potential to stimulate prompt investment in resilience and incentivise utilities to adopt proactive measures. One potential approach is to establish innovation facilities that provide utilities with direct assistance and direction. These facilities should have the capacity to assist utilities in navigating the intricacies of resilience investment and furnish them with the necessary tools and resources to make well-informed decisions (Robinson, 2014). Following multiple snow storms in the central part of the country, the Italian regulator introduced an incentive-based regulation aimed at improving the resilience of the distribution networks. Distribution system operators are entrusted to make plans for resilience investment based on designing the system to withstand and recover from events such as ice formation, heatwaves, flooding and fallen trees, including the use of cost-benefit analysis. Italy is also working on developing a risk-based methodology to improve resilience by including preventive, recovery and monitoring interventions. This includes the critical steps of developing climate scenarios, understanding vulnerabilities and evaluating the probability of multiple, simultaneous outages (CERRE, 2023).

Examples of regulatory mechanisms to support resilience include (Sandia National Laboratories, 2021):

- Cost of service regulation
- Regulation based on performance
- Regulation to improve and implement integrated planning
- Regulation on tariffs and programmes to incentivise private sector investment
- Enabling alternative business lines for utilities
- Improving cost recovery
- Securitisation of resilience investments

BOX 5 Developing national resilience strategies – an example

National Resilience Development Strategy, Dominica

Dominica's National Resilience Development Strategy for 2030 outlines the country's ambitious goal to be the world's first climate-resilient nation and presents the priorities that must be pursued to attain sustainable economic growth.

In the power sector, the strategy identifies measures such as: undergrounding of major transmission lines throughout the country and distribution lines in urban centres, increasing standby or backup electricity capacity, increasing the penetration of renewable energy with both centralised and distributed systems, and establishing mini-grids for remote communities that can serve customers independently of the grid. This includes exploring and developing hydropower potential for power generation, encouraging the installation of solar PV on public and residential buildings and solar-powered streetlights and lighting for public spaces, and looking to mini-wind systems (Government of Dominica, 2018).

2.3 DEPLOYING A RESILIENCE FRAMEWORK

Grid operators face the challenge of designing reliable networks and response plans that can help the system withstand the impact of and recover quickly from an extreme event. Most systems are inherently designed to be resilient to some extent. But with the addition of new types of resources and changes in the nature of demand, such as increased end-use electrification, there is need for the system to be resilient on different levels. Enhancing resilience is a task that utilities should undertake in view of the changes likely to happen within the system. This includes putting in place effective strategies such as resilient enhancement frameworks.

A resilience enhancement framework represents a comprehensive approach to improving resilience. It supports the planning for resilience and developing strategies to ease and enable a faster recovery. The framework should provide clear steps for assessing risk, analysing vulnerability, identifying infrastructure hardening requirements and other resilience measures, and improving information sharing and communication channels. This is in addition to establishing clear objectives and identifying performance metrics for measuring resilience levels and indicating improvements. Developing and updating the utility's existing emergency management plan is an important part of this framework.

The framework also identifies key stakeholders and the cross-sector strategies needed to ensure that resilience measures are not implemented in isolation. Box 5 discusses the strategy adopted by Dominica, to be climate resilient.

Resilience measures should serve to improve damage prevention, system recovery and the survivability of the system. The classification of resilience measures varies. One way of categorising resilience enhancement measures is as planning measures and operational measures (Afzal *et al.*, 2020). Planning measures typically boost the resilience of infrastructure, that is, by strengthening infrastructure. In terms of time horizons, planning measures are normally medium- to long-term strategies that are ideally implemented prior to the event. Examples of this include emergency actions and day-ahead preventive actions. Operational measures are addressed in the following section.

Building resilience should not only account for extreme events, but in the case of power systems also for the impact of climate variables such as temperature and precipitation. Rising temperatures increase resistance in transmission lines, thereby increasing losses in the system and limiting the current carrying capacity of the line. Additionally, at higher temperatures the power flow causes greater heating and therefore expansion of transmission lines, which tend to sag. The impact of climate change is also seen in extreme hot and cold temperatures increasing demand for cooling and heating, respectively. Since much heating and cooling equipment relies on electricity, peak demand sees a significant increase that requires an increase in electricity generation. The use of storage here would be beneficial.

2.3.1 Hardening the power system: Planning for targeted infrastructure upgrades

Several preventative measures can be taken to harden the grid, targeting common threats and vulnerabilities, such as:

- Addressing fuel interdependency and shortage: increasing situational awareness of the possibility of fuel shortage and establishing effective communication and co-ordination channels with suppliers. Diversification of energy generation sources is an additional failsafe solution to this severe issue.
- Implementing redundancy, such as redundant transmission lines (alternative paths) and having backup facilities (Dillip Kumar Mishra *et al.*, 2024).

- Weatherproofing, which includes:
  - Hardening and reinforcing structures, that is creating and implementing higher engineering standards, improved infrastructure design and better construction using specific strong and/or waterproof materials, for example upgrading poles to metal lattice structures, using stronger materials for towers, and providing additional support against strong winds in sections that are at more risk; weatherproofing substations from flooding includes using improved flood monitoring, raising of flood walls, using submergible transformers and switches (EPRI, 2016; Kandaperumal and Srivastava, 2020), elevating substations and using modular components (Daeli and Mohagheghi, 2023).
  - Hardening renewable energy assets: improving standards for PV and wind to cover a whole range of extreme weather conditions and promoting industry's adherence to them is key to maintain security of supply. This gains more relevance in the context of climate change and due to the geographical location of these assets, which are impacted by events such as dust storms, floods, hail and typhoons to a greater extent than conventional centralised generators (IRENA, 2025).
  - Enhanced vegetation management, by clearing vegetation and tree branches and removing dead trees near T&D infrastructure, which are prone to wildfires.
  - Undergrounding T&D infrastructure in targeted areas – such as lines and substations connected to critical customers – to lessen vulnerability to strong winds, wildfire and hurricanes.
- Building interconnections: regional grid interconnections help build resilient energy systems by helping to utilise the full potential of spatially diverse renewable resources. In the Texas winter blackout of 2021, a combination of factors contributed to more than 4.5 million households losing power and consequential failures in other services such as water systems and medical services. One of the factors identified was the grid design, which was disconnected from neighbouring grids, restricting the amount of electricity that could be imported. Increasing transmission connections with neighbouring regions is one solution that has been highlighted by many as supporting greater resilience (Busby, 2021).

The implementation of resilience measures often requires significant capital investment. Therefore, decision makers and regulators need to be able to financially assess investments to ensure that their benefits outweigh the costs. A powerful and well-used tool to identify beneficial measures and support investment decisions is cost-benefit analysis (CBA). A CBA of the alternative measures provides insights into the benefits that can be accrued from the measures and allows them to be prioritised accordingly. CBA compares the costs of an investment with the expected benefits that will be generated and is a valuable tool in cases where there are large upfront investment costs, but benefits that will be generated for a long time ahead. CBA is performed by assessing the costs of measures (*e.g.* reinforced support structures, anchor components, increased maintenance and inspections) and the benefits (*e.g.* costs savings or avoided costs such as repair costs, avoided outage). A cost-benefit ratio (CBR) is then calculated, and measures can be identified and prioritised accordingly. Another important assessment is the multi-hazard assessment, which evaluates if the resilience measures for one event negatively impact the resilience measures for another event.

The CBA of preventive maintenance versus ongoing repairs after equipment failure and outages reveals significant advantages of preventive maintenance and proactive resilience investment. The US Department of Energy claims that compared to reactive maintenance, preventive maintenance can save 12-18% on costs. This is because preventive maintenance reduces the likelihood of sudden equipment failure, which can lead to costly downtime and lost production (Virdhagiri, 2024). Value of lost load (VoLL), which can include the costs associated with recovery, business interruption, and asset and perishable loss, is the most widely used metric for valuing resilience (NREL, 2022).

The Federal Energy Management Program (FEMP) estimates that a good preventive maintenance programme can reduce downtime by 35-45%. Furthermore, research by Jones Lang LaSalle found that preventive maintenance can increase equipment lifespan by up to 30%, which results in fewer replacements and lower capital expenditure in the long run (Virdhagiri, 2024).

When addressing climate resilience in power systems, it is crucial to move beyond mere infrastructure "hardening" towards enabling capabilities that unlock new markets. Decentralisation and DERs present a significant market opportunity, aligning with emerging trends such as energy-as-a-service and localised energy trading. This shift not only safeguards communities, but also fosters innovative market models, driving economic growth and adaptability (IRENA, 2019). DERs can participate in wholesale and ancillary service markets complying with market prices and enable demand-side flexibility.

Recognising the pivotal role of the private sector as a partner in resilience efforts is paramount. Resilient power systems open doors for local businesses to thrive, particularly with the help of solutions like solar PV and energy efficiency improvement mechanisms. This is not merely about building infrastructure; it is also about job creation, fostering entrepreneurship and ensuring sustainable development.

By embracing these principles, policy makers can steer towards resilient power systems that not only withstand climate shocks but also catalyse economic prosperity and societal well-being. The integration of enabling infrastructure, decentralised market models and robust private sector partnerships lays the foundation for a resilient energy future, driving innovation and fostering inclusive growth.

2.3.2 Preventive and corrective operational strategies

Operational measures relate to implementing preventive and corrective strategies to deal with an adverse event as it unfolds. Operational measures are short term and target the effective management of the event in real time. They are divided according to temporally based resilience, *i.e.* whether they should be implemented before, during or after the event. Table 2 describes some of these measures in detail.

Table 2 Operational measures

BEFORE THREAT (PREVENTION STATE)	DURING THREAT (DEGRADATION)	AFTER THREAT (RESTORATION STATE)
Accurate weather forecasting (including estimation of severity and location) and power generation forecasting, applying AI	Selective dispatch of diesel generators	Load restoration; advanced and adaptive restoration
Disaster assessment and priority setting	Emergency response (*e.g.* topology switching and load shedding)	Network reconfiguration and restoration algorithm
Proactive charging of BESS for dispatch during threat	Demand-side management and other customer engagement procedures to support resilience strategies	Microgrid or islanded operation
Advanced visualisation and situation awareness systems (*e.g.* predicted power outages)	Load curtailment of non-priority loads	Activation of advanced protection schemes and decentralised control; adaptive wide-area protection and control schemes (*e.g.* defensive and controlled islanding of affected areas)
Preventive response (*e.g.* SCOPF); preventive control (*e.g.* preventive generation rescheduling)	Automatic source transfer	Repair crew mobilisation and co-ordination
Mobile direct current de-icing device		

Source: (Bhusal et al., 2020; Hossain *et al.*, 2021; Jufri *et al.*, 2019)
Notes: AI = artificial intelligence; BESS = battery energy storage system; SCOPF = Security Constrained Optimal Power Flow.

Box 6 highlights the steps involved in developing an emergency management plan.

BOX 6 Developing an emergency management plan

One of the key steps within the resilience framework is to develop an emergency management plan, which includes preparing a checklist, developing and reviewing outage recovery plans, procuring and conducting periodic review of back up resources, and coordination between different personnel and stakeholders. It is also important to create schemes to enhance the capacity of the system to withstand an event, minimise damage, recover rapidly and adapt to it.

In short, emergency management in a power plant could entail the following steps:

- Classifying the types of events and detailing the kind of response for each event.
- Establishing operational procedures and communication protocols.
- Establishing duties and responsibilities of personnel or staff.
- Identifying the additional resources and facilities needed.
- Establishing a strategy for collaboration with external entities.

3.
TECHNOLOGY AT THE CORE: SOLUTIONS FOR A CHANGING CLIMATE

3.1 DISTRIBUTED RESOURCES FOR LOCAL RESILIENCE

Distributed generation systems – such as renewable mini- and microgrids – are modular and therefore faster and easier to deploy than large-scale power plants or high-voltage transmission lines. Rooftop solar PV solutions coupled with batteries can, if equipped with the appropriate components enabling isolated operation, continue powering homes when a disruption occurs, offering local resilience at the building level. In addition, their modular design and scalability not only make them easier to rebuild if damaged, but also easier to adjust to a changing climate and changing load profiles over time (Cox *et al.*, 2016).

Distributed generation further reduces the vulnerability of power systems by decreasing their dependency on long transmission lines. A decentralised power system is far less impacted by damage to the T&D system and can avoid the widespread outages a centralised power system would experience (Ginoya *et al.*, 2021). Consequently, the occurrence of extreme events that cut off more susceptible components and consumers along the electrical distribution network is prevented from causing cascading effects (Liu, G., *et al.*, 2020).

Examples of the application of decentralised renewable generation include:

- Solar-powered end uses such as water pumps and water purification systems.
- Emergency lighting for streetlights, traffic lights, communication repeaters and variable message boards.

This consequently increases resilience by increasing energy independence, that is, local decentralised renewable projects reduce the reliance of communities on centralised power plants and T&D infrastructure under extreme weather conditions.

A complex and isolated power system reliant on fossil fuel imports and with vulnerability to weather events resulted in power outages in Puerto Rico, leading to damage and loss of billions of dollars. Harnessing marine energy from ocean currents and waves, and ocean thermal energy from ocean thermal gradients, hold great potential in Puerto Rico according to a technical resource assessment (Yang *et al.*, 2024). Additionally, there is technical potential for floating PV systems in several reservoirs in the country, in addition to rooftop and large-scale ground-mounted solar according to a study conducted by the National Renewable Energy Laboratory (NREL) (Driscoll, 2024; Pastor *et al.*, 2024). Box 7 highlights the experience in Australia, where rooftop solar PV and microgrids were promoted to improve resilience.

BOX 7 Rooftop solar PV growth in Australia

By early 2025 over four million Australian households were generating their own electricity (AEC, 2025). Australian federal and state governments have been offering grants and interest-free loans for the purchase of home solar batteries, such as South Australia's Home Battery Scheme (Sykes, 2024).

Extreme events such as flooding and power outages in the state of Victoria led the government to announce AUD 7.5 million (USD 4.7 million) in funding to improve energy resilience through rooftop solar back-up systems on community buildings and batteries across 24 towns deemed vulnerable to extreme weather events. It also invested a further USD 9.8 million to form microgrids with a mix of solar, batteries, heat pumps and generators (Ev Foley, 2025).

Renewable technologies can equally be impacted by extreme weather events. Variability in rainfall, solar irradiation and wind speeds have a direct impact on power generation. Wind turbines, as opposed to thermal generation assets, are less affected by droughts and heatwaves, but can be seriously impacted by storm events where wind speeds exceed design limits. Offshore wind turbines, especially, can be destroyed in extreme weather. Additionally, extreme cold weather can lead to ice formation on turbine blades, reducing output.

High winds and hailstorms are the main vulnerabilities of solar PV systems, which can damage the PV modules. Changes in solar irradiation, cloud cover, wind speed and precipitation affect power production from solar panels. Higher temperatures arising from climate change or wildfires can affect the efficiency of the panel and therefore its power generation capacity. The torsional and dynamic loading of the panels, as well as the failure of bolts and the foundation due to corrosion and erosion, can also contribute to failure. Solar PV panels can be redesigned to strengthen or harden their components against extreme weather conditions. The suggested method is to enhance the mechanical design of solar PV panels.

A non-exhaustive list of recommended standards for improving the structural capabilities of power assets helping to build a robust and resilient system are highlighted in Box 8.

BOX 8 Key technical standards addressing resilience

Design standards introduced by the Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC) set out how protection against extreme events can be ensured. They include:

- IEEE standard 693, which provides design recommendations that qualify various substation equipment for areas susceptible to seismic activity and includes performance requirements and structural capacities. It has been formulated with the objective of ensuring that equipment is not damaged and continues to function during the defined seismic spectrum (IEEE, 2006).
- IEEE P2856, which provides a definition of resiliency for electric power distribution systems. It also covers how to measure and report resiliency metrics.
- IEC TR 62351-12, Part 12 of which discusses cybersecurity recommendations and engineering/operational strategies for improving the resilience of power systems with interconnected DER systems.

3.2 GRID FORMING INVERTERS: FUTURE-PROOFING GRIDS WITH HIGH RENEWABLE PENETRATION

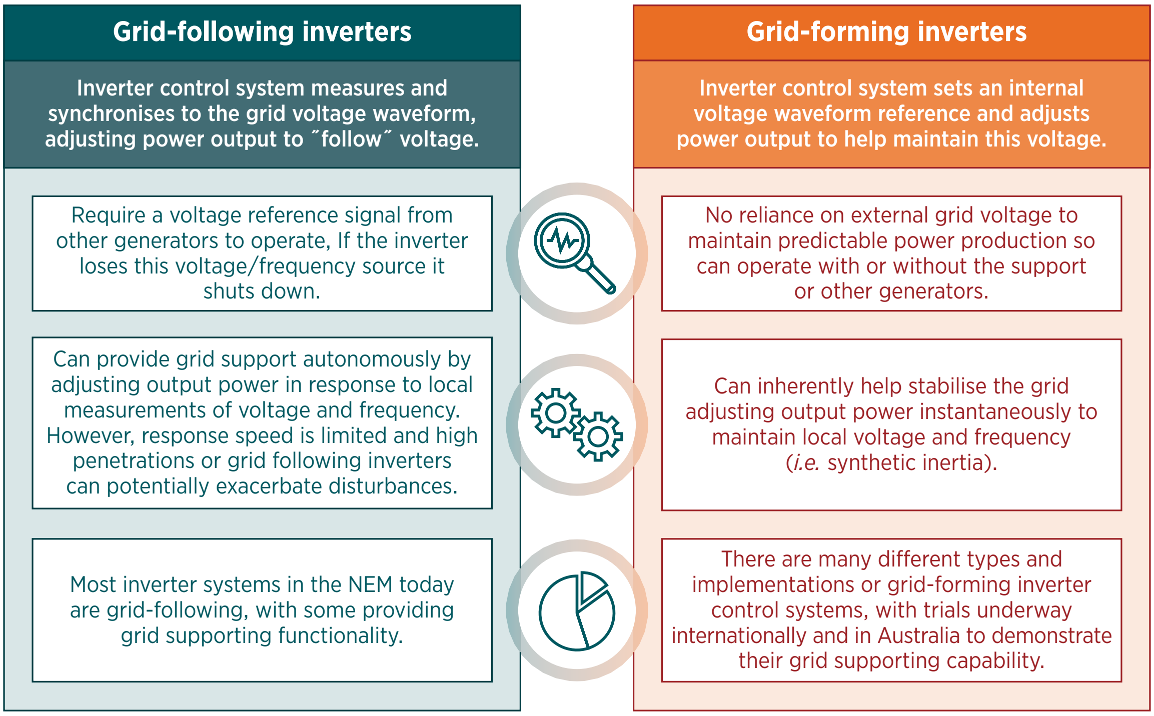
Renewables can help to improve power system resilience because they have the following key characteristics (Resilient Energy Platform, n.d.; UtilitiesOne, 2023):

- They have **no (fossil) fuel requirements**, which eliminates the risk of reduced or no production capability due to fuel supply disruption and exposure to price volatility associated with fuel imports, and further diversifies the energy supply mix.
- Renewables can be **modular** and **decentralised**, allowing for locational flexibility as well as individual ownership and installation to ensure uninterrupted power supply following an HILP event. This approach reduces the system's vulnerability to natural disasters, cyberattacks and physical damage, resulting in a more resilient energy grid.
- Renewable energy helps to **mitigate climate change** and **reduces exposure to health risks** by emitting few or no emissions.

However, variable renewable energy (VRE) power output, *i.e.* from solar PV and wind, is more difficult to integrate into power systems than other technologies like fossil-fuelled generators or dispatchable renewable energy generators (*e.g.* biomass, geothermal and reservoir hydropower) due to its uncertainty, variability, location-specificity and non-synchronous nature. This has implications for power system security and stability (IRENA, 2018).

The power system is changing quickly due to the rapid deployment of renewable technologies, and it is crucial to preserve the stability and dependability of the grid. VRE generation units are also called inverter based resources (IBRs), connected to the grid through inverters, which do not have any intrinsic behavior but can be controlled to provide responses as required. Traditionally IBRs are grid following. Grid-forming inverters are a technological advancement that is accelerating the deployment of renewables; they can interface with renewable resources such as solar, and wind in conjunction with BESS or other storage systems and can function as voltage source converters (VSC) independent of an external reference, in contrast to conventional grid-following inverters, which must rely on (*i.e.* follow) the grid references of voltage and frequency to function. This can enable standalone operation of renewables (refer to Figure 4).

Figure 4 Grid-following vs. grid-forming inverters



Source: (AEMO, 2021).

Batteries with grid-forming inverters can offer black start capabilities and offer services such as synthetic inertia since they have the capability of mimicking characteristics inherent in synchronous machine technologies (Lin *et al.*, 2020).

Grid-forming inverters can enhance power system resilience in several ways (Lin *et al.*, 2020):

Support for grid stability and resilient renewable energy grid integration. Grid-forming inverters can provide stability in power systems with a high penetration of variable renewables (Bellini, 2022; Gui *et al.*, 2023). They offer the speed and flexibility of electronic power equipment in combination with the stabilising characteristics of synchronous machines. This is particularly relevant when extreme weather events cause disturbances and sudden disconnection of load or generation, jeopardising the power balance.

Fast fault response support during extreme events. The ability of grid-forming inverters to quickly limit their output current during grid disturbances in order to prevent potential overcurrent damage is known as fast fault current limitation (ENTSO-E, 2020; He *et al.*, 2024), while fault ride-through (FRT) is the ability of power system equipment (like grid-forming inverters) to remain connected to the grid and continue operating during and after a fault or extreme event (Kou and Park, 2020). Grid-forming inverters can quickly limit fault currents at a prescribed level while preserving voltage angle control for grid-forming-type synchronisation and dynamic ancillary services provision during FRT procedures (Gui *et al.*, 2023).

Black-start capability: A “black start” is a process to restore power in an electric power station or part of an electric grid that has been shut down completely (Badakhshan *et al.*, 2024). Grid-forming inverters can provide black-start services by using their ability to control voltage and frequency to kick-start the power grid following an extreme event, unlike traditional “grid-following” inverters, which would require grid voltage and frequency to be established already, such as through a natural gas or hydropower plant, before injecting power into the grid (Jones-Albertus, 2024; Sawant *et al.*, 2023).

Figure 5 Hornsdale Power Reserve, South Australia

Source: (Peacock, 2022).

Today, more than 80% of the resources that are routinely powering Hawaiian islands like Kauai and Maui are inverter-based (Lin *et al.*, 2020). Field tests of a grid-forming inverter were carried out at the Hornsdale Power Reserve (Figure 5), a transmission-connected BESS (ESIG, 2022).

While the industry has made tremendous progress in grid-forming inverter technology, there is still work to be done around the development of the technology, its application and the impact on operations and transmission planning (Lin *et al.*, 2020). As the power system continues to be transformed by the rapid deployment of renewable technologies, grid-forming inverters will play a crucial role in maintaining the resilience, reliability and stability of the grid (NREL, 2024). High-voltage direct current (HVDC) systems with grid-forming capabilities (*i.e.* terminals with VSC technology) are projected to play a crucial role, becoming active grid assets capable of withstanding extreme events and greatly contributing to rapid service restoration in the surrounding grid.

3.3 UNLOCKING GRID RESILIENCE THROUGH THE POWER OF ENERGY STORAGE

Energy storage can supply electricity for a finite period before it must be recharged, in contrast to a power plant that can provide power on demand so long as it is connected to its fuel source. Energy storage comprises a vast array of distinct technologies, each endowed with its own set of restrictions and capabilities. With the economic, environmental and resilience-based benefits of renewable energy sources and storage, developing nations can leapfrog traditional systems and deploy decarbonised energy infrastructure from the outset.

The capabilities of energy storage technologies are evaluated differently from those of generation assets due to their distinct characteristics. The most prevalent types of energy storage evaluation metrics are: duration, cycle life, round-trip efficiency and response time (Andersen *et al.*, 2021).

Storage can enhance overall system resilience and reliability in addition to enhancing system resilience against extreme events. Services that batteries provide to improve overall system resilience are balancing the grid and managing peak events. As backup service providers they can support critical infrastructure during outages. An overview of the different energy storage technologies and the resilience services provided is illustrated in Table 3.

Table 3 Power system resilience services provided by energy storage technologies

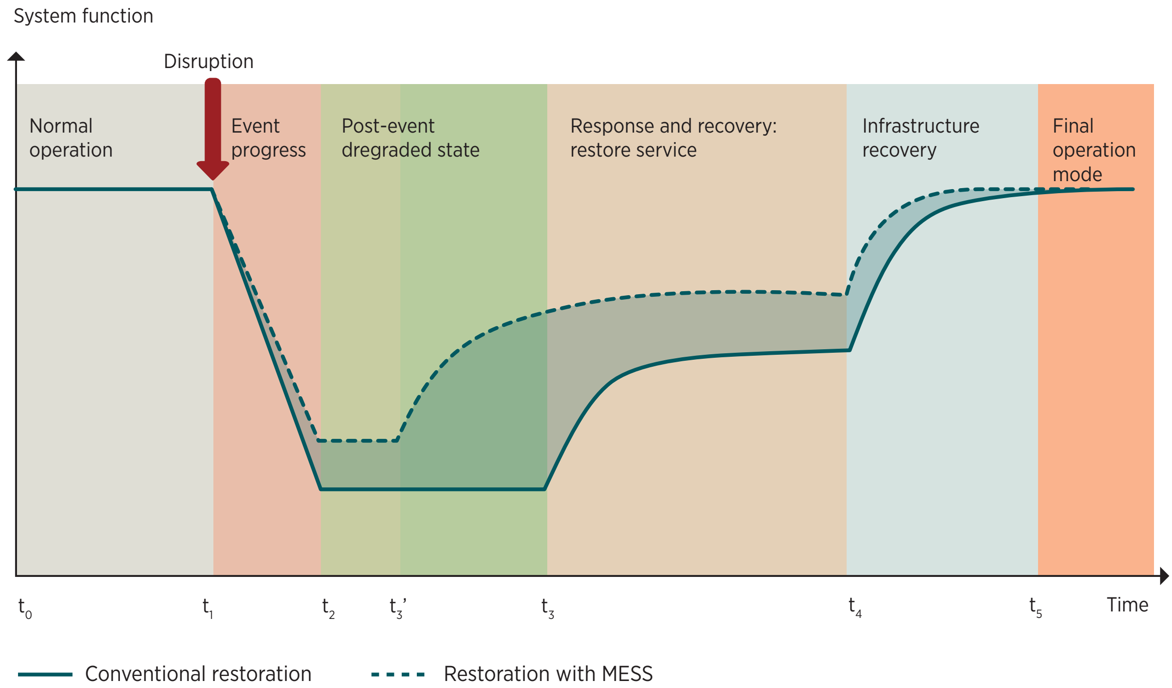
RESILIENCE SERVICE PROVIDED	ENERGY STORAGE CATEGORY	ENERGY STORAGE MODALITY	COMPLEMENTARY CAPABILITIES	RESILIENCE OPTIMISATION USE CASE
During the event (instantaneous *i.e.* seconds–minutes)	Battery energy storage (BES)	Electrochemical systems that store energy through reversible chemical reactions. Battery technology encompasses a wide range of chemistries (lithium-ion, lead-acid, flow batteries, *etc.*) with varying energy densities, discharge rates and lifespans.	Batteries offer near-universal applicability across grid levels due to their modularity and diverse chemistries. Their versatility makes them an adaptable technology for enhancing grid resilience.	Batteries excel in their modularity and scalability, allowing for flexible deployment at various grid levels (transmission, distribution, behind-the-meter). Their rapid response times and diverse discharge profiles make them well-suited to mitigating supply–demand fluctuations, enabling rapid islanding and restoration of critical systems after major outages through black-start capabilities.
	Pumped-storage hydroelectricity (PSH)	A mature technology that utilises surplus electricity to pump water to a higher reservoir, storing potential energy. During peak demand periods, the water is released back down through turbines to generate electricity. It can work across timescales from sub-second to days.	PSH boasts significantly higher energy storage capacity compared to batteries, making it ideal for long-duration backup power. It can offer support through variable weather conditions and droughts, reductions in coal or gas generation or fuel availability, and extended transmission outages.	PSH offers unmatched capacity for long-duration energy storage (hours to days), ensuring reliable power supply during extended outages, extreme weather events or disruption to fuel supply chains (LDES, 2023). PSH can offer between 12-hour and 31-hour storage depth (AEMO, 2019). Its ability to store vast amounts of energy and participate in black-start protocols makes it a critical component of a resilient grid. PSH generates inertia with its large rotating turbines, enabling it to react quickly to the electrical grid's second-by-second needs.
Mitigating the impact of an extreme weather event (*i.e.* medium-term [hours] on demand profile)	Battery systems	Battery systems can store excess energy from renewable generation, preventing their curtailment.	N/A	Batteries' near-instantaneous power injection capabilities enable them to reduce strain on the grid during critical peak periods. They can be sited strategically across the grid, from transmission level to behind-the-meter applications.
	Thermal energy storage (TES)	Systems that capture and store thermal energy (heat or cold) for later use. TES technologies utilise various materials with high heat capacity for thermal storage, often integrated with concentrating solar power, industrial processes or district heating/cooling systems to optimise energy use.	TES provides high energy storage capacity for long-duration applications and focuses on storing thermal energy rather than electrical energy. This makes them a valuable tool for optimising energy use within industrial processes and district energy systems, contributing to resilience through improved efficiency and reduced reliance on peak grid power.	Thermal energy storage can store and retain energy efficiently so combining the storage with backup generation will make them capable of providing cooling through long outages. This ensures that critical cooling requirements such as data centres and hospitals are met, thus offering additional cost savings from prevented equipment damage and downtime.
	Compressed air energy storage (CAES)	A technology that uses electricity to compress air and store it in underground caverns or salt formations. Compressed air is released when necessary to power turbines and produce electricity.	CAES boasts high energy storage capacity for long-duration applications.	CAES offers flexibility in energy storage, delivering both long-duration (similar to TES/PSH) and short-duration (like batteries) support. CAES systems have the potential to provide black-start capability, contributing to grid restoration after major outages.

Table 3 (continued)

RESILIENCE SERVICE PROVIDED	ENERGY STORAGE CATEGORY	ENERGY STORAGE MODALITY	COMPLEMENTARY CAPABILITIES	RESILIENCE OPTIMISATION USE CASE
Outage handling and optimising restoration	Battery backup system	Essentially smaller-scale battery systems deployed behind the meter, typically at residential, commercial or industrial facilities. These systems provide localised energy storage and backup power capabilities.	While utilising similar battery chemistries, backup systems differ from large-scale grid batteries in deployment and focus. They prioritise localised power backup, whereas grid-scale systems typically aim for broader grid-balancing services.	Battery backup systems increase power reliability at the local level, providing crucial energy continuity during outages for homes, businesses and critical facilities.
	Fuel cells	Electrochemical devices that convert the chemical energy of a fuel (often hydrogen) and an oxidant into electricity through a controlled reaction. While several fuel cell types exist, hydrogen-powered cells hold significant promise for long-duration energy storage and backup power.	Fuel cells rely on an external fuel source (hydrogen) to generate electricity. Their storage capacity depends on tank size rather than battery chemistry.	Hydrogen fuel cells offer high energy density and long-duration energy storage (days to weeks), particularly suitable for ensuring power supply during extended outages or disruptions in fuel supplies. They provide an alternative for critical facilities where reliability is paramount, potentially mitigating the need for diesel generators.

Based on: (Andersen *et al.*, 2021; Smart Energy International, 2023; Thomson *et al.*, n.d.).

Figure 6 Conceptual comparison of a distribution system with and without MESS



Source: (Dugan *et al.*, 2021).

In addition to smoothing the variation in wind and solar generation, large-scale grid-connected storage units can provide backup power during outages and contribute to frequency and voltage control. The flexibility offered by these storage technologies can also enhance the restoration process by utilising black-start capabilities, including sector coupling.[2] This introduces a new dimension to the interaction patterns required between electrical transmission system operators and distribution system operators, as well as utilities from other sectors (Liu, J., *et al.*, 2020; Oleinikova, 2022).

Energy storage systems can also be used or aggregated in the formation of a microgrid. They allow energy to be transferred from a location outside the affected area. Portable storage or mobile energy storage systems (MESS) can be positioned at vulnerable locations ahead of the event or dispatched to a critical piece of infrastructure upon the event occurring, allowing for reduced outages, to offer backup and/or black-start services. Electric vehicles (EVs) can be considered as another type of mobile battery that can help a system recover faster from an event. Figure 6 depicts a conceptual comparison of a system with MESS and without (Dugan *et al.*, 2021).

[2] *E.g. by coupling with power to heat (PtH) or combined heat and power (CHP) (Stahl, 2024).*

3.4 SMART GRIDS, SMARTER DECISIONS: ANTICIPATION AND ADAPTATION

As previously mentioned, using climate and weather data can help identify threats to the system and, therefore, is essential to enhancing resilience. Forecasting and identifying the specific threats and vulnerabilities to a system needs accurate temporal and spatial data of past low-probability events. This involves modelling extreme events and their specific impacts on the power system, assets or components, which requires past records of asset or component failure in detail.

Predictions of future climate change hazards are usually obtained from general circulation models and then downscaled with dynamic or statistical techniques (Tabari *et al.*, 2021). India serves as an illustrative case in which weather forecasting agencies have provided adequate advance notice regarding the anticipated landfall and movement of cyclones over 12, 24, 36, 48, 60 and 72 hour forecast time periods since 2009 (Mohapatra, 2018). This has served as the foundation for subsequent actions predicated on these predictions, including emergency restoration system readiness and efforts to mitigate the effects of these occurrences on the power grid (voltage control and load-generation equilibrium maintenance) (Jacobs *et al.*, 2020).

Power system operators may employ various strategies, including demand-side management, real-time controls and predictive tools, to bolster the resilience of the power system in an operational timeframe, such as during the HILP event. Predictive tools refer to software applications that possess the capability to anticipate power demand and supply and grid conditions by leveraging a multitude of data sources and scenarios. They can assist power system operators in preparing for load shedding, islanding and black starts, among other contingencies.

BOX 9 Smart grid functionalities to improve resilience

Smart grid functionalities that can improve resilience include:

- **Remote metering**. Automated remote metering can provide metered data to the utility, enabling it to monitor the health of the grid and identify potential issues such as overloads, faults or abnormal consumption patterns, and locate faults with a proactive approach to prevent or mitigate disruption.
- **Outage management**. Smart meters can send outage information, also known as "last gasp outage notification", to the utility, which is used to locate the area of the outage.
- **Cybersecurity**. Depending on the communication infrastructure, smart grids can detect, diagnose and aid response by monitoring data and exchanging detection and diagnosis messages.

A grid can achieve self-healing capabilities by employing intelligent fault identification modules, smart metering units, advanced communications infrastructure and reconfigurable network topology. Automatic network reconfiguration mostly happens in distribution systems, and is the capability of the network to change connections dynamically and involves opening and closing switches. This is enabled by automatic throw over switches or automatic transfer switches, which are switches equipped with sensors and logic controllers, capable of making decisions. A drop in voltage or abnormal current flow triggers a switch in the load to backup generation during an outage and a switch back in the event the supply is restored. They can also isolate a faulty section using circuit breakers, and re-route power using healthier feeders. This prevents the propagation of the outage to larger areas.

Remote fault indicators are sensors that use data from telemetry channels to identify fault locations remotely, assisting in directing repair crews, reducing delays and preventing cascading system damage. In addition, monitoring equipment working in conjunction with automatic throw over switches can assist in relaying information regarding voltage and other crucial variables to operators so they can take the most appropriate action. Adaptive islanding of interconnected networks can prevent the propagation of the outage to larger areas. The tripping of protection systems can create islands, but maintaining the island is done by maintaining the load and generation balance.

Remote monitoring can provide utilities with real-time data and this granular information enhances situational awareness, allowing for more accurate load forecasting, tracking of real-time generation, faster identification of potential outage zones, and more informed operational decision making. During a disruption, these capabilities streamline resource allocation and can ultimately contribute to faster service restoration.

Real-time controls refer to apparatus or algorithms that possess the capability to monitor and modify the power flow, voltage, frequency or any other grid parameter in real time. They have the capability to enhance grid stability, avert the propagation of failures and promptly reinstate service following a disruption (Bhusal *et al.*, 2020; EPRI, 2020; Lin *et al.*, 2018).

3.4.1 Smart metering for resilience

The ability of smart meters to send outage notifications provides utilities with near-instantaneous information about the location and extent of power disruptions. This significantly accelerates outage identification and response, compared to traditional reliance on customer calls. Precise outage information empowers utilities to quickly dispatch repair crews, prioritise critical infrastructure and effectively manage communications during restoration efforts. Thay can also be enabled with remote connection and disconnection, which will allow utilities to prioritise critical infrastructure.

Demand response mechanisms, enabled by smart grid technologies, allow for the automated curtailment or shifting of energy loads in response to system needs. This creates a crucial tool for grid operators to balance supply and demand during times of stress, preventing potential blackouts or cascading failures. Demand response programmes can also incentivise energy users to be active participants in managing grid stability, fostering resilience.

While smart grids can introduce new cyber-vulnerabilities, their potential to enhance security of supply is hard to ignore. They allow better situational awareness through proactive monitoring, intelligent threat detection and the ability to exchange information between distributed devices, which can bolster defences against weather events and cyberattacks that aim to disrupt critical power systems. Resilient smart grids require robust cybersecurity protocols and continuous vigilance as part of their design and operation. Smart grids can enable dynamic system operation such as rerouting power flows to prioritise critical loads. An advanced version of a smart grid can use predictive analytics to optimise reserve allocation and prioritise response strategies, and offer enhanced communication with consumers to empower them with safety instructions

4. RESILIENCE IN ACTION: LEARNING FROM SUCCESS

4.1 WEATHERING THE STORM: A CASE STUDY IN RESILIENCE – MOZAMBIQUE

Mozambique, characterised by its vast coastline and nine international river basins, is exceptionally susceptible to natural disasters such as cyclones, droughts and flooding that are intensified by climate change (World Bank Group, 2020). Climate change models predict that Mozambique will continue to experience an increase in the frequency and severity of floods and heavy rainfall, which will further exacerbate the power sector's vulnerability. Additionally, heavy precipitation and flooding heighten the risk of landslides, thereby increasing the T&D system's susceptibility (World Weather Attribution, 2022).

Climate change has significant economic repercussions for Mozambique. According to a 2015 study, climate change may cause the national economy to contract by as much as 13% by 2050. Moreover, the escalating occurrence and severity of climate-related catastrophes exert strain on agricultural revenue, thereby compromising 25% of the nation's economy and 70% of livelihoods (Arndt and Thurlow, 2014; World Food Programme, 2021).

Mozambique possesses a substantial capacity for renewable energy owing to its ample supply of solar, wind, hydro and biomass resources. The Mozambique Renewable Energy Programme (MREP) and the Mozambique Energy For All (MEFA) programme have been established by the government with the objective of promoting the adoption of VRE and facilitating the nation's transition to renewable energy sources.

BOX 10 Mozambique's power sector: Building resilience

A crucial step to building resilience in Mozambique was the comprehensive grid assessment study conducted in collaboration with IRENA. Despite progress in expanding the grid, electricity access remains low (only about a third of the population). The country has significant untapped renewable potential (23 TW solar and 4.5 GW wind), which is crucial for both decentralising energy and building resilience. Guided by the IRENA study (unpublished), Mozambique is taking steps to:

- **Upgrade infrastructure**: modernising the 5 660 km electrical network, including the crucial 1 400 km HVDC line to South Africa, will enhance efficiency and reliability.
- **Diversify the energy mix**: implement four renewable energy projects with a unit capacity of 30 MW to 50 MW interconnected to the national grid (CMS, 2024). This will support energy access and make renewable energy a significant share of power generation.
- **Strengthen the system**: the unification of Mozambique's segmented grid and its integration within the Southern African Power Pool will improve energy security across the region.

These resilience-focused strategies align with Mozambique's broader goals of expanding energy access, promoting economic development and building a sustainable energy future. Investment from organisations such as Sustainable Energy Africa Fund for Africa (SEFA) and the World Bank are crucial in driving progress towards a more secure and adaptable power system.

Following Cyclone Idai in 2019, concrete resilience enhancement measures highlighted within the post-recovery needs assessment include the use of self-supporting transmission towers, concrete distribution poles to replace wooden ones, the strengthening of pole foundations, shortening the spans between poles and raising the platforms of new substations 1-2 metres above the ground with additional flood protection to existing substations. These initiatives are in accordance with the national objectives of the power sector, as outlined in the National Programme of Energy for All (*Programa Nacional de Energía para Todos* [PNEPT]) (AfDB, 2022; GoM, 2019).

A grant of USD 2.5 million was authorised by SEFA, managed by the African Development Bank, to assist in the execution of the MREP (Tena, 2022). Furthermore, a grant of USD 300 million from the International Development Association was sanctioned by the World Bank to assist the government of Mozambique in its endeavours to expand the availability of broadband and energy services (World Bank Group, 2021).

Additional resilience enhancement measures that have been implemented in Mozambique following several studies, financing schemes and lessons learnt include the following:

- An **early warning system** has been developed and implemented with the aim of enabling the relevant national authorities to track potential hazards ahead of time, fostering early action and therefore minimising the impact of these hazards on lives and infrastructure within Mozambique (World Bank Group, 2023a). Mozambique is investing USD 7.8 million aimed at the installation of six new land surface stations, upgrading 15 existing stations and putting in place four upper-air stations in the country. Through these devices, the aim is to improve significantly the nation's weather forecasting and warning capabilities (Early Warnings for All, 2024).

- A **rainwater drainage system rehabilitation project** is currently being implemented in the city of Beira to strengthen flood resilience. The first phase was completed before Cyclone Idai hit the nation, and the second phase, to construct a second retention basin for stormwater as well as a drainage ditch extension of approximately 12 km, is currently being implemented (Dutch Water Sector, 2024).
- With the aim of enhancing the financial resilience of the country, a **catastrophe risk model and parametric index for tropical cyclones** has been developed in collaboration with the World Bank, CelsiusPro and Royal HaskoningDHV. This model has equipped the government of Mozambique with the ability to rapidly calculate the economic impact of tropical cyclone events, further guiding the prudent use of the country's Disaster Management Fund and National Disaster Risk Finance Strategy for (Haskoning, n.d.).
- From a policy perspective, a **national adaptation plan (NAP)** for Mozambique has been developed, which indicates the commitment of the government to resilience enhancement across all sectors of the economy. Furthermore, resilience aspects have been integrated into the national Five-Year Programme. This aligns with the National Strategy for Adaptation and Mitigation of Climate Change (ENAMMC), which prioritises creating resilience and reducing climate risk (Government of Mozambique, 2023).

It is anticipated that the execution of these programmes will exert a substantial influence on the market. Through the expansion of energy accessibility, these endeavours have the potential to bolster economic productivity, foster inclusive expansion and construct long-term resilience. In addition, the programmes seek to capitalise on investment by the private sector and expand upon interventions by development partners with a specific focus on clean energy solutions. This has the potential to attract novel industries to the area, thus safeguarding employment opportunities and making a positive contribution to the broader economic progress of Mozambique (World Bank Group, 2023b).

4.2 SCALING SUCCESS: COLLABORATION AND KNOWLEDGE SHARING

Enhancing the resilience of a developing nation's power system necessitates the implementation of a comprehensive strategy that encompasses developing resilience frameworks, regulatory reforms and novel funding mechanisms, and the replication of effective resilience enhancement models. By implementing these measures, developing nations can bolster the resilience of their power systems and be more adequately equipped to confront future challenges.

Stakeholder engagement and cross-sectoral collaboration are key to successfully evaluating resilience and implementing appropriate measures. This is because the resilience of the system depends on the individual components and also the system as a whole. This includes not just the power infrastructure, but also other interlinked infrastructure such as gas, water and telecommunications. Dependency on other infrastructure such as natural gas increases the vulnerability of the power system. Any disruption to this could cause an outage. Selected measures need to be discussed with stakeholders to ensure buy-in and that the implementation of a measure is feasible. In order to obtain buy-in from decision makers, it is important to communicate risks and proposed measures in a clear and useful manner, that is, translating technical information into understandable and relevant information. Consulting and engaging stakeholders on the collection of data and information on infrastructure, threats, vulnerabilities, past events and other relevant areas will ensure more accurate evaluations and informed decision making. Collaboration and data sharing between utilities, power producers, governments, regulators and research institutions are not only necessary to obtain buy-in, but will also speed up and facilitate the improvement of evaluation methods and the development of necessary policies, regulations and standardised processes for power system resilience frameworks.

Roles and responsibilities within organisations should also be made clear, with asset managers adapting project development, maintenance and replacement strategies to account for an appropriate range of extreme operating conditions and designing system defence plans to consider an appropriate range of events. Training in emergency operational procedures needs to be provided to prepare for extreme conditions.

Establishing clear institutional responsibilities and incentives is essential to enhancing power system resilience in the face of evolving threats. This promotes accountability and fosters a proactive approach to addressing challenges. Incentives must be structured to encourage all stakeholders within the electricity system to prioritise resilience, aligning their actions with the broader goal of grid security and reliability. Successful examples, such as the recent legislative efforts in the United States, illustrate how policy-driven incentives can accelerate decarbonisation, boost flexibility and ultimately contribute to a more reliable and resilient grid.

The consumer now has the ability to be a prosumer and have a dynamic relationship with the power grid. Consumers can play an important role in maintaining the flexibility and therefore the security of the grid. Their involvement with grid operators is not restricted simply to times of crisis or maintenance, but also extends to providing innovative grid support services. This could be facilitated by reducing complexity in operation and access to digital platforms that allow them to contribute. Customers should be involved from the very early stages of the process, so that they can understand the benefits of the measures. For customer engagement, it is crucial that their participation is regulated by operational agreements and technical requirements on connection and disconnection and the provision of services to the grid. It should be noted that the flexibility available from customers is expected to decrease as an extreme event unfolds.

To ensure that the system recovers rapidly from an event, it is essential to have staff trained to operate resilience measures effectively and efficiently. Utilities must invest in developing the skills of their workforce so they can make use of the implemented technological advancements and review the emergency procedures to provide improved response during an event. The resilience framework should also highlight the need for regular utility staff training either at the beginning of the season or on a regular basis.

4.3 RISK MITIGATION FOR RESILIENT POWER INFRASTRUCTURE

A resilient power grid is characterised by the ability to anticipate, withstand and rapidly adapt to disruption. Risk mitigation is therefore an indispensable cornerstone of resilient power infrastructure in an era of increasing uncertainty. Even with meticulous planning, disruption cannot be fully eliminated. Resilience is also about the ability to adapt to unforeseen events and build back in ways that reduce future vulnerabilities. Achieving this requires a multi-faceted risk mitigation approach that emphasises ongoing evaluation and proactive measures.

The accelerating frequency and intensity of climate-driven extreme weather events, the sophistication of cyberattacks and the growing interdependence of critical systems underscore the need for proactive risk identification and mitigation. While progress is being made in some regions, effectively future proofing our power grids requires greater investment in resilience enhancement measures such as predictive modelling, stress testing under increasingly complex scenarios, and the seamless integration of risk assessment into both infrastructure upgrades and operational protocols. This must be underpinned by robust regulatory frameworks that foster collaboration across utilities, technology providers and governments at both national and sub-national levels.

Exchanging international best practice exchange is key, recognising that resilient infrastructure requires customised approaches. Mixed models[3] also offer valuable lessons – for example the collection and quantification of data on asset and network vulnerability and electricity supply diversification in Australia (Infrastructure Australia and Infrastructure NSW, 2021). Transferability depends on careful analysis of individual power systems, local regulatory contexts and the specific risk landscape faced. Key elements of this approach (Arner *et al.*, 2021; Hillberg *et al.*, 2022; Perry *et al.*, 2023; Robinson, 2014; Thomson *et al.*, 2024) include:

Risk identification:

- **Comprehensive assessment:** employ a combination of probabilistic hazard modelling (*e.g.* assessing flood-prone areas) and scenario-based analysis to address both traditional risks and evolving cyber threats (*e.g.* co-ordinated substation attacks).
- **Systemic analysis:** extend risk assessment beyond individual components to understand potential cascading impacts across interdependent critical infrastructure, such as the effect of power grid disruption on telecommunication systems.

Managing and mitigating risks:

- **Market alignment:** explore the use of market mechanisms to incentivise investments that directly enhance grid resilience, such as those that value flexibility and rapid response.
- **Adaptive standards:** regularly update standards to the latest technical and cybersecurity standards (*e.g.* NERC CIP standards) to reflect the continually evolving nature of threats, ensuring systems remain robust and adaptable.
- **Proactive investment:** prioritise targeted infrastructure upgrades based on risk assessments, such as the strategic undergrounding of vulnerable power lines in regions with a high fire risk (*e.g.* those outlined in California's Wildfire Mitigation Plans).

Monitoring progress:

- **Resilience metrics:** develop metrics that go beyond basic reliability indices, focusing on the speed and effectiveness of restoration efforts, particularly for essential services. This enables informed prioritisation of future investments.
- **Real-time monitoring:** implement technologies like phasor measurement units (PMUs) to detect system anomalies that could signal impending instability, triggering proactive intervention.
- **Stress tests:** regularly conduct realistic simulations (*e.g.* gridex exercises) under complex scenarios to identify vulnerabilities and refine co-ordinated response protocols.

Responding to and recovering from disruptions:

- **Clear roles and responsibilities:** establish unambiguous regulatory frameworks that delineate preparedness requirements and outline the roles of various stakeholders (power system operators, emergency services, government entities) in crisis response.
- **Recovery planning:** develop detailed, risk-informed recovery protocols that prioritise essential infrastructure and incorporate localised resilience strategies such as microgrid capabilities.

[3] *The combination of various strategies, technologies and practices that are used to enhance the resilience of power systems. These models often involve a mix of traditional and innovative approaches, and may include elements such as infrastructure hardening, the use of renewable energy sources, the implementation of smart grid technologies and the development of robust emergency response plans.*

4.4 ENABLING RESILIENCE: INNOVATIVE FINANCING MODELS

Effective financial mechanisms are essential for facilitating investment in resilience enhancement measures (Guibert *et al.*, 2019). Diverse financial mechanisms are available to enable investment in resilience. As an illustration, green bonds can be utilised to fund infrastructure that is both climate-resilient and low-carbon (Center for Climate and Energy Solutions, 2019). Furthermore, diaspora investment can serve as a pivotal source of funding, especially in developing nations where it can be of substantial importance (Ollikainen *et al.*, 2021).

BOX 11 Smart Grid Investment Grant Program: Key outcomes and lessons

The Smart Grid Investment Grant Program was introduced under the Grid Resilience and Innovation Partnerships (GRIP) program of the US Department of Energy (DOE). The Smart Grid Investment Grant Program was designed to increase the flexibility, efficiency and reliability of the power system by increasing transmission capacity and fault prevention, integrating renewables and increasing the share of EVs and the electrification of end uses. Between the fiscal years 2022 and 2026, the DOE is due to invest up to USD 3 billion (USD 600 million/year) in grid resilience technologies and solutions. The focus of the programme is to deploy grid strengthening measures to help utilities improve their resilience against extreme climate events.

This includes:

- Deploying advanced conductors and controls.
- Deploying self-healing devices and enabling accurate dispatching of recovery teams during outages.
- Upgrading lines to meet the projected load growth and renewable integration.
- Upgrading transmission infrastructure.

This will help reduce the likelihood of outages, speed up restoration times and increase grid operational resilience.

Source: (U.S. DOE, n.d.).

Table 4 provides a brief, non-exhaustive overview of existing and available resilience finance types (Center for Climate and Energy Solutions, 2019).

Table 4 Types of resilience finance

TYPE	DESCRIPTION	EXAMPLES	INSIGHTS FOR RESILIENT INFRASTRUCTURE
Grants and concessional financing	Key players include international funds and multilateral development banks. Their purpose is to catalyse resilience projects deemed too risky for the private sector, especially in early stages, by providing grants or loans with favourable terms.	The Asian Development Bank funded a grant to Tonga to strengthen its electricity system's resilience to extreme weather events and disasters after Cyclone Ian damaged the country's electricity network in 2014; the European Bank for Reconstruction and Development (EBRD) also provided a loan to a power utility in Tajikistan to upgrade a hydropower facility that implemented innovative climate resilience measures in the face of potential future change in the country's hydrology (Power Technology, 2018); the Green Climate Fund funded the development and implementation of a biomass energy project in Belize, increasing the country's resilience and power sector self-sufficiency by using a local fuel source for electricity production (Caribbean Community Climate Change Centre, 2018); the Green Climate Fund was established within the framework of the United Nations Framework Convention on Climate Change (UNFCCC). Its primary purpose is to assist developing countries in adaptation and mitigation practices to combat climate change.	These funding sources are vital catalysts for resilience initiatives in developing countries, particularly where project risk is initially perceived as too high by the private sector. Understanding eligibility criteria, the specific mandates of different funds, and the potential to leverage grants to attract subsequent private investment is essential. Success depends on strong proposals demonstrating both climate vulnerability reduction and positive socioeconomic impacts on local communities.
Public–private collaborations	Government agencies, private developers, technology providers and often insurers are crucial. These partnerships leverage public resources alongside private sector innovation and risk-sharing capabilities to implement complex, large-scale resilience projects.	By using a public–private partnership (PPP) funding approach to build a 25.5 MW wind farm in Cape Verde, Africa Finance Corporation increased resilience by lowering the island's reliance on imported fossil fuels (African Development Bank, 2012).	PPPs can deliver complex, large-scale infrastructure projects in a financially sustainable and equitable manner. They offer a powerful mechanism for developing nations to leverage private sector expertise and financing while ensuring projects align with national development priorities. Early engagement with potential partners, risk-sharing frameworks and clear articulation of benefits for all stakeholders are crucial.
Market-based risk management	Insurance companies, reinsurance markets and investors in risk transfer instruments (*e.g.* catastrophe bonds) are key. They provide financial protection against climate-related risks, enhancing the bankability of investments and safeguarding against potential losses.	Uruguay has made an investment in hydropower insurance to protect against potential losses to its hydroelectric generation facilities during years of drought or low rainfall. Up to 90% of the country's electricity comes from hydropower, thus dry years result in expensive fuel imports. An insurance payout can now be initiated to cover the expense of fuel imports during drought years (Center for Climate and Energy Solutions, 2019).	Detailed risk assessments, including hazard mapping and probabilistic loss projections, provide the foundation for securing optimal insurance and risk transfer solutions. Understanding the range of available instruments, from traditional to parametric,[1] is key to tailoring coverage to specific vulnerabilities. Risk management strategies, when well-designed, can significantly enhance the bankability of resilience investments, opening up new private capital sources.
Specialised green finance institutions	Green banks play a critical role by using public–private capital blends to fill gaps left by traditional lenders. They incentivise investment in clean and resilient infrastructure that might not secure conventional financing.	New Jersey Energy Resilience Bank: The Bank is investing in water and wastewater system improvements and in solar-powered microgrids and distributed energy resources at critical facilities (hospitals, schools, law enforcement centres and shelters). The Clean Energy Finance Corporation: Australia's green bank boasts a substantial capital foundation of AUD 30.5 billion. By leveraging debt and equity co-investment models, it targets a return of 2-3% across renewable energy infrastructure. In the 2022/2023 fiscal year it demonstrated remarkable efficiency by mobilising private capital at a rate of AUD 5.02 per public dollar, marking a significant enhancement from the preceding year's rate of AUD 2.82 (Trivedi, 2024).	Green banks play a pivotal role in mobilising private investment for clean and resilient infrastructure in areas where traditional financing might be lacking. Close collaboration with these institutions can improve project design, streamline the financing process and demonstrate commitment to sustainable development. Their potential to unlock technical expertise and concessional capital makes green banks valuable partners for developing countries.

Table 4 (continued)

TYPE	DESCRIPTION	EXAMPLES	INSIGHTS FOR RESILIENT INFRASTRUCTURE
Green and resilience-themed debt instruments	Issuers include governments, corporations and municipalities, while investors are attracted to environmental, social and governance (ESG) alignment. These bonds raise capital specifically for projects focused on environmental sustainability and/or infrastructure designed to withstand climate-related stresses.	The World Bank supported the development of 150 MW of geothermal power plants in Indonesia by issuing a green bond, thus offering a reliable and domestic electricity generation source. The EBRD has issued the world's first dedicated climate resilience bond, raising USD 700 million. The bond, which saw demand from approximately 40 investors across 15 countries, will finance the bank's new and ongoing climate resilience initiatives. These projects usually fall under three categories: climate-resilient infrastructure, climate-resilient business and commercial operations, and climate-resilient agriculture and ecological systems. Currently, the EBRD has over EUR 7 billion worth of climate-resilient projects in its portfolio. The bond aligns with the Climate Resilience Principles published by the Climate Bonds Initiative, providing clarity on potential resilience investments and incorporating climate resilience in the Climate Bonds Standard (Bennett, 2019).	Issuing green or resilience bonds can attract a wider pool of investors seeking to align their portfolios with ESG goals. Developing countries must ensure rigorous reporting and transparency, and the use of reputable third-party verifiers. This builds trust and confidence in the bonds, potentially translating into lower borrowing costs. Collaboration with experienced underwriters helps navigate the complex bond market and articulate projects' positive environmental and social outcomes.
Community-driven solutions	Local communities, microfinance institutions and crowdfunding platforms are essential. They empower local stakeholders to finance resilience initiatives addressing their specific needs, aligning financial objectives with social and equity outcomes.	Jamaica, a small island developing state vulnerable to climate change, has implemented effective microfinance mechanisms for enhancing power system resilience. Using a private sector co-operative mutual bank as an intermediary, Jamaica provides concessional loans to communities in agriculture and tourism sectors. These loans address pressing needs such as water scarcity due to droughts and shifting rainfall patterns. The microfinance approach minimises adaptation costs and empowers local communities to build climate resilience. By empowering intermediaries, monitoring investments and supporting borrowers, Jamaica exemplifies successful community-based financing for climate adaptation (Climate Investment Funds (CIF), 2018; Green Climate Fund (GCF), 2023). Solar microgrids in Puerto Rico: After Hurricane Maria devastated Puerto Rico's power grid in 2017, community-led crowdfunding campaigns emerged to install solar microgrids. These decentralised systems provide reliable electricity to critical facilities, such as hospitals and community centres, even during grid outages (Miguel Yañez-Barnuevo, 2023). Microgrids can sell energy back to the grid creating revenue streams and improving economic viability (Alec Kostovny, 2025). Microgrid-as-a-Service (MaaS) is a financing mechanism that enables organisations to deploy microgrids without any upfront investment. This is made possible through modified power purchase agreements, which allow companies to own and operate systems (Philip Barton, 2017). Nepal: crowdfunding initiatives have supported the development of resilient microgrids in remote mountainous regions in Nepal. These systems combine solar, hydro and battery storage to ensure continuous power supply, especially during natural disasters or grid failures (UNDP, 2023).	Microfinance and crowdfunding initiatives can be highly effective for smaller-scale, locally tailored resilience projects that directly benefit vulnerable communities. Building trust with local stakeholders is essential for long-term success. These models prioritise community engagement and bottom-up financing, prioritising projects that might not be attractive to large institutional investors, but which deliver high social impact alongside financial gains.

Table 4 (continued)

TYPE	DESCRIPTION	EXAMPLES	INSIGHTS FOR RESILIENT INFRASTRUCTURE
Dedicated investment vehicles	Resilience investment funds attract impact investors and others seeking exposure to climate resilience projects. These funds, managed by asset managers, target various risk–return profiles, technologies and geographic regions, promoting long-term, risk-adjusted returns.	The US Department of Energy (DOE) allocated USD 42 million to support 15 projects across 11 states. These projects aim to develop next-generation semiconductor technologies that enhance the reliability, resiliency and flexibility of the domestic power grid. By advancing semiconductor technology, the United States seeks to improve power system performance and adapt to changing climate conditions (US DOE, 2023). The European Union has been actively promoting climate resilience in its power systems. Investments focus on upgrading ageing infrastructure, integrating renewable energy sources and implementing smart grid solutions. These efforts enhance the system's ability to withstand extreme weather events and adapt to a changing climate (Eurelectric and EPRI, 2022).	Resilience-focused investment funds offer the potential to access larger pools of capital aligned with specific project needs. Thorough due diligence on fund mandates, focus areas and track records is crucial. Presenting scalable solutions, clear risk-return profiles and a strong focus on social equity aligns well with the goals of many impact investors seeking opportunities in developing countries.
Regulated tariffs	Regulated tariffs play a crucial role in enhancing power system resilience to extreme weather by providing financial incentives for asset owners to invest in climate-related resilience projects.	United States: The Federal Energy Regulatory Commission has implemented mechanisms allowing utilities to recover costs for resilience investments through regulated tariffs (Kumar and De, 2024). Australia: the Australian Energy Regulator has approved tariff adjustments to fund grid-hardening projects aimed at mitigating the impacts of bushfires and extreme heat (Panteli *et al.*, 2024). United Kingdom: The UK Office of Gas and Electricity Markets (Ofgem) has introduced a regulatory framework that includes resilience incentives, enabling network operators to earn returns on investment in flood defences and storm resilience (Pan and Li, 2022).	These measures ensure that asset owners are financially motivated to enhance the resilience of power systems, thereby reducing the risk of outages and improving overall reliability in the face of increasing extreme weather events.

Note: [1] Parametric insurance is a non-traditional insurance product that offers pre-specified payouts based upon a trigger event.

The most effective financial solutions for resilience are context- and location-dependent and can and should be incorporated into broader resilience planning initiatives (Guibert *et al.*, 2019). Some examples include:

Australia: Rooftop solar PV with batteries

Australia presents a noteworthy example of government-led incentives to accelerate the adoption of rooftop solar PV and battery storage systems. Their approach includes a combination of grants, rebates and interest-free loans with flexible repayment terms. This tiered, multifaceted strategy offers lessons for other regions seeking to encourage distributed energy resources at both residential and commercial scales. Key takeaways include the potential of combining diverse financial incentives tailored to project size, as well as the importance of strong government commitment and a robust supply chain in achieving rapid adoption rates (Evergen, n.d.).

United States: Microgrids and EVs

The United States demonstrates the value of integrating energy resilience planning into broader disaster preparedness frameworks. The Federal Emergency Management Agency (FEMA) Hazard Mitigation Grant Program prioritises resilient infrastructure, including microgrids, providing a model for other regions seeking to reduce the impact of natural disasters (FEMA, n.d.). Additionally, federal tax credits for renewable energy technologies, which vary according to system size, highlight the potential for size-based incentives to align with diverse energy needs. However, successful replication hinges on several factors, including adequate funding streams, streamlined regulatory processes to support microgrid deployment, and proactive measures to manage potential grid integration challenges associated with large-scale EV adoption.

Rwanda: Mini-grid financing options

Experiences in mini-grid financing offer valuable insights for regions seeking to expand energy access in areas with limited infrastructure. Notably, Rwanda's Renewable Energy Fund exemplifies creative financial mechanisms tailored to local needs. This fund offers lines of credit to domestic financial institutions, capital subsidies for project development and performance-based incentives (BRD, 2017). Other regions can draw lessons from the importance of adaptable funding models, the critical role of local financial institutions in facilitating project success and the need for well-defined performance metrics to track outcomes. It is important to consider the challenges associated with these models, including the need for long-term support to ensure project sustainability and the complexities of co-ordination across multiple stakeholders.

5. CONCLUSION

Power systems are exposed to several kinds of extreme events, mostly natural or climate-related, but also man-made. With HILF events becoming more frequent, a greater understanding of the system-wide cascading impacts on power systems, and the ripple effect they have on the economics of the various other sectors becoming more evident, building resilient power systems is becoming crucial. In addition, with the rapid global progress of grid modernisation and digitalisation efforts, power systems are now exposed to cyberattacks by malicious agents. Therefore, robust cybersecurity measures need to be implemented.

Power system resilience planning and enhancement must be given a high priority, and a greater focus must go on capacity building among power system stakeholders so that they can understand and identify the threats to and vulnerabilities of their power system. System vulnerability is a combination of threats that exist to the different parts or assets of the power system. To improve resilience to events and vulnerabilities, system resilience first needs to be assessed using resilience metrics, which highlight the gaps in resilience and thereby enable the identification of measures to improve it. Measures to enhance power system resilience should be tailored appropriately to cater for each unique power system segment and its specific design and operation. Strategies must be developed to evaluate, enhance and implement power system resilience measures in power systems.

It is also important to understand key system interdependencies, such as the energy–water nexus or the power–communication nexus, and the roles they play within the context of defining, quantifying and enhancing power system resilience. In recovery and adaptation strategies, it is vital to identify the stakeholders who are best placed to make informed decisions following a HILP event. Accuracy must be ensured within data collection and exchange. This would allow multi-dimensional impact modelling to identify the most appropriate measures and cross-sectoral requirements.

The establishment of an enabling framework that creates and validates the need for the implementation of resilience enhancement measures is critical to building a robust and resilient power system. In implementing the enhancement of power system resilience, stakeholders must adopt a multi-faceted approach: planning, operational, financial and policy.

The implementation of decentralised generation is a key building block for increasing power system resilience by reducing the exposure of end users to the impacts of extreme weather on long transmission and distribution lines. Increasing the renewables share of a power system has high economic, social, environmental and resilience benefits. This is evident in the global examples provided in this report, which demonstrate how renewables have bolstered the resilience of power systems.

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