The Coming Storm – Building electricity resilience to extreme weather

Eurelectric report with technical assistance provided by EPRI

December 2022

Eurelectric represents the interests of the electricity industry in Europe.

Our work covers all major issues affecting our sector. Our members represent the electricity industry in over 30 European countries.

We cover the entire industry from electricity generation and markets to distribution networks and customer issues. We also have affiliates active on several other continents and business associates from a wide variety of sectors with a direct interest in the electricity industry.

Contact:

Caoimhín Ó BRIAIN, Senior Advisor
Distribution and Market Facilitation
cobriain@eurelectric.org

We stand for

The vision of the European power sector is to enable and sustain:

- A vibrant competitive European economy, reliably powered by clean, carbon-neutral energy
- A smart, energy efficient and truly sustainable society for all citizens of Europe

We are committed to lead a cost-effective energy transition by:

investing in clean power generation and transition-enabling solutions, to reduce emissions and actively pursue efforts to become carbon-neutral well before mid-century, taking into account different starting points and commercial availability of key transition technologies;

transforming the energy system to make it more responsive, resilient and efficient. This includes increased use of renewable energy, digitalisation, demand side response and reinforcement of grids so they can function as platforms and enablers for customers, cities and communities;

accelerating the energy transition in other economic sectors by offering competitive electricity as a transformation tool for transport, heating and industry;

embedding sustainability in all parts of our value chain and take measures to support the transformation of existing assets towards a zero carbon society;

innovating to discover the cutting-edge business models and develop the breakthrough technologies that are indispensable to allow our industry to lead this transition.

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TOGETHER...SHAPING THE FUTURE OF ENERGY®

Who We Are

With a foundational mission to benefit society, EPRI delivers **independent, objective thought leadership and industry expertise** to help the energy sector identify issues, technology gaps, and broader needs that can be addressed through effective, collaborative research and development programs

Founded in 1972, EPRI is **the world's preeminent independent, non-profit energy research and development organization**, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Contact:
Alexander Summe, *Chief of Staff*
asumme@epri.com

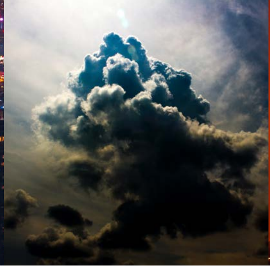
Who We Work With

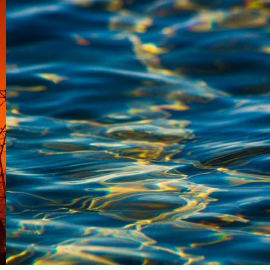
Rooted in science and rigor, EPRI collaborates with scientists, engineers, government, and experts from academia and industry to shape and drive technology advancement by pushing the frontier of innovation from concept, pilot, operation to end-of-life.

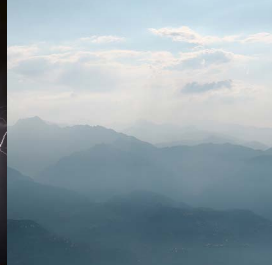
Our mission is accomplished by an extensive researcher network and a comprehensive advisory structure. Leaders and technical experts from the electricity sector, academia, and government help EPRI develop and conduct its research, deliver results, and provide for technology transfer and the application of research findings.

EPRI's work is funded by hundreds of organizations around the world, including the energy sector, academia, and government. Organizations who engage in EPRI research, development, and demonstration programs have unique opportunities to:

- Identify and solve critical and emerging industry issues.
- Stay at the forefront of technology innovation.
- Gain access to a comprehensive, timely RD&D portfolio.
- Collaborate and network with industry peers through advisory councils and committees.
- Implement technology through the support of our researchers and technical advisors.
- Reduce future investment risks.
- Inform policies with objective, science-based findings and facts.





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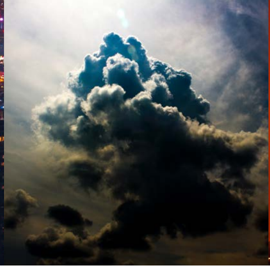

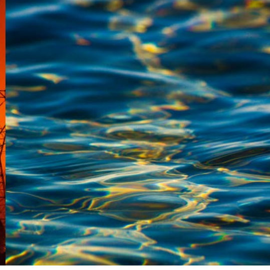

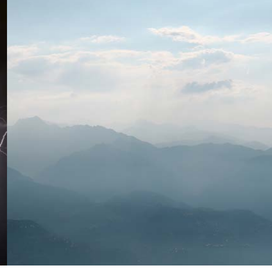

Abstract

This report, which is a joint initiative of Eurelectric and EPRI (Electric Power Research Institute), explores the resilience of the power system as a whole and promotes a proactive approach to climate change adaptation of the power sector. The technical expertise and research work already ongoing at EPRI are complemented by Eurelectric's expertise in European affairs and the whole electricity value chain it represents.

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Executive Summary

In the eye of the storm: unprecedented challenges for the power sector

The European power system is facing unprecedented challenges. COVID-19 challenged how staff and systems worked together and the Russian invasion of Ukraine has sparked an unprecedented energy crisis across Europe. The way out of this major crisis requires decisive action to shift away from imported fossil fuels. Electrification, allowing us to regain our energy independence, must become the norm – and it must go with guarantees on the reliability of the electricity system.

+ 1.5°C by 2030: the dramatic increase in extreme weather events

Latest climate projections suggest that the world is well on its way to +1.5°C by 2030 and each new season brings further proof that climate change contributes to more and more extreme weather events.

Such an increase will affect us all. The Intergovernmental Panel on Climate Change (IPCC) projects an increase in extreme heat, fire weather, heavy precipitation, pluvial flooding, sea level rise, coastal flooding, and severe windstorms across all of Europe, with only Northern Europe being spared fire weather. Droughts are expected to increase in the Mediterranean and Western & Central Europe. Meanwhile, heavy precipitation, mean precipitation and pluvial flooding are expected to increase across Northern Europe.

All power assets are exposed

All power system assets are exposed to the effects of these growing number of extreme weather events, from generation and transmission to distribution and the final customer.

Hydropower generators face changes in water inflow patterns. Summer droughts cause security of supply and price issues for particularly dependent countries, while winters with increased precipitation and icing in certain regions cause blockages and overtopping.

Thermal and nuclear power plants can have their operation and efficiency reduced during heat waves when cooling water and cooling air temperatures are higher than usual. Most generation assets are exposed in some way to the effects of coastal and inland flooding.

However, some of the biggest impacts of extreme weather affect transmission and distribution systems. Overhead power lines are exposed to high winds, when trees and other vegetation can collide with them, resulting in physical damage and electrical faults. The joints and insulation of underground cables are put under strain during heat waves, especially during sustained heat over several days. Substations, if not well located or sufficiently protected, can be damaged by floods. Wildfires, floods, and high winds can limit the ability of staff to safely access substations and other assets.

From a customer perspective, increased electrification puts more focus on resilience and reliability of the electricity system, with the rollout of EVs, heat pumps, and industrial electrification. Customers can also support the grid during extreme weather events with innovations in flexible markets and microgrids.

More adaptation measures needed for a warming continent

The power system already has a host of adaptation measures available to face climate hazards. These include physical hardening and uprating of networks, physical protection measures, additional spill gates for hydropower dams, resizing of thermal and nuclear plant cooling systems, additional redundancy of distribution network design, preparedness plans, backup systems, and digital tools to enhance visibility and control of the power system down to low voltage level.

Yet, more needs to be done to ensure a resilient energy system. The power sector needs to invest in the decarbonised economy of tomorrow, adapting to climate change and serving the needs of millions of electric vehicles, heat pumps and flexible prosumers. Assets of the power system must be designed to withstand the effects of climate change over their full service life. It is necessary to invest now in adaptation measures and system hardening to lower costs in the aftermath of an extreme weather event.

Invest now to avoid higher costs later

Eurelectric's Connecting the Dots report estimated that €33 billion would be required in the decade 2020-2030 to support distribution system resilience in the EU. Notably, this figure predates the higher ambitions of the REPowerEU plan, so the necessary investments need to be scaled up appropriately and must be complemented by resilience investments in generation and storage.

Such investment is critical to the realisation of Europe's electrification and climate objectives. Investment in growing the system share of renewables with lower wholesale prices and the flexibility opportunities provided by new technologies and services will reduce Europe's dependence on imported gas. Connecting the Dots estimated that the net increase in customers' bills arising from distribution investments would amount to only 1,5% per annum.

Regulators should thus promote anticipatory investment frameworks, with special attention to grid resilience and promote a Resilience Incentive Mechanism to stimulate the uptake of adaptation measures and smart grid technologies like smart meters and automation.

Increase coordination to strengthen resilience

Stronger coordination and communication between all power sector stakeholders is needed. These stakeholders are heavily interdependent on each other as well as a host of external parties such as suppliers and telecom providers.

This spirit of collaboration immediately applies to the implementation of the Risk Preparedness Regulation, where each competent national authority must establish a risk-preparedness plan. To improve the effectiveness of these plans it is vital that DSOs and market actors are effectively consulted.

Given the exposure of power system assets to the effects of climate change, this same attitude of cooperation must also be applied to the proposed Resilience of Critical Entities Directive (CER).

An integrated approach that brings together national climate adaptation plans and market actors' investment projections will be key to securing the resources needed to construct a truly resilient grid. The cost of doing nothing as climate change provokes more extreme weather events will be felt throughout all of society and quickly outstrip the investment needs of a digitalised and modernised power system.

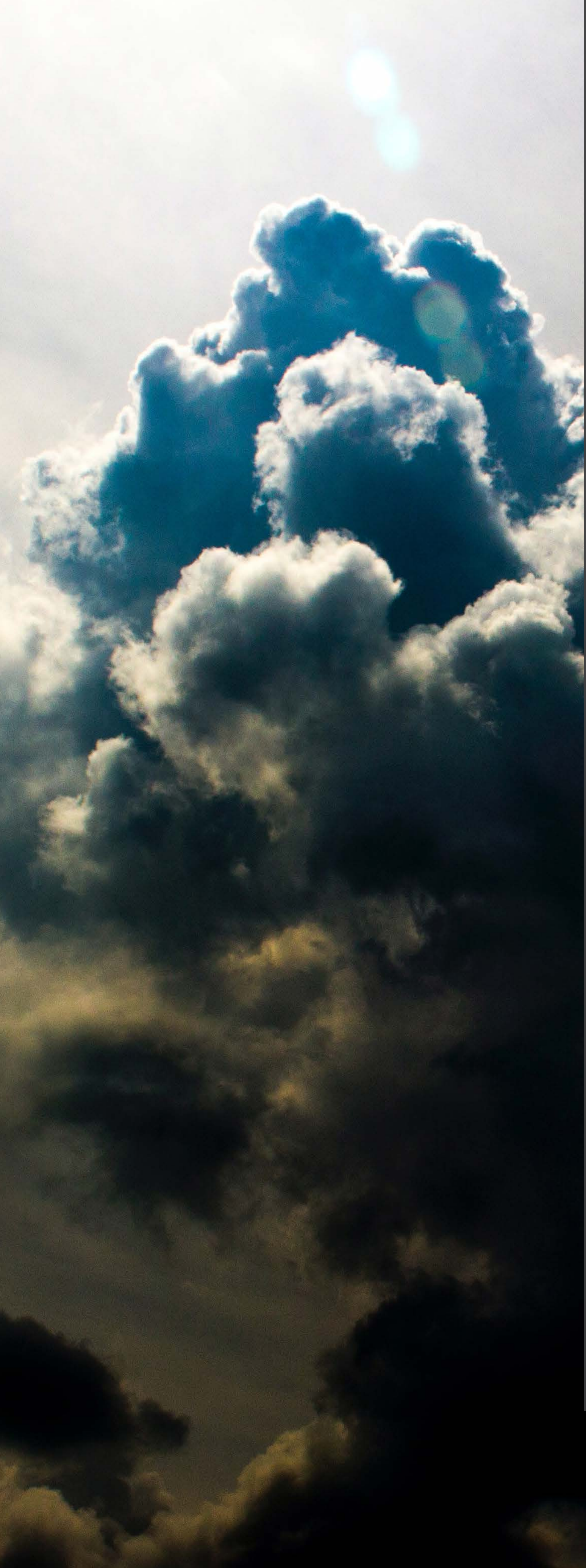
Strong coordination also means consistent and transparent methodologies for assessing climate risk and informing resilience strategies so that both utilities and external stakeholders can have confidence that the most prudent and effective approach is being utilised. EPRI's Climate READi project has taken the first steps to establishing a holistic and comprehensive framework and is convening a broad spectrum of stakeholders to promote consensus and advance climate resilience strategies.

Tackle adaptation and mitigation together

It is clear today that climate mitigation and adaptation can no longer be tackled in silos. A failure to reach decarbonisation goals could result in increased climate adaptation costs in the long term, and a failure to adapt to climate change could be devastating for the European economy. Indeed, the price of inaction now far outweighs the cost of building a sustainable, resilient society. Nowhere is this truer than regarding Europe's crucial electricity infrastructure.

Conversely, the benefits of such a reinforced system will reverberate through society by acting as a solid foundation for the widespread electrification of transport, heating and cooling, and industrial processes. This, in turn, will benefit climate mitigation by reducing direct emissions and climate adaptation by facilitating the flexibility of the grid. This would then lower costs for final customers by reducing demand peak and the need for expensive hardening of the grid.

While topics such as cybersecurity and military threats are not the primary focus of this project, they are referred to due to ongoing developments in Europe and synergies between resilience to climate change and overall system resilience.



Introduction

Background

Climate change is an existential threat which requires urgent action on an international level. To address this threat countries committed to the 2015 Paris Agreement which set a framework to limit global warming well below 2°C, to pursue efforts to limit it to 1.5°C, and to reach global net zero carbon emissions by 2050.

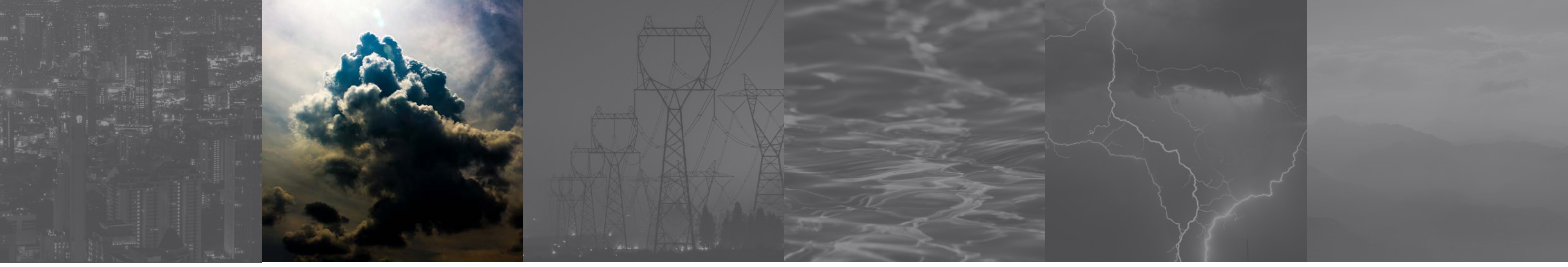
Climate mitigation through decarbonisation is essential to guarantee the long-term sustainability of the global economy, and the power sector is committed to leading this transition. If mitigation efforts do not reach these goals, Europe and the world will be left with even higher adaptation costs as temperatures continue to rise. Thus, climate mitigation and adaptation are inextricably linked.

In Europe, the Green deal, the Fit for 55 package, and the REPowerEU plan have set increasingly ambitious targets for renewable integration and the facilitation of e-mobility, heat pumps, and flexibility solutions. With coal and gas plant closures, more renewable capacity, increased digitalisation – including the rollout of smart meters and smart grids – and the growing numbers of 'prosumers', the shape and composition of the electricity system are going to transform over the coming decades.

Despite all these efforts, projections for Europe still expect an increase in average temperatures with warmer summers, more heatwaves, fewer cold spells, and an increase in the number of severe storms. Recently, we have seen heat waves, droughts and wildfires scorch the Mediterranean, unprecedented flooding in central Europe, and more frequent storms hitting Ireland and the UK. Europe and its infrastructure needs to brace itself for more extreme events.

The electricity industry has a key role to play in adapting to climate change by building, maintaining, and enhancing a secure and resilient infrastructure that can withstand these increasingly severe and frequent weather events and so ensure security of supply. This requires continued investments in the power system and requires supporting action from a broad range of stakeholders and policymakers.

Customers will have ever higher expectations when it comes to resilience as they become more reliant on the power system for e-mobility, e-heating and cooling and electrified industrial processes. The power sector has the solutions at hand to face these challenges and adapt to climate change in a decarbonising power system. This report will describe those challenges and their solutions.



Natural Disaster in Europe (number of climate related events)

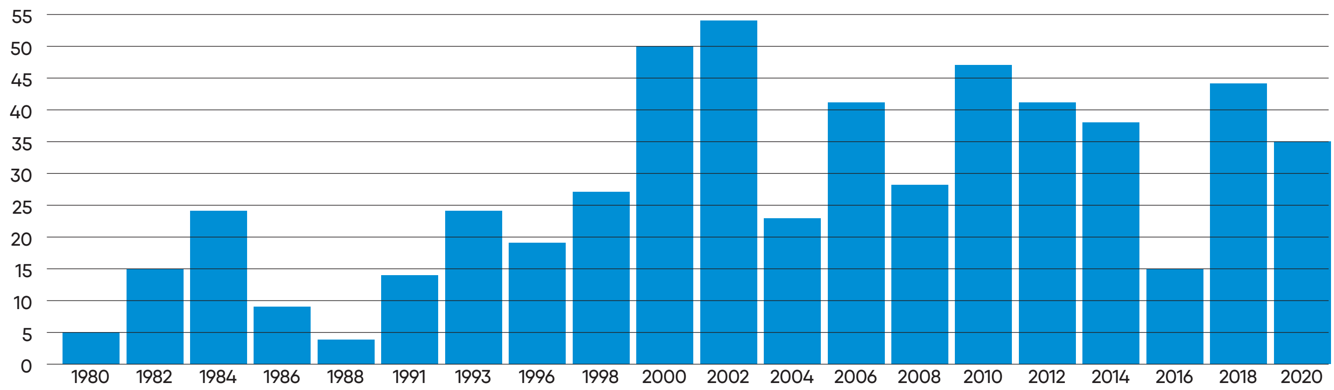


Figure 1: Trend for increases in climate related natural disasters in Europe EM-DAT - CRED

Scope & Objectives

The purpose of this report is to create an agenda-setting reference point on the resilience of the power system to climate change. It is aimed at policymakers and key decision-makers to encourage integrating best practices and solutions in relevant legislation and develop funding mechanisms and incentives for climate change adaptation-driven investments.

While topics such as cybersecurity and military threats are not the primary focus of this project, they are referred to throughout the report due to ongoing developments in Europe and synergies between resilience to climate change and overall system resilience.

The extent of the climate change threat is presented as well as the exposure of the power system to it. The response strategies of the power sector are described including an inventory of regulatory and investment-related tools at European level. Policy recommendations are put forward to help advance the agenda regarding cost-impacts, additional investment needs, and investment decision-making frameworks for resilience in the power sector.

Definitions

Mitigation: Mitigation means making the impacts of climate change less severe by reducing the emissions of greenhouse gases (GHG) into the atmosphere or enhancing activities that remove these gases from the atmosphere. Mitigation can be achieved either by reducing the sources of these gases, increasing the share of renewable energies, establishing a cleaner mobility system, or by enhancing the sinks for these gases — e.g. by increasing the size of forests.

Adaptation: Adaptation means anticipating the adverse effects of climate change and taking appropriate action to prevent or minimise the damage caused. It is the process of adjusting to the current and future effects of climate change.

Resilience: CIGRE Working Group SC C4.47 defines power system resilience as the ability to limit the extent, severity, and duration of system degradation following an extreme event.

Reliability: The System Average Interruption Duration Index (SAIDI), helps quantify power system reliability by measuring the total amount of time that an average customer experiences service interruption during the measurement period, typically a year. Similarly, the System Average Interruption Frequency Index (SAIFI), measures the number of interruptions an average customer experiences during the measurement period. Typically, Major Event Days, such as storms, are excluded from reliability calculations as they constitute "force majeure", however, there is no one accepted standard for interpreting what constitutes a Major Event Day.

GWL: Global Warming Levels are a way of communicating levels of future climate change in addition to projections based on emissions scenarios. GWLs were first introduced in the IPCC AR6 Working Group I report and refer to a set of common global average temperature change levels relative to pre-Industrial times.

Climate Change Data

The climate is changing with strong evidence that human activities are driving this change. Although climate conditions and global sea levels have varied throughout the millennia, the rate, scale, and drivers of current climate change and sea levels differ dramatically compared to the past. Emissions of greenhouse gases, including carbon dioxide and methane, are the primary contributors to currently observed global warming (see Figure 2). By trapping heat in the Earth's atmosphere, these gases perturb the planet's radiative balance and lead to global warming.

The impacts of climate change are already apparent and are affecting every inhabited region of the globe. Weather extremes such as heat waves, severe wind storms, floods, and wildfires are either already increasing or projected to increase in frequency, magnitude, and intensity. Permafrost is melting. Global sea levels are rising. Ocean acidity is increasing. Even if GHG emissions are reduced to zero in the near term, the long-lasting effects of their presence in the atmosphere will persist for decades.

The International Panel on Climate Change (IPCC) regularly publishes reports on observed and projected climate change. These reports, as well as country and local climate assessments, publicly available climate datasets, and climate change decision support tools can better inform decisionmakers – including those in the power sector.

The Coupled Model Intercomparison Project (CMIP) is an international climate modelling effort that standardises scenarios and frameworks for climate model simulations. Results from CMIP experiments underpin the IPCC assessment reports and can be downscaled to finer spatial and temporal resolutions. Although downscaled data is not essential for climate impact analysis, higher-resolution data can be important for evaluating future climate outcomes in regions with complex topography or significant climate variability.

CMIP6 includes a set of climate scenarios that follow the naming convention SSPx-y. SSPx refers to a socioeconomic narrative around societal development, while the "y" number corresponds to the radiative forcing in 2100 (O'Neill et al, 2016).

Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850–2020)

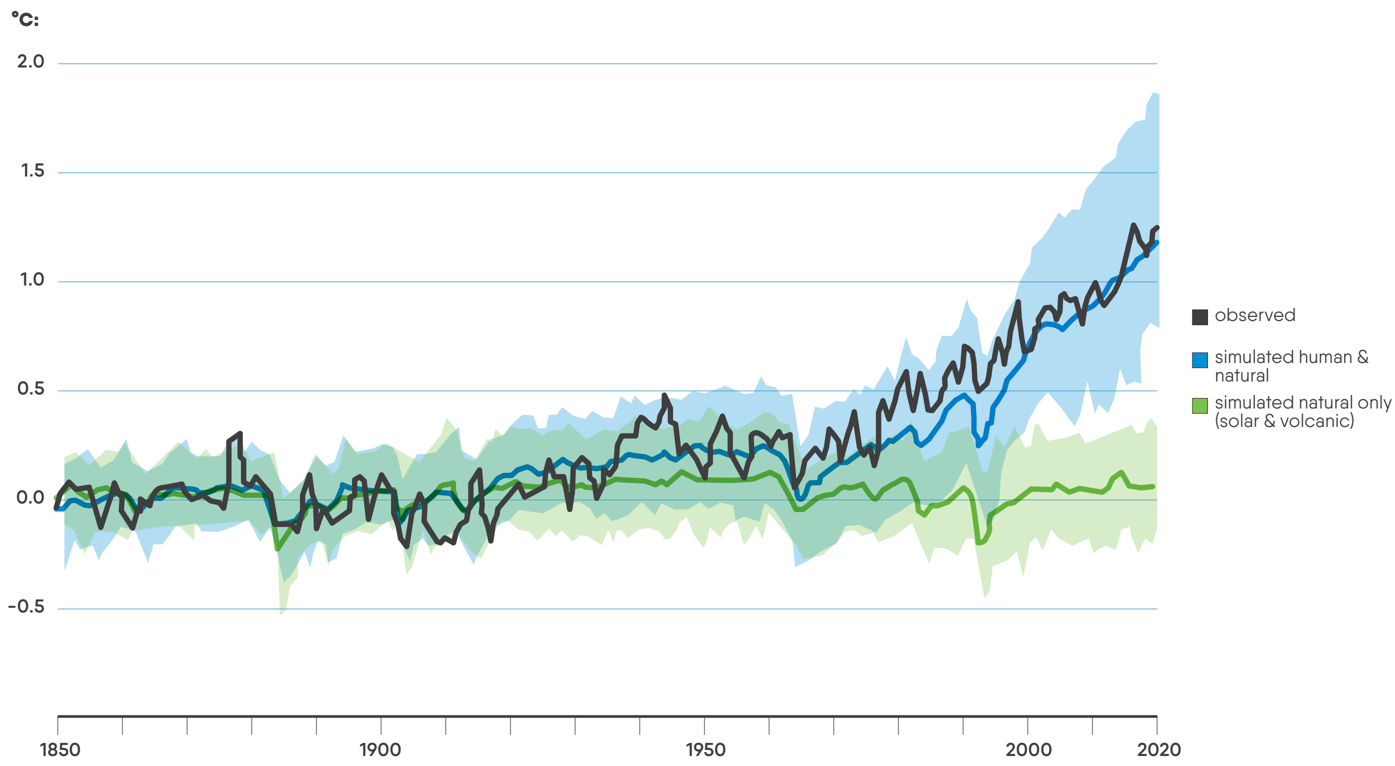


Figure 2: IPCC ARG WGI Figure SPM.1. Change in global surface temperature as observed (black line) and simulated using climate models (coloured lines). Coloured shaded areas show the very likely range of simulations.

Global climate models project the trajectory of atmospheric GHG concentrations and estimate changes in primary climate variables (such as air pressure, temperature, humidity, precipitation, wind speed, and solar irradiance) under these different scenarios. Secondary process or hydrological models can use projections from climate models as inputs to estimate changes in secondary climate variables such as drought, wildfires, and streamflow. Ranges of uncertainties are always displayed since projections cannot be exact. Users of forward-looking climate data are advised to consider outcomes from a range of scenarios and from a range of models to capture the inherent uncertainty.

In addition to changes in mean climate conditions (such as average temperature), climate change can affect the intensity, duration, and magnitude of several types of extreme weather events, although specific changes vary by event type, climate scenario, region, and other factors.

Some types of 1-in-10-year events and 1-in-50-year events are expected to become more frequent and/or intense with climate change (see Figure 4). For instance, the temperature of the annual hottest day, the number of extreme heat wave days, the maximum of consecutive dry days and the level of precipitation for consecutive five raining days are all expected to increase in the coming decades.

Changes in global mean temperature can manifest in different ways around the world. For organisations based in Europe, it will be critical to evaluate how global climate change will manifest locally. Severe heatwaves, drought, and fire weather are all examples of conditions that have been attributed to climate change. Temperatures in Europe are projected to rise faster than the global average. Additionally, while the frequency and intensity of extreme heat, heavy precipitation and severe windstorms are likely or very likely to increase across Europe, the IPCC projects large regional variation across the continent. For example, though the Mediterranean area is expected to experience impacts from fire weather events, aridity, hydrological, agricultural and ecological droughts, Western and Central Europe will probably face significant river flood increases. As for Northern Europe, the IPCC projects an increase in mean precipitation. Figure 6 presents a table of observed and projected trends in multiple climate impact drivers for four regions in Europe.

Global surface temperature change relative to 1850–1900

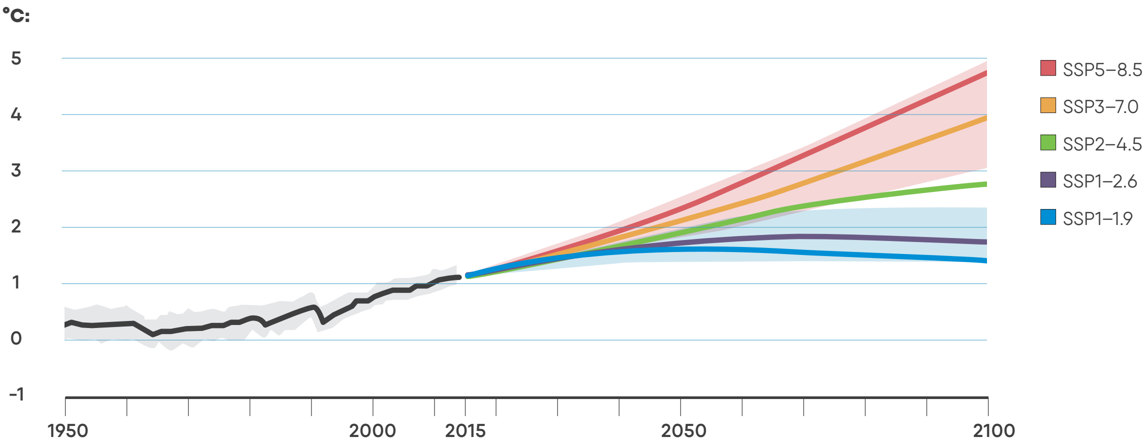


Figure 3: IPCC AR6 WGI Figure SPM.8a

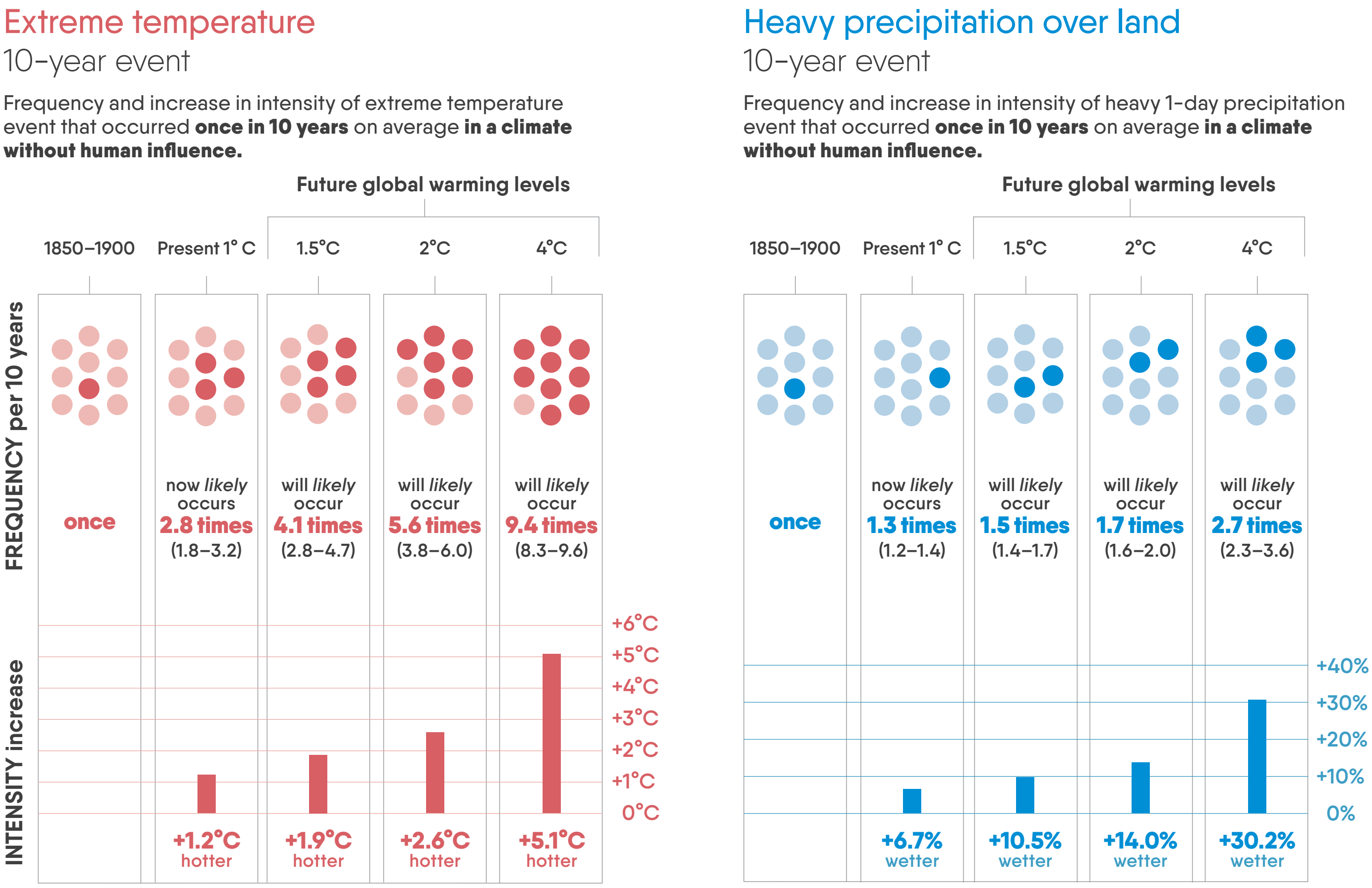


Figure 4: IPCC AR6 WGI Figure SPM.6. Projected average changes in frequency and intensity of select extreme weather events for several Global Warming Levels (GWLs).

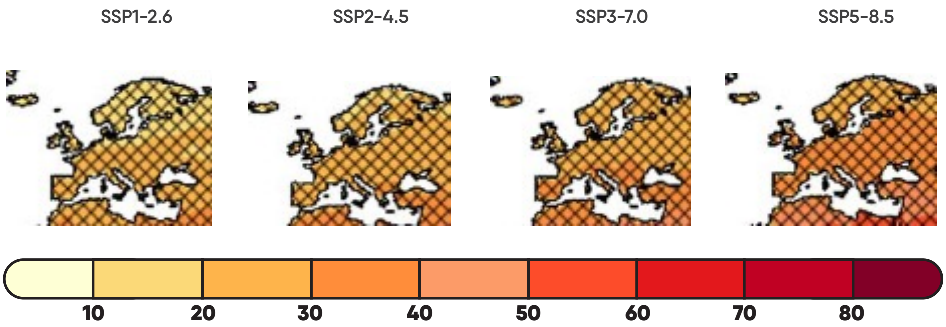


Figure 5: Projected number of annual heat wave days in Europe across four climate scenarios for the 2036-2065 period

As can be seen from figure 5 there is a high probability in all European regions for a noticeable increase in extreme weather conditions for which adaption measures need to be identified and developed. Information from global and regional assessment reports provides valuable insights into observed trends and projected directions of change. Depending on the specific context of risk assessment application, localised data at higher spatial and temporal resolution can be used for specific local risk assessment applications. Physical climate variables may require additional interpretation or analysis to provide meaningful input to power system analysis.

At national level, several governments fund the downscaling of physical climate scenarios, electing specific climate variables to improve decision making in the long term. Downscaling to finer spatial and temporal resolutions can produce data that better represent more complex phenomena or complex topography. With any type of projection data, however, it is important to represent the future uncertainty relevant to decision-making. Governments should consider in their climate scenario work new climate variables aligned with the power sector and other infrastructure needs, along with what is already being done for the agriculture or the public health sectors.

	Climatic Impact-driver																																
	Heat and Cold				Wet and Dry								Wind				Snow and Ice						Coastal and Oceanic					Other		
Region in Europe	Mean air temperature	Extreme heat	Cold spell	Frost	Mean precipitation	River flood	Heavy precipitation and pluvial flood	Landslide	Aridity	Hydrological drought	Agricultural and ecological drought	Fire weather	Mean wind speed	Severe wind storm	Tropical cyclone	Sand and dust storm	Snow, glacier and ice sheet	Permafrost	Lake, river and sea ice	Heavy snowfall and ice storm	Hail	Snow avalanche	Relative sea level	Coastal flood	Coastal erosion	Marine heatwave	Ocean and lake acidity	Air pollution weather	Atmospheric CO_2 at surface	Radiation at surface
Mediterranean	↗	↗ •••	↘ •••			↘	5			↗ ••	↗ ••		↘ 6	7			↘						↗		2	↗	↗		↗	
Western and Central Europe	↗	↗ •••	↘ •••		↗	↗	↗	4			↗		↘				↘	↘					↗		2	↗	↗		↗	
Eastern Europe	↗	↗ •••	↘ •••		↗		↗						↘				↘												↗	
Northern Europe	↗	↗ •••	↘ •••		↗	↘ 1	↗ •••						↘				↘	↘					↗	8	2, 3	↗	↗		↗	

KEY

Observational trend evidence ↗ Past upward trend *(medium or higher confidence)* ↘ Past downward trend *(medium or higher confidence)*

Attribution evidence ••• ***High confidence*** *(or more)* •• ***Medium confidence*** *(or more)*

Level of confidence in future changes ***High confidence*** of increase (or more) ***Medium confidence*** of increase (or more) ***Low confidence*** in direction of change ***Medium confidence*** of decrease ***High confidence*** of decrease Not broadly relevant

Figure 6: IPCC AR6 WGI Table TS.5, expected evolutions of climate impact-drivers

Climate change mitigation measures will need to be deployed to avoid the worst effects of climate change. How fast we can reduce GHG emissions will also influence the amount of climate change experienced in the future. Large scale climate change mitigation, however, will not be able to prevent all impacts of climate change. Changes in climate have already been observed and more are projected in the future, rendering adaptation inevitable.

Society, including the power system, should evaluate the potential impacts of these changes in average (chronic) and extreme (acute) climate conditions on human, social, and technical systems, including the built environment and infrastructure. Proactive adaptation can help reduce some of the harm associated with these impacts. Regional variation and disparities in adaptive capacity must be also considered when determining which adaptation measures to implement.

Early detection and forecasting of extreme weather can improve our ability to withstand them. Today, many early warning systems are used to identify weather events and give the public time to prepare. Several others are developed to predict events whose frequency and intensity are projected to increase, like extreme heat. These systems help people prepare for hazardous weather-related events. In the end, it "saves lives and jobs, land and infrastructure and supports long-term sustainability" by "saving money in the long run and protecting economies", according to the United Nations.

Additionally, since adaptation measures are designed in response to projections, decisionmakers must also consider their inherent uncertainties. Indeed, the further into the future we look, the greater the uncertainty related to GHG emissions trajectories and the response of the climate system to global warming. Adapting our ecosystem and infrastructure to climate change, therefore, consists of identifying, as of now, the actions needed to prevent climate damage. Adaption is therefore a question of "insurance" which comes at a price but will help to contain risks once extreme events do happen.

Case 1: "Once in a century flooding" in Germany July 2021

Heavy precipitation over Central Europe (Germany, Netherlands, Belgium), with up to 150 litres of rain per square meter within 24 hours, on already soaked soils, caused "Once in a century flooding" in July 2021.

The flooding was prompted by a weak, wiggly, and shifted jet stream, which forced a low-pressure system to be stationary and recirculate around the region. This led to exceptionally high precipitation for multiple days. The jet stream is primarily driven by the difference in temperature between the polar and mid-latitudinal regions. If the temperature rate over the Artic circle is increasing at a rate of two to three times higher than at the equator, the equator-to-pole thermal gradient diminishes, potentially leading to a weakened and meandering jet stream similar to that witnessed in the July event. If global temperatures continue to rise, these types of events will continue to increase in frequency. Improved climate projections that show how, where, and when these events may happen can inform which power systems assets will be affected, influencing resilience planning.

Topographical features in the affected central European regions increased the impact of heavy precipitation. For example, one of the most hit areas in West-Germany, the Ahr river valley, is characterised by narrow valleys, steep slopes, and the fact it is fed by a number of smaller streams. Within hours the Ahr flooded whole villages. A disaster alert was called and ten of thousands of rescuers from police, fire brigades, technical aid organisations and the military were busy for days rescuing people and providing food, water, and medical first aid.

Occurred: July 2021

Where: Central Europe (West-Germany, East-Netherlands, East-Belgium, East-France and Luxembourg)

Impact: >200,000 without power, more than 220 people died, over 196 alone in Germany.

Damage in total 1st estimate: The storms caused devastating damages to houses and infrastructure, amounting to more than 46 billion euros.

Current EU Regulatory Framework

There are several legislative initiatives in Europe which affect the resilience of the power system to climate change. A selection of relevant legal instruments is summarised below, with further details included in Appendix I.

The **2015 Paris Agreement** sets adaptation and resilience as one of its key objectives for addressing climate change. In Article 7, countries commit to ensuring adaptation measures take into account the impacts of global warming.

The **2019 Risk Preparedness Regulation** aims to avert, adapt to and handle electricity crises including those driven by extreme weather. The regulation mandates the European Network of Transmission System Operators for Electricity (ENTSO-E) to submit to ACER a methodology to identify regional electricity crisis scenarios. Since this, Member State competent authorities have set up national risk-preparedness plans establishing measures to avoid or deal with these electricity crises in each country.

The **2020 EU Taxonomy Regulation** and the associated 2022 delegated act on climate change adaptation and mitigation activities provide a methodology and screening criteria to define environmentally sustainable activities. Sustainable activities must contribute to at least one of the six objectives of the Taxonomy without doing significant harm to others. For instance, an activity contributing to climate change mitigation must avoid significant harm to climate change adaptation. A sustainable adaptation activity must make best efforts to reduce all material physical climate risks, must not adversely affect adaptation efforts by others, and have adaptation-related outcomes that can be defined and measured using adequate indicators.

The Commission proposed in December 2020 a new directive on the resilience of critical entities (**CER Directive**) to supersede the European Critical Infrastructures Directive. The proposal includes more assets and the latest risks such as the growing impact of climate change. The Commission states the new Directive will "ensure that critical entities are able to prevent, resist, absorb and recover from disruptive incidents". The proposal enlarges the scale of the Critical Infrastructure Directive from two sectors to ten, still including energy. Based on a national risk assessment, Member States must identify critical entities, establish measures to foster the resilience of their infrastructure and ensure disruptions are reported to national authorities.

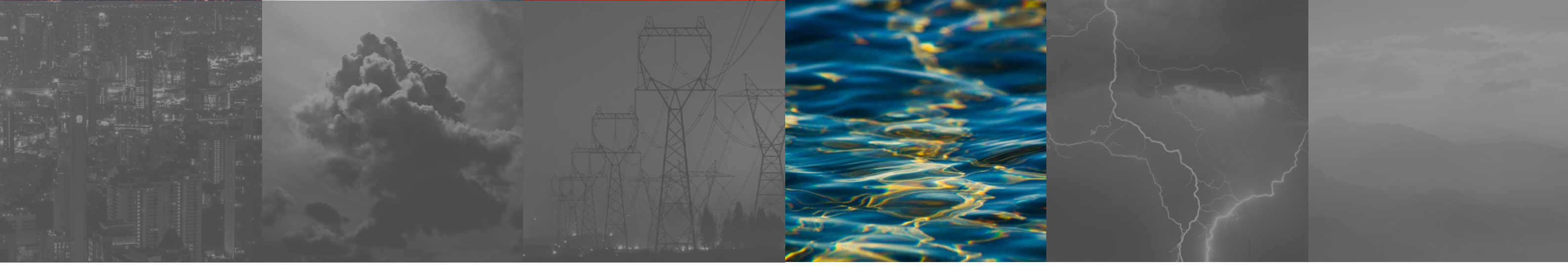


Figure 7: Interaction between climate change mitigation and climate change adaptation

The **EU Strategy on Adaptation to climate change** aims to strengthen Europe's resilience to its growing effects. The strategy also led to the creation of Climate-ADAPT, a European platform for adaptation knowledge.

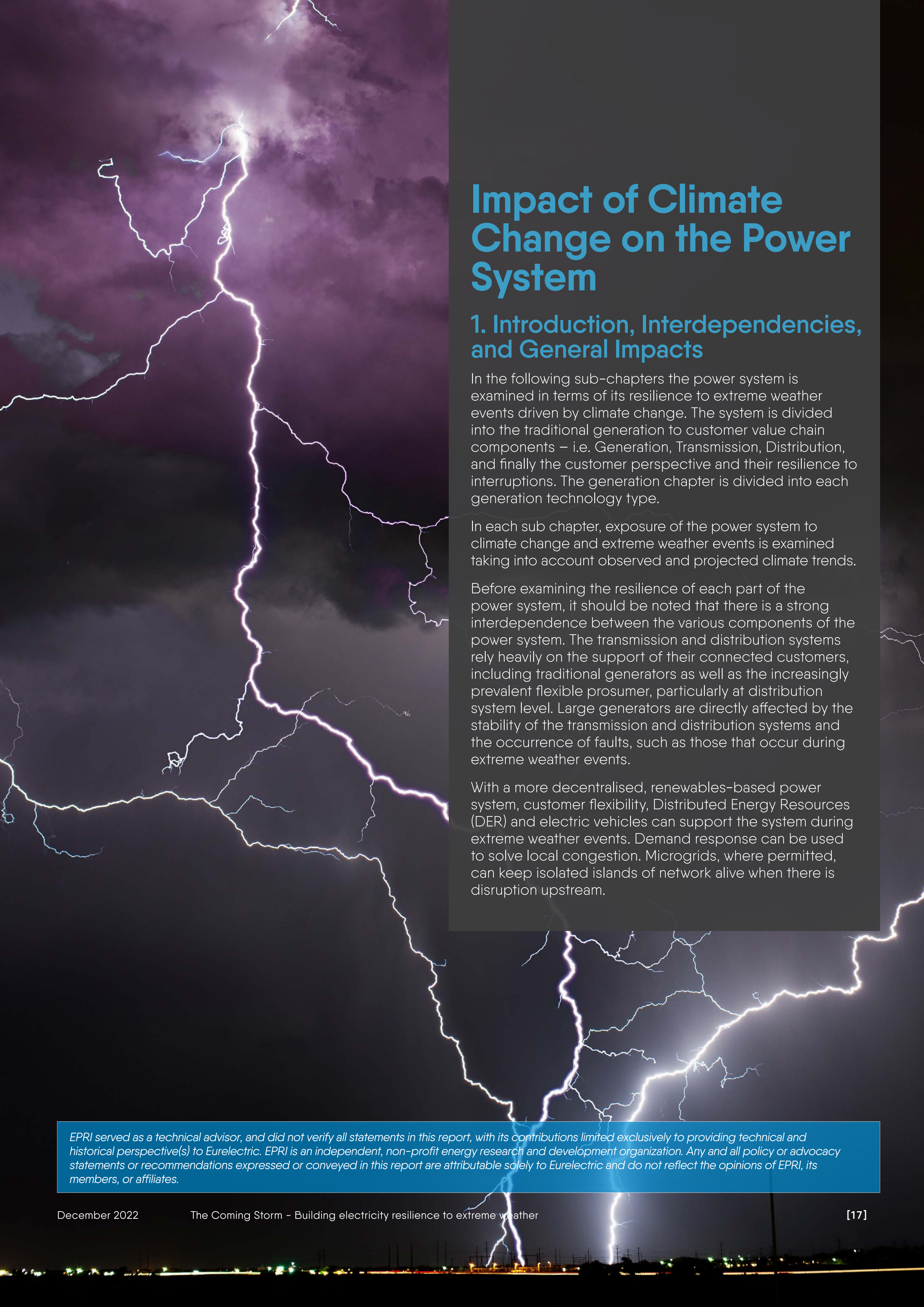
The **EU Civil Protection Mechanism**, established by the European Commission in 2001, aims to strengthen cooperation between EU countries and seven participating states on civil protection to improve prevention, preparedness, and response to disasters, including extreme weather events. When an emergency overwhelms the response capabilities of a country, it can request assistance through the mechanism which has been activated over 600 times since 2001. Further details of resilience and adaptation-related legislative instruments are included in Appendix I.

Case 2: European Civil Protection Mechanism for Cross Border Support

The war in Ukraine started by Russia on 24 February 2022 has caused unprecedented damage to electricity infrastructure. Direct physical damage has included the destruction of distribution grids that necessitates the replacement of circuits and substations. Indirect damage also covers the inability to source materials and spare parts for the operation and maintenance of electricity grids and thermal power generation.

In meeting these emergency needs, Ukraine benefits from the European Civil Protection Mechanism (ECPM). The requests for assistance under this mechanism are channelled through the Emergency Response Coordination Centre (ERCC) which operates 24/7. Since the first days of the war to mid-August 2022 the EU coordinated delivery of 66,224 tonnes of in-kind assistance to Ukraine from 30 countries. This assistance also included support via ERCC and ECPM mechanisms, used to facilitate supplies from more than 10 countries.

The experience of sending emergency supplies to Ukraine and the broader crisis response could feed into the ongoing work of the European Commission on the revision of the ERCC mechanism (ERCC 2.0). In particular, "how Europe collectively and the ERCC specifically might respond to any future such conflict in/outside the EU". In ensuring emergency supplies for the Ukrainian energy sector, the Energy Community Secretariat plays an important role and accumulates significant expertise. These activities include active engagement with European energy associations and companies that results in better knowledge of how sourcing and delivery of critical energy equipment and materials could be activated. By end of August 2022, the Energy Community Secretariat, with help of ERCC, ensured delivery of 19 transports of in-kind assistance to Ukraine with 20 more shipments under preparation. This assistance amounts to 300 metric tonnes and a value of €3 million.



Impact of Climate Change on the Power System

1. Introduction, Interdependencies, and General Impacts

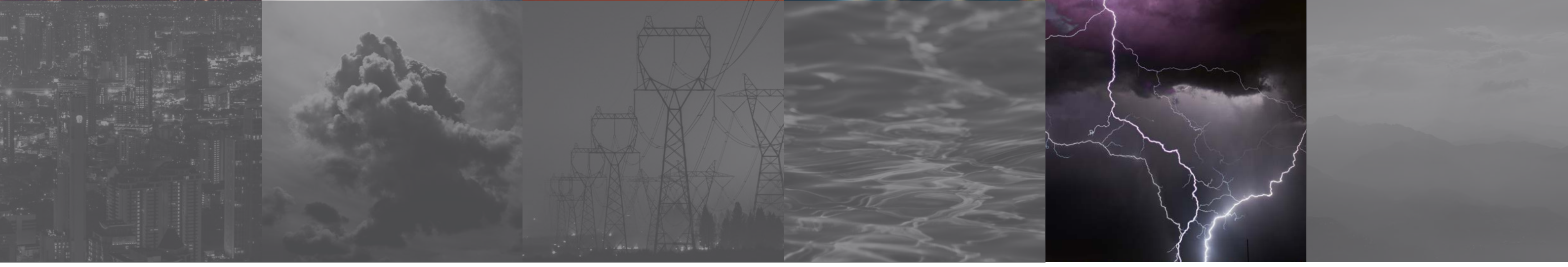
In the following sub-chapters the power system is examined in terms of its resilience to extreme weather events driven by climate change. The system is divided into the traditional generation to customer value chain components – i.e. Generation, Transmission, Distribution, and finally the customer perspective and their resilience to interruptions. The generation chapter is divided into each generation technology type.

In each sub chapter, exposure of the power system to climate change and extreme weather events is examined taking into account observed and projected climate trends.

Before examining the resilience of each part of the power system, it should be noted that there is a strong interdependence between the various components of the power system. The transmission and distribution systems rely heavily on the support of their connected customers, including traditional generators as well as the increasingly prevalent flexible prosumer, particularly at distribution system level. Large generators are directly affected by the stability of the transmission and distribution systems and the occurrence of faults, such as those that occur during extreme weather events.

With a more decentralised, renewables-based power system, customer flexibility, Distributed Energy Resources (DER) and electric vehicles can support the system during extreme weather events. Demand response can be used to solve local congestion. Microgrids, where permitted, can keep isolated islands of network alive when there is disruption upstream.

EPRI served as a technical advisor, and did not verify all statements in this report, with its contributions limited exclusively to providing technical and historical perspective(s) to Eurelectric. EPRI is an independent, non-profit energy research and development organization. Any and all policy or advocacy statements or recommendations expressed or conveyed in this report are attributable solely to Eurelectric and do not reflect the opinions of EPRI, its members, or affiliates.



2. Generation

In each of the following sub-chapters, the generation technology types are examined in terms of their resilience to extreme weather events driven by climate change. The relevant design parameters considered are outlined taking into account observed and projected climate trends.

Before discussing each individual generation technology type, the overall system trends should be outlined in terms of the changing technology mix in the generation fleet.

With the closure of coal plants there is a challenge to ensure the stability of the system since renewables typically do not provide the same inertia or resistance to system frequency changes as traditional thermal plants. A system with high inertia reduces cascade tripping events and so there is a challenge to develop the power system in a way that minimises this risk.

In Ireland for example, in 2022 up to three-quarters of electricity flowing in the system at any one time can now come from variable renewable sources. This is made possible following technical measures taken in the TSO's "Delivering a Secure Sustainable Electricity System" (DS3) programme, as well as largescale investment in renewables by industry supported by the TSO, DSO and the government. Work will continue now in Ireland to allow operation with up to 95% renewables at times by 2030, facilitating delivery of the Irish government's renewable energy targets.

Facilitating this target through power system stability measures, such as interconnection, battery storage, flexibility, and other measures, ensures the resilience of the system during extreme weather events. The measures taken to support this renewables-dominated system, both in Ireland and in other Member States, should be carefully weighed up for the best cost-benefit while contributing to decarbonisation targets.

Thermal

Climate change could erode thermal power plant reliability and performance, which may lead to unplanned shutdowns and curtailments; increase operations and maintenance (O&M) expenses, challenge environmental compliance, and decrease plant efficiency. Climate change may also impact the ability of these units to provide flexibility (ramping up and down) in response to rapid power system changes due to factors such as renewable generation variability.

Changes in chronic climate conditions may significantly impact plant cooling systems and turbine performance. Cooling system performance is likely to be impacted by changes in the following climate variables: cooling water temperature, precipitation, air temperature, humidity, and wind speed. EPRI has performed preliminary work on examining the impacts of these variables on different types of cooling systems, including once-through cooling (OTC), air-cooled condensers (ACC), and cooling towers.

- Increased cooling water temperature may reduce OTC efficiency, increase bio-growth, and reduce discharge limits.
- Drought may reduce cooling water levels and restrict flow rates.
- Higher ambient air temperatures may reduce the efficiency of ACC and cooling towers.
- Higher air temperatures also may reduce generation capacity.
- Increased wind speeds may cause ACC and cooling towers to experience performance penalties.

Research has also examined potential climate impacts on steam turbines and condensers, as well as gas turbines. For example, higher air temperatures can potentially reduce the generation capacity of both types of turbines, while reduced cooling system performance due to increased air and water temperatures directly reduces the generation capacity of steam turbines. Furthermore, increased air temperatures may also impact gas turbine efficiency and output due to decreases in air density.

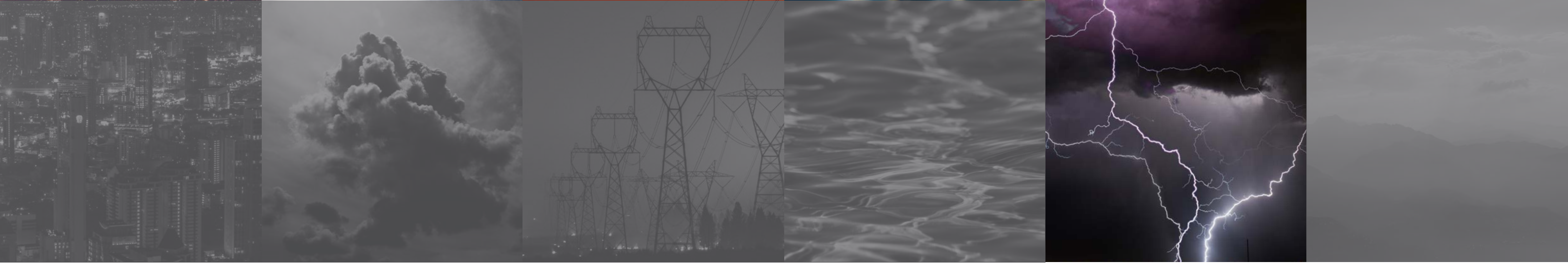
As renewable generation assets have been added to the power system, existing thermal power plants have had to operate in fundamentally different ways from how they were designed. Thermal assets offer important flexibility service options to the power grid.

But ramping up and down quickly, as well as other changes in responding both to the fluctuating output of solar and wind assets and to market conditions, can stress steam and natural gas turbine components. Increased air temperatures also may limit plant flexibility (e.g., power output and range limitation), constrain operations, and threaten thermal plant reliability.

In addition to impacts from changes in chronic climate conditions, extreme weather events may pose challenges to thermal assets. These challenges may include operational impacts to plants (such as going offline or operating at reduced capacity) coinciding with peak demand, adapting plant operation to new extreme weather threats for which the plant was not designed, and the performance of ageing power plants during extreme events.

Hydropower

All types of hydropower plants, including run-of-river, those with reservoirs as storage and pumped-storage, are impacted by climate change. Water inflow patterns change due to droughts or increased precipitation, melting of snow and ice, as well as increased evaporation. Other functions of reservoirs are affected such as flood control and provision of drinking water. In heavily forested regions, wildfires pose a threat, especially as a knock-on effect from interruptions to power system connections and telecommunication systems, or difficulties with physical access to the station. In the Nordic region there are also more frequent challenges related to icing.



When assessing the contribution of hydropower to overall power system resilience, there are differing challenges depending on site-specific parameters. The operation of hydropower assets differs between rivers with only a few individual stations and cascaded river systems with numerous stations, where each station directly affects the others. Similarly, run-of-river stations differ from those with reservoirs and those with pumped storage. The same holds for reservoirs with multi-use purposes where certain water levels must be maintained, for example to act as flood control structures, supplying drinking water or water for irrigation, or providing suitable water levels downstream to guarantee ship traffic.

Some of these challenges are not new to hydropower as they are inherent by design. Hydropower plants have dealt with inflow variations, flood control and icing for many decades. Methods have been developed and continuously refined over the years. The main challenge is that such events will increase both in frequency and severity. The factors affecting hydro plants are worth exploring in greater detail.

Managing Inflow Variations and Changed Inflow Patterns

Hydropower production offers both energy and flexibility services to the power system. To be dispatched optimally, both weather forecasts and market price forecasts are essential. Where there are reservoirs in a river system, the operator must decide when to produce energy with the available water. This becomes more complex with more reservoirs and power stations in the the river system as well as with additional constraints such as flow restrictions or mandatory water levels.

Hydropower is dependent on inflow forecasts which in turn are based on an accurate description of hydrological processes, such as the melting of glaciers and snow covers. These forecasts rely heavily on precipitation and temperature forecasts which are an output of weather models. Since climate change is impacting weather patterns, described further in the Climate Change Data chapter, it will also change future inflow patterns.

Climate change is expected to cause more extreme weather events such as cloudbursts. Challenges arise if the additional inflow is large compared to the flexibility that the river system provides. More frequent and severe drought periods will directly impact power generation in run-of-river plants and extended droughts will affect systems with reservoirs. This emphasises that both the length of time for the variation and the geographical size of the extreme weather event is of importance. The overall effects on the power system will differ from country to country depending on the percentage share of hydropower and whether the plants are providing power production or flexibility services. Water scarcity arising from droughts creates a competition for water. Hydropower developments in affected areas (especially southern areas of Europe) may consider other uses of their reservoirs or promoting other uses to reduce their water needs or creating their own reservoirs.

Managing River Ice

In colder climates, such as in the Nordics, icing is an important issue for hydropower because there is a risk of undercooling if air temperatures are too unstable to guarantee formation of a solid ice cover. Climate change can affect temperature variations around freezing point during the winter. If not well managed, it can significantly affect both production and safety. While serious problems do not occur frequently, they can have a large impact [Johan Casselgren et al., 2015].

Poor icing conditions affect hydropower operations in several ways. Ice can reduce the flow in the intake channel. Frazil ice can clog the trash gates at the intake and in spill gates and can reduce the capacity of spill gates and spill ways. Ice can also increase the pressure on dams and reservoir structures. All types of flow reductions due to blocking the intake/outlet, lead to “head losses” which reduce the hydropower station’s efficiency. Therefore, icing needs to be considered during the design stage when building a power station. Meanwhile, to reduce the risk of ice “clogging” trash racks and spill gates, these structures can be heated.

It is also important to keep a stable ice cover on the rivers in order to prevent formation of ice obstacles under the water surface which can block the river leading to significantly reduced energy production and even flooding. For example, in 2010, an ice obstacle blocked Luleälven in Northern Sweden. Operation had to be reduced on the whole river to avoid flooding and other knock-on effects.

The most prominent way to manage icing is to create a solid ice cover on the river by facilitating the natural process of ice formation. To successfully achieve this, three parameters must be appropriate: air temperature, water temperature and water velocity.

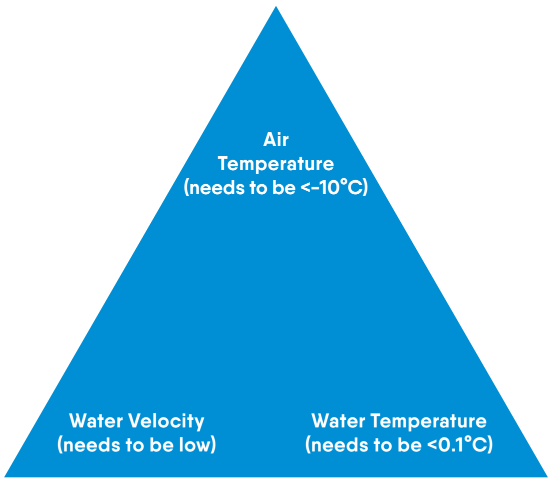
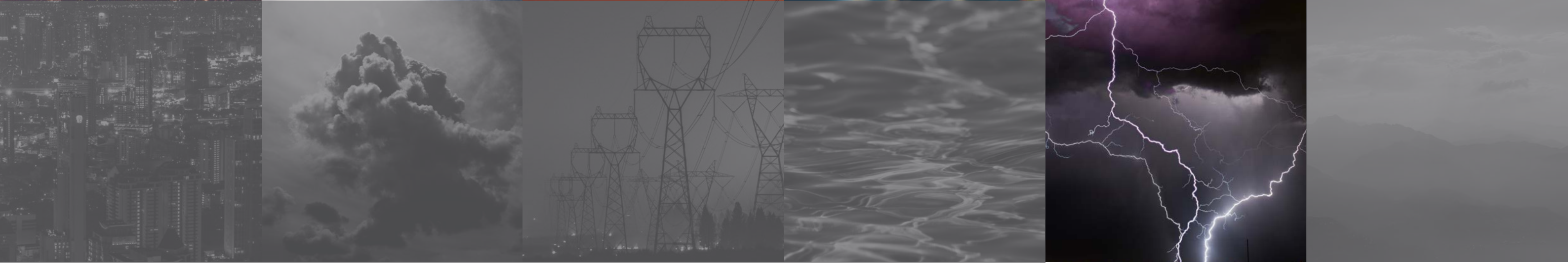


Figure 8: Parameters that affect icing



While the first two cannot be altered, operations change as soon as weather forecasts show positive conditions. Ice formation on rivers takes approximately one week. During this time, production is reduced to lower water flows and velocity. This impacts electricity production during the time it takes to build a stable ice cover but it ensures safe and efficient production during the winter. However, if different parameters for ice formation coincide for several rivers, this can temporarily increase electricity prices, as happened in two northern Swedish price areas in the winter of 2021–2022.

Flood Control

Flood control is a positive effect of hydropower, as shown in case 3 which illustrates the value of water management:

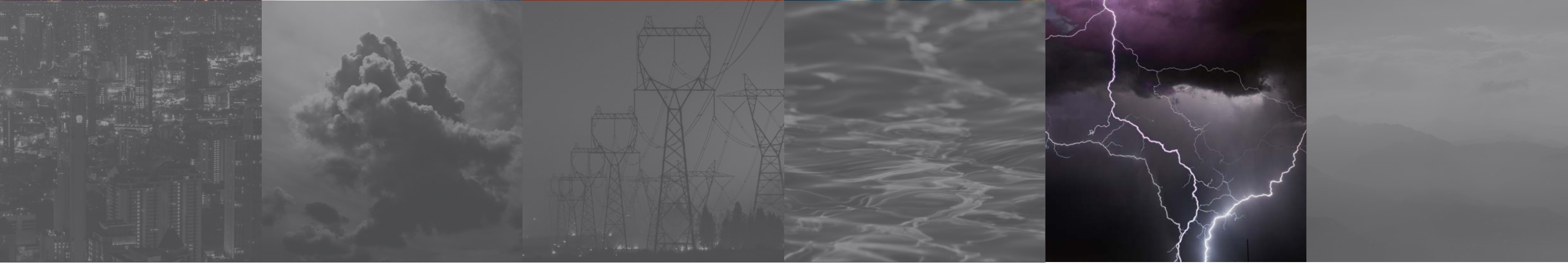
Case 3: Preventative Actions for Hydro Plants Using Forecasts

Since the end of the 15th century, flood events have been reported in the Ziller valley, in the Austrian region of Tyrol. This region lies at the heart of Europe and is connected directly to the Austrian and German grid and indirectly to Switzerland and Italy. Since the 1940s, hydropower development in this region has meant that severe flood events have not caused any major damage to either the local population or infrastructure.

In 1956, heavy rainfalls led to a massive increase of inflows. A flood wave without the outflow-damping measures that had meanwhile been implemented (construction of power station storage, the Ziller expansion and river regulation, and the switching off the Mayrhofen power station) would have resulted in a flood peak of 750 m^3/s.

Today, the reservoirs of existing hydropower plants and their operation support power system resilience. The reservoirs and dam walls of the Zillertal have helped keep the natural forces of water under control during the heavy rain events of recent years. The Schlegeis, Stillupp, Zillergrund and Durlassboden reservoirs – all together leading water flows into the hydropower plant group of Zillertal (owned and operated by VERBUND Hydro Power GmbH) held back 230 m^3 of water per second during the heavy rain event of 2014. Without this contribution to flood protection, the Ziller river in the area of Hart im Zillertal would have had to cope with around 600 m^3 of water per second. In addition to the retention effect of the reservoirs, the pumps were also used for flood protection while the storage capacities of the reservoirs during heavy rain were guaranteed by the targeted shifting of water.

Figure 9: Schlegeis reservoir and dam, one of the high attitude Alpine reservoirs in the Zillertal valley.



Nuclear

The nuclear fleet must adapt to a changing climate while maintaining an excellent level of safety and contributing to security of supply. Cooling systems of nuclear power plants are affected by the changes in the same variables impacting the thermal fleet, as described in previous paragraphs. For instance, the 2003 heat wave in France as well as recent heat waves in the summer of 2022 have posed challenges, especially regarding cooling water temperatures. Analysis showed that to deal with the consequences of climate change, it is necessary to consider factors beyond the technical parameters of the nuclear plants themselves and to widely mobilise and engage with local stakeholders around the power plants.

The focus of this chapter is on the resilience of nuclear power plants as part of the whole power system, with a particular focus on plant availability as well as continuity of supply to end customers. Nuclear facilities are, at the design stage, sized to deal with significant meteorological hazards such as temperature, flooding, wind, tornados and other threats. The levels of these hazards are reassessed (in France every ten years) considering international best practices and adapted to climate projections. By design, this approach incorporates the impact of climate change on external hazards.

The experience from the exceptionally hot summer in France in 2003 led to a vast program of modifications to installations to better cope with extreme heat waves. The cooling systems of the power plants were resized, and operating practices were reviewed. Regulations have also been improved to better consider climatic conditions.

EDF continues to analyse plant adaptations to climate change, examining the implications beyond nuclear safety and the preservation of the environment. These studies have highlighted broader consequences that could affect the production capacity of its facilities. Thus, to maintain a reliable and resilient level of production, it is necessary to ensure the resilience of the whole supply chain, of key infrastructure (such as electricity and telecommunication networks), and of the installation's surroundings. EDF has thus initiated a specific project called ADAPT which aims to take into account the consequences of climate change on the production capacity of French electro-nuclear sites.

Nuclear power is very resilient in the face of climate change, and the extreme events which may occur more frequently in the years to come, such as in the example described in Case 4.

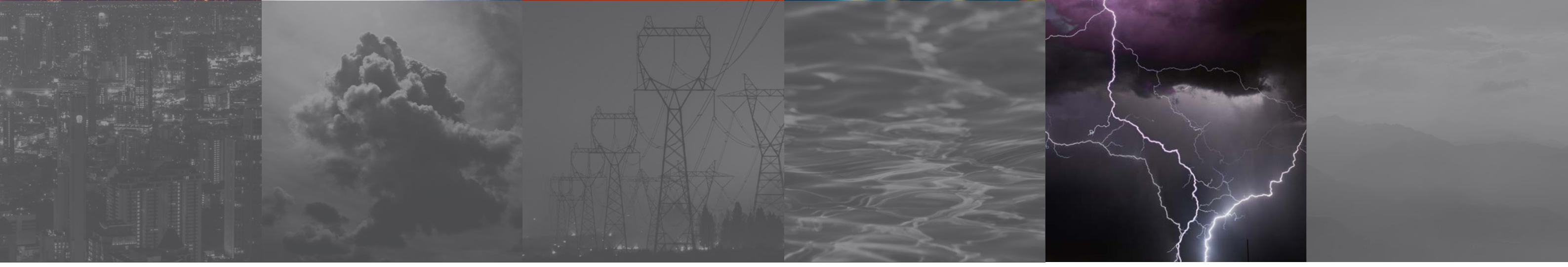
Case 4: Storm Eunice's Impact on Gravelines Nuclear Plant, France

18 February 2022, Storm Eunice caused winds of around 140 km/h at Gravelines (Hauts-de-France) which proved the resilience of the nuclear site and the ability of nuclear power to cope with such an extreme event. There was no impact on the safety of the facilities and no site employees were injured. It also made it possible to verify the relevance of the criteria used for triggering the vigilance and pre-alert phases.

As of Thursday, February 17, the Gravelines power plant entered the "high winds early warning" phase with wind speed criteria > 130 km/h in gusts, scheduled for Friday afternoon. The pre-alert phase was triggered on Thursday afternoon with a peak of expected winds above 130 km/h, then again on Sunday afternoon with the arrival of a second storm, Franklin.

Ultimately, these storms caused only minimal damage despite the violence of the winds recorded (138 km/h in Calais, 130 km/h in Dunkirk). Any loss was a result of their impact on the transmission network.

- During a storm, the major risk is the loss of power supplies via the 400 kV or 225 kV line. The site, therefore, prepares for the loss of external sources. This network failure did indeed occur but, as anticipated, islanding was carried out safely and the site was able to resume its place on the network from February 20 at 11:24 a.m.
- Protections against projectiles generated by high wind are also taken into account via the reinforced grids which protect the gas parks and the metal cages around diesel generators.
- Finally, the last risk is the safety of staff. All staff were therefore asked to leave the site on Friday noon and to telework as much as possible. Only those whose presence was necessary for reasons of safety, security, operation of the units and on-call duty were authorised to remain on the site, subject to wearing a helmet with chinstrap and protective goggles during all external movements.



A Holistic Approach is Required

Assessing the consequences of climate change shows that it is not possible to limit analysis to the perimeter of the plant site. The production capacity of a nuclear plant, like other industrial facilities, depends on its capacity to maintain links with a very large ecosystem. Each site must be able to exchange data, buy conditioning chemicals, source spare parts, be accessible to employees and suppliers, and these personnel must be able to physically get to work.

These effects were observed during the COVID-19 pandemic when employers faced a strain on human resources. Fortunately, the disruption did not have a direct operational consequence on many nuclear sites but resulted in organisations adapting their systems and processes.

Adapting a generation fleet to climate change cannot be limited to technical work carried out by the operator alone. It must be part of the collective evolution of the industrial and territorial ecosystem.

The adaptation of nuclear power to climate change is not only a matter of demonstrating nuclear safety but of a broader dynamic approach. This extends beyond the technical elements of production to the chain of suppliers in the territory of each site.

A nuclear site may be hampered in its production performance in the event of a heat wave due to school closures, as occurred in June 2019 in central France due to lack of childcare. This shows that an incomplete adaptation of the host territory can influence a plant's operation, leading to a drop in performance. Similar difficulties can arise if a supplier's premises become unusable due to flooding or unbearable heat in a prefabrication workshop.

A very flexible cross-functional team is required, which focuses on monitoring, developing analysis tools and leading work with teams of climatologists, nuclear fleet engineering, operators, and all the players in the territory including suppliers of the nuclear fleet. This cross-functional team oversees both the communication of climate science work and the mobilisation of internal and external actors, whether industrial or territorial, so that adaptation to climate change is prioritised. This team also monitors the impacts of climate change on industrial buildings and the site's ability to produce.

Tasks must be allocated to each stakeholder to ensure action in the face of an extreme weather event. Access to water is of particular importance since water is the subject of competition between economic actors and essential to biodiversity.

There is a risk that extending the scope of adaptation measures to the entire ecosystem around the nuclear site could dilute adaptation efforts. In the case of EDF, a French operator, an experimental phase was planned before rolling out the adaptation methodology across further sites. Initial efforts are therefore concentrated on one of the twenty French nuclear sites.

The territory chosen, in the north-east of France, includes a nuclear installation among the most recent in the EDF fleet. This allows the development of methods of analysis of the local socio-economic situation considering local conditions. These methods can then be replicated and adapted to other nuclear sites.

Due to the consequences of climate change on the whole energy system, nuclear operators suggest a broader mobilisation including network operators and other industrial and local partners.

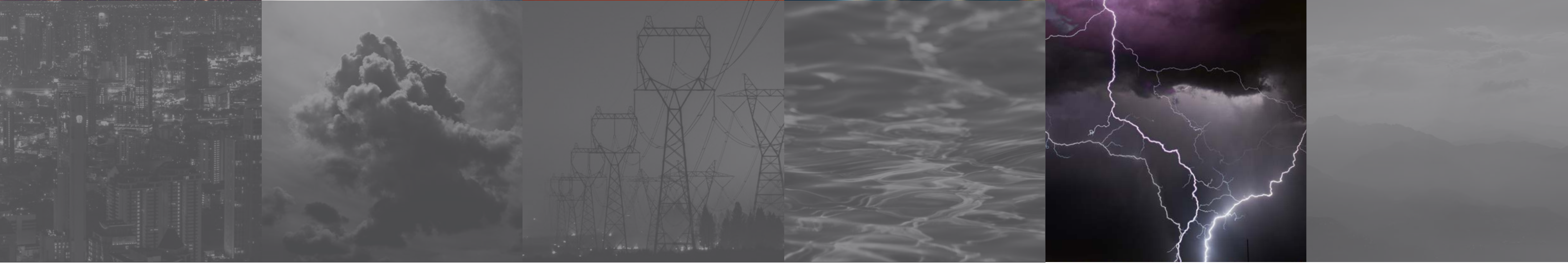
Wind & Solar

As part of the REPowerEU plan, Europe intends to increase installed wind capacity from 190GW in 2022 to at least 480GW by 2030 and double solar photovoltaic capacity by 2025 and reach 600GW by 2030. The resilience of the power system, particularly its stability and ability to deal with increased variability, requires other measures over time including greater interconnection, storage, demand response, and flexible generation sources. The exact solution will depend on the climate action plans and particular technical and political challenges of each Member State.

The risk of extended periods of low wind resources should be balanced by sufficient quantities of storage or other resources for those periods. Similarly, standard typical operational temperatures could be considered beyond the current typical range of -30C to 40C if cold or hot climate countries wish to incorporate significant amounts of wind energy.

However, Wind farms are already well prepared to deal with extreme weather events. During high wind speeds (at least Beaufort Storm Force 10, 25m/s or 55mph) modern wind turbines shut down to prevent excessive mechanical loading. Regional forecasts for wind speeds must be considered to predict wind farm outputs for the whole asset life cycle and along the path to net zero emissions, as slight variations in average and extreme wind speeds can have an impact on wind farm output.

Solar installations are also well prepared to deal with extreme weather events driven by climate change. The smoke, deposition, and debris associated with wildfires can potentially reduce solar farm output, especially when maintenance is not executed. This can lead to unwanted and unexpected side effects, especially where wildfires are spread over a large area as occurred in California in September 2020, when solar farm output was reduced by 30%.



3. Transmission & Distribution

System Developments

Electricity systems are experiencing a transformation driven primarily by the ambitious deployment of renewable energy, electrification and the development of digital technologies. Within this evolving context, the Russia-Ukraine war has introduced additional complexities to the overall power system and electricity markets.

Meanwhile, the extent of damage to transmission and distribution networks from extreme weather events is increasing, resulting in interruptions in supply to electricity consumers. Traditional "availability" analysis must be complemented with system resilience analysis. Reliable infrastructure is not necessarily resilient infrastructure.

The power system consists of closely interconnected elements, therefore, the fluent interoperation of all elements, notably coordination of services between key network operators (TSO and DSO), is of utmost importance.

This evolving environment creates a more dynamic energy system based on distributed, variable generation, with a change from one-directional to bi-directional power flow. This creates a new role for transmission and distribution system operators managing the system, allowing customers to both inject and withdraw power, thus contributing to security of supply.

Distribution system operators (DSOs) are at the centre of this transformation, as the distribution network is the connecting site for an unprecedented scale of new renewable energy sources and is equipping network users with smart meters and systems, thus enabling the development of new products and services.

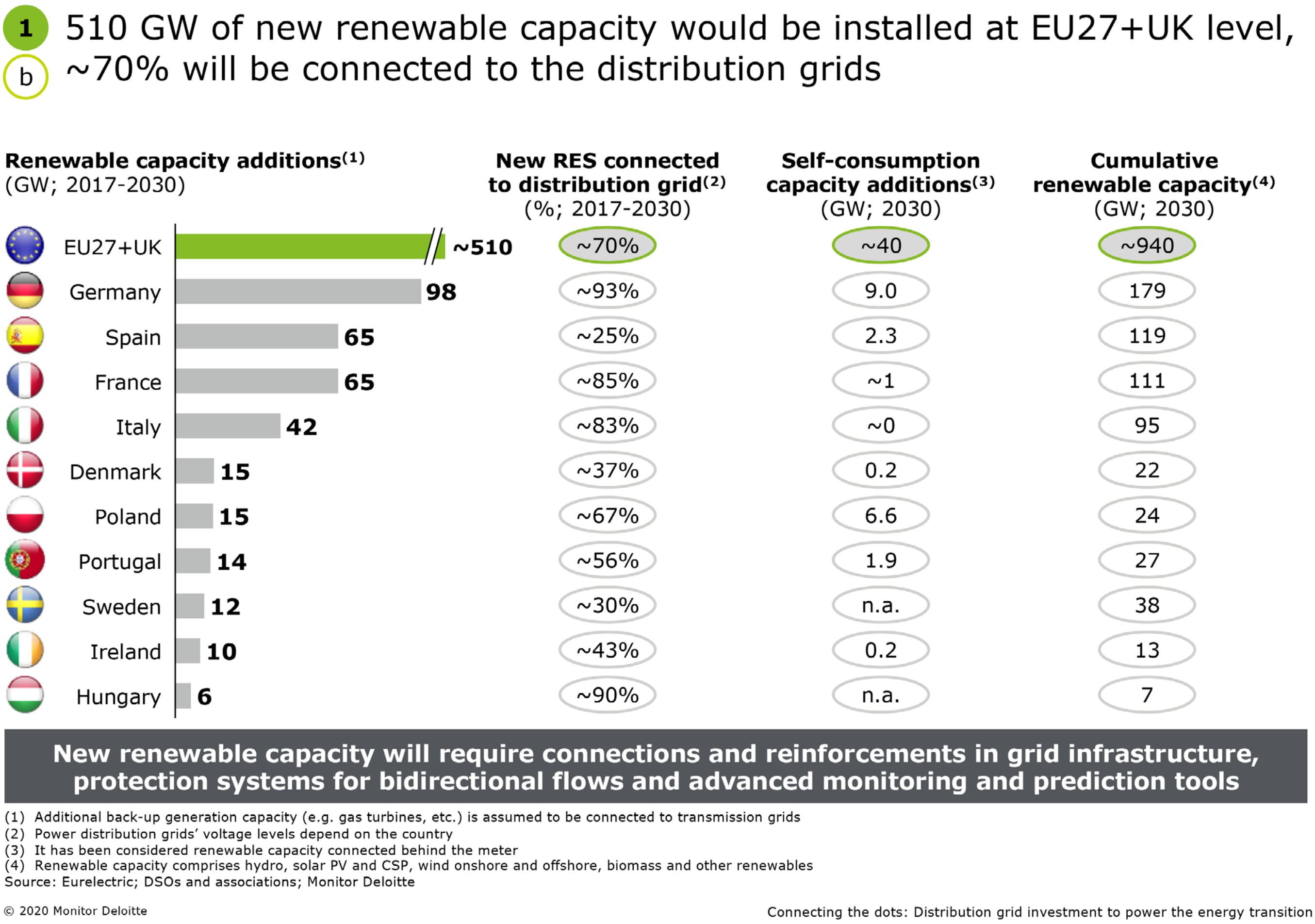
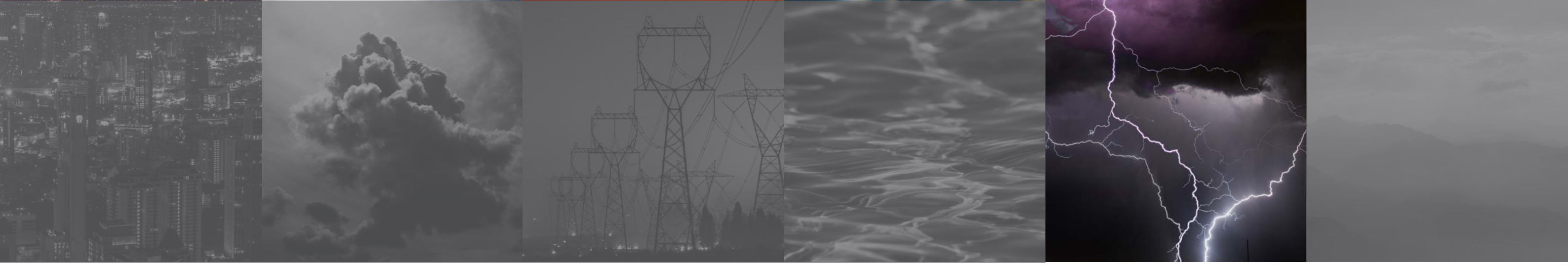


Figure 10: Connecting the dots: Distribution grid investment to power the energy transition – November 2020



Flexibility and its Role in a Resilient System

The power system should support customers that want to actively participate in flexibility markets. Where the primary grid capacity is insufficient, DSOs may procure flexibility from system users as a service.

New forms of flexibility are key in a renewables-led power system. Flexible technologies help integrate large volumes of renewable generation by shifting excess demand to periods of high renewable generation, or by storing the excess renewable generation for periods of high demand. Because of this decentralisation, grids will be the enabler, ensuring higher hosting capacity for Renewable Energy Sources, exploiting local flexibility services and markets, leveraging the increasing amount of DERs, and promoting more active participation of customers and stakeholders.

From a power system resilience perspective, using flexibility for congestion management or voltage regulation in a specific DSO area can be very important. Local energy sources or active customers can be used during a crisis caused by extreme weather conditions. To manage this, the relevant system operator must understand the flexibility framework of its system, including knowledge of the network topology, energy flows, and available power in the system.

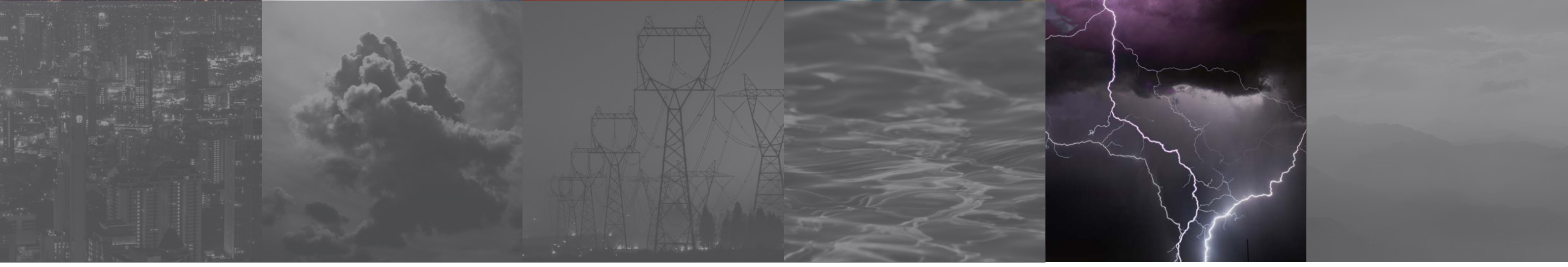
In such a situation, until normal operation of the network is restored, a specified area of the distribution network with a significant amount of connected distributed energy resources or electric vehicles may reduce energy consumption or supply the network with a certain amount of energy. This gives more flexibility to react in a crisis scenario. Where there is knowledge of the potential withdrawals or injections to the grid in an area this can enhance the resilience of the local system.

Climate Events Affecting DSOs

Typical effects of extreme weather for DSOs include heavy snowfalls with wet snow leading to icing, intense and concentrated rainfall with large floods, lightning storms, heat waves, and winds of exceptional intensity. Regional variations of these conditions will exist in line with the IPCC predictions outlined in the climate data chapter – see Figure 6 for characterization of understanding of future trends for these types of events.

Ice Sleeves

One of the main threats to electricity lines is linked to snow and icing. Winter snowstorms can lead to ice sleeves on bare power line conductors. This can be a result of the interaction of various phenomena, including snowfall, low clouds, wind and rain on the bare conductors. “Wet snow” is particularly dangerous for overhead powerlines, as it can easily adhere to the external surface of the conductor. It occurs with an air temperature between 0°C and +2°C, with low wind speeds (<30 km/h) and high ice density reaching up to 500 kg/m3. The accumulation of wet snow can lead to the formation of heavy sleeves on the conductors, with overloads in excess of 20 kg/m, potentially causing the collapse of the conductors and their support structures.



Case 5: Heavy Snow in Italy leading to Icing in 2017

January 15-18, 2017 the regions of Le Marche and Abruzzo in central Italy experienced an extreme snow event that led to the prolonged disconnection of more than 100,000 customers and isolated entire cities.

After the recent intense snowfalls in Italy, institutional stakeholders took the first steps towards the introduction of Resilience in the regulatory framework. Specifically:

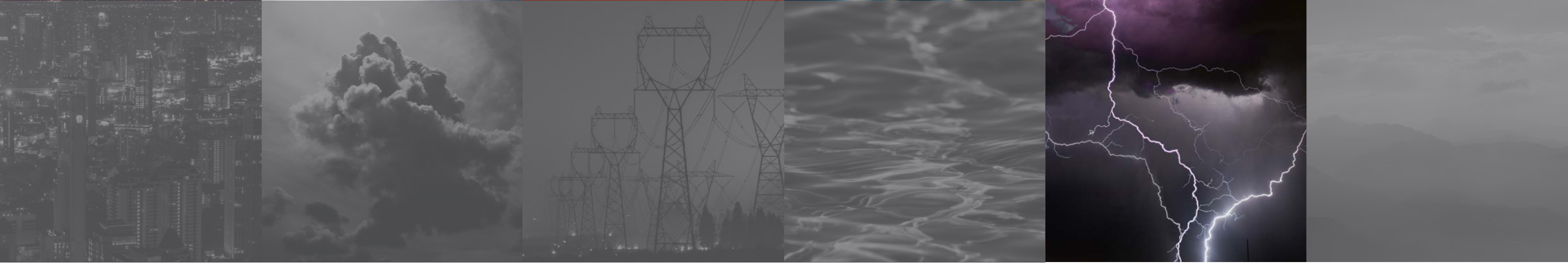
- The Italian Ministry of Economic Development (MiSE) launched a commission of inquiry on emergency management activities.
- ARERA (National Regulatory Authority) defined Resilience guidelines asking DSOs to provide investment plans dedicated to resilience, concerning two aspects:
  - the design of a network able to withstand extreme events
  - the ability of the system to restore its standard condition operation after extreme weather events

Starting from these guidelines, DSOs have to publish an ad-hoc plan (3-year period) by **30th June each year**. Subsequently, considering the extraordinary heavy snow in 2017 in Abruzzo, ARERA added some further requirements to the Resilience Plan to be prepared by each DSO. The new mechanism, starting from 2019, also included:

1. Classification of the recognized intervention towards 3 typologies of extreme events:
   - Snow-Cable icing (overhead MV line)
   - Heatwaves (Underground MV cables in urban areas)
   - Windstorm-Tree fall (overhead MV lines)
2. Introduction of the reward/penalty mechanism according to the planned project timeline, following an output-based approach

Therefore, implementation of individual interventions of the Plan in compliance with the planned time involves significant economic benefits for the system operator, reputational benefits and improvement of network response to an extreme weather event, benefitting customers through reduced duration and frequency of outages.

Following the guidelines approved by the Authority a cost-benefit analysis (CBA) is required for each intervention. The Regulator defined three clusters of resilience interventions, according to the conventional Return Time and Cost Benefit Analysis associated with each intervention to rank the interventions proposed.



Wind Storms, Flooding and Wildfires

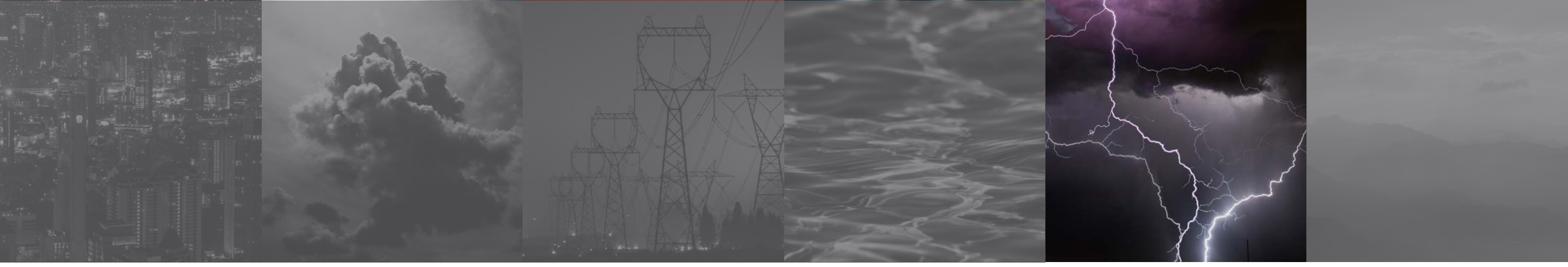
Diverse weather events can cause trees to fall on overhead power lines. In certain conditions a combination of factors can occur. Wind causes trees to fall, while wind gusts can break branches and sustained winds can uproot trees. Snow can overload tree crowns especially in the presence of foliage of deciduous trees. Rain softens the soil and the tree roots. Plant diseases can weaken the trees in combination with the above effects.

Storms, floods and wildfires have caused increased stress on the distribution system in recent years.

In addition to rain, snow or strong wind, heavy storms and in some cases even small cyclones can cause trees to fall on overhead lines.

Floods impact the safe and secure operation of distribution system secondary substations, transformers, and underground cables. Indirect impacts of flooding include weakened pole and tower foundations, as well as causing dangerous rock falls and landslides.

Finally, increases in temperature and low humidity for several days can lead to spontaneous fires in arid areas or a system fault itself could ignite a wildfire in such dry conditions.



Case 6: Storms Arwen and Eunice UK

Over the winter of 2021/22 the UK and the Republic of Ireland experienced a series of storms commencing with Storm Arwen (26–27 November 2021) and concluding with Eunice (17–18 February 2022) and, to a lesser extent, Franklin (20 February 2022). While the UK is impacted by storms during most winters this was the first time since the winter of 2013/14 that a series of storms had affected large areas of the UK.

Arwen was considered to have a larger impact, particularly in the North-East of England and Southern Scotland; Eunice windspeeds were slightly lower with gusts up to 70mph, even so, areas of the South-East of England were without power for up to four days.

26–27 November 2021, Storm Arwen was an exceptionally severe storm and brought significant and widespread severe weather to the UK, including exceptionally high windspeeds, icy conditions, and deep snow. As a result, just under 1 million households experienced power outages, 59,000 of whom were without power for over 48 hours and 3,000 for a week or more. Storm Arwen was the worst storm in 10 years in terms of the combination of wind direction, speed and temperature.

The majority of faults occurred on lower voltage overhead lines supported by wooden poles individually serving only a small number of customers, making the restoration effort resource intensive. Mobile generators proved a critical part of the solution to reducing the length of power cuts and re-connecting some customers before full repairs could be completed, although they are resource intensive to install and refuel at scale.

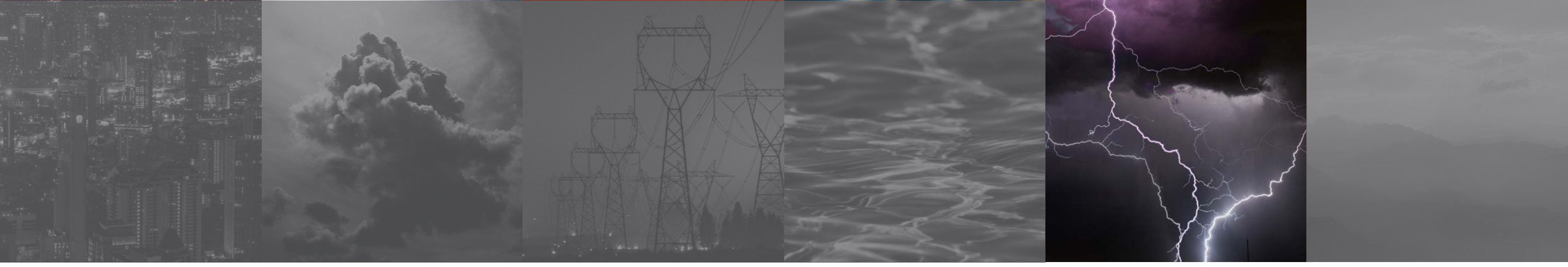
Customers found themselves not only without power but also in some cases without water and communications as other essential services lacked full resilience to a loss of power. The interdependence of these services highlights a need for a holistic approach to resilience.

The UK operates a resource sharing agreement between all of the regulated Distribution Network Operators and this was found to work well with field staff being sent from the unaffected or less impacted parts of the country to the North East during and immediately after Arwen and to the South-East during and after Eunice.

Storms on a par with Arwen and Eunice have historically been exceptional events. They may not be repeated for several years, even as the United Kingdom becomes subject to more extreme weather driven by climate change.

As a result of the widespread damage to the electricity network, and the extensive and lengthy loss of supply, the UK government (Department for Business, Energy and Infrastructure Strategy (BEIS)) and regulator (Ofgem) commissioned two reports and produced over 30 actions and recommendations. The actions fell into eight categories:

- Review of resilience standards and design standards
- Improving overhead line wooden pole health assessment
- Review individual company and national winter preparedness plans
- Review options to improve early fault detection measures including use of smart meter data
- Improve mutual aid, customer communications and notification of entitlement to compensation for loss of supply
- Improve Estimated Times of Recovery
- Improve working relationships with communities and local resilience forums
- Review welfare arrangements and agreements



Heatwaves

Heatwaves can affect underground cables, especially where a combination of climate variables coincide. Due to climate change there is a projected increase in days with **drought**, high **average temperatures**, and only a slight temperature variation between day and night.

Dehydration of the soil causes a reduction in its thermal transmittance. **High ambient temperatures** can cause the **inversion of the thermal flow** between buried cable, the ground and free air. At the same time, cables can experience increased loads due to increased air conditioning demand. The consequences on the underground network are an increase in the probability of **hot spots** in cable insulation and in joints, which can lead to isolation failure, in the underground **grid fault rate**, and in **double-fault** probability.

The grid is designed with (n-1) reliability criteria, but unpredictable **multiple faults** can provoke partial disruptions and require a lot of time for restoration.

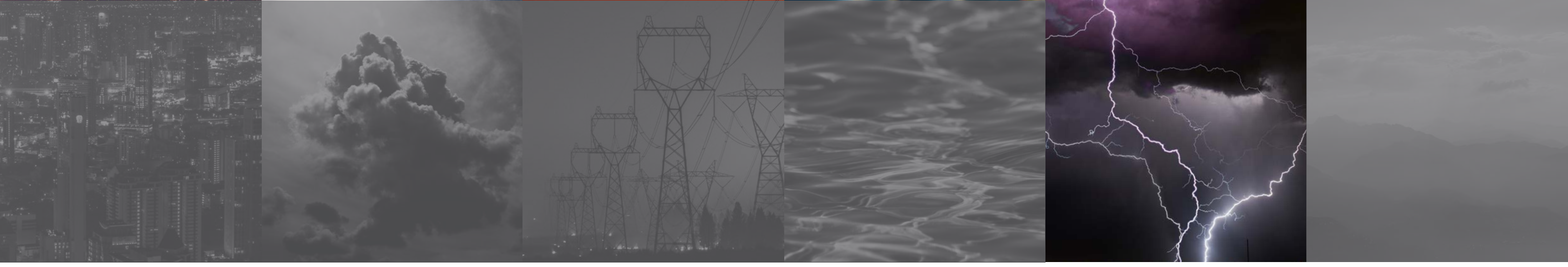
Heatwaves can also cause increased sagging of overhead lines and can cause transformers in substations to overheat at a lower-than-usual load level, although the prevalence and severity of these effects are less than the effects of heatwaves on underground cables, particularly in the Mediterranean area.

Case 7: ENEL GRIDS's 4R Resilience Strategy

The challenges posed by climate change require an innovative approach to resilience to prevent and manage risks to communities and represent an opportunity to make the grids ever more flexible.

For instance, Enel Grids has adopted an integrated approach called "4R" which foresees measures to be taken both in the preparation of a network emergency and for immediate restoration, even before a weather event has caused damage to assets or continuity of supply. The 4R strategy consists of:

1. **Risk prevention**: interventions to increase the robustness of infrastructure, reducing the risk of prolonged and extended interruptions in the event of rare and high-impact events, according to a probabilistic approach.
2. **Readiness**: interventions that aim to improve the timeliness with which a potentially critical event is identified, ensure coordination with local institutions, and provide the necessary resources once a fault has occurred.
3. **Response**: the phase in which the operational capability to cope with an extreme event is assessed. This is directly related to the ability to mobilise operational resources in the field and the ability to carry out remote control activities, thanks to resilient backup redundancy.
4. **Recovery**: returning the network to normal operating conditions after an extreme weather event has led to service interruptions despite all the resilience enhancement measures previously taken.



4. Adaptation Measures

Generation

Nuclear & Thermal

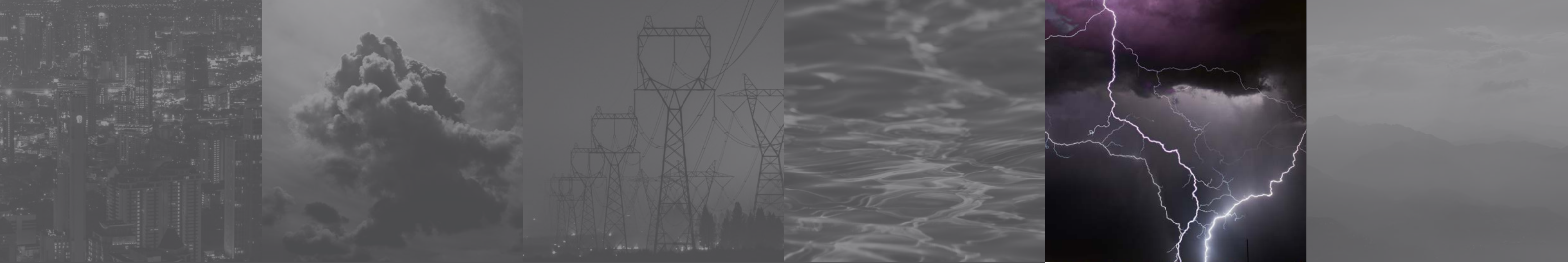
The level of climate change hazard is reassessed (in France every ten years, for example), anticipating future climate projections and taking into account international best practice to adapt assets. This approach incorporates the impact of climate change by design.

The experience of the exceptionally hot summer in France in 2003 led to a vast program of modifications to better cope with extreme heat waves. The cooling units of power plants were resized, and operating practices were reviewed. The regulations were also improved to better consider these climatic conditions.

Hydropower

While climate change will have direct impacts on the management of reservoirs and the dispatch of hydropower plants, mature methods exist to handle inflow variations and to react to different inflow patterns as long as the flows remain within capacity of the existing infrastructure. These methods are under continuous development. Inflow forecasts are important, too. Here, recent advances in higher spatial resolution of hydrological models facilitate dispatch decisions. While climate change presents challenges for hydropower plants, they can contribute to a resilient power system.

Maintaining a high level of resilience within hydropower assets is a top priority for operators. Their close regional connection to the surrounding environment leads to benefits in flood protection and management. Furthermore, maintaining and modernising major hydropower assets will in turn increase the resilience of the power system. A high level of predictable and dispatchable hydropower in the generation portfolio supports the integration of other variable renewable energy sources such as wind and solar power. In addition, it leads to low levels of power system disruption, limits the risk of blackouts, and fulfils the need of the future European power system: being renewable, independent of energy imports, and stable.



Transmission & Distribution

The new operating environment requires specific adaptation measures aimed at increasing electricity grid resilience. The main solutions can be summarised as:

- **Overhead Distribution Reinforcement:** some of the most effective actions are relatively simple and straightforward, such as adding structural reinforcement to existing distribution lines (using aerial cable, increasing the degree of insulation, increasing mechanical strength of conductors, cross-arms and insulators);
- **Undergrounding of overhead lines:** installing distribution lines underground takes them out of harm's way of trees, cars, and most lightning strikes – these works must take account of flood risks as well as the carbon footprint of the TSO or DSO;
- **Pole and Line Design:** adoption of pole and line configurations less susceptible to damage from trees and falling limbs. It is important to better understand the way overhead systems fail and to use new technologies to ensure that the systems fail in a manner that minimises the restoration effort. Assessing overhead components and cross-arms, pole treatment options, as well as the effect of third-party components (telephone, cable television, fiber optic cables, etc.) is also needed. Adoption of techniques to reduce probability of conductors' breakages due to ice sleeve overload (adoption of mechanical fuses) can be very useful;
- **Vegetation management near overhead lines.** Tree trimming and pruning is a fundamental practice for mitigating local distribution outages risk. Given the increasing demands for maintaining biodiversity, new forms of vegetation management near overhead lines must be devised, in conjunction with the stakeholders;
- **Substation design:** in areas with a high risk of flooding, civil works can be undertaken to protect substations, technologies can be adopted to make substations more waterproof, and less exposed sites can be selected.
- **Remote control, grid automation and digitalisation:** to prevent outages automated distribution grid components (e.g., switches/sectionalisers/reclosers, sensors) could automatically reconfigure supply restoration within few minutes. In this way it is possible to enact fault selection and so reduce the number of customers affected and the number of field operations in extreme conditions;
- **Provision of alternative power network paths** (network meshing, backfeeding for laterals with many customers, etc.) to reduce outage risk and increase redundancy of supply.
- **Preparation of electricity networks for future connections** of distributed energy resources (such as photovoltaic plants, wind farms & storage) and implement measures to use their flexibility to limit the effects of extreme weather events.

5. Investment Framework

Effective policy measures and adequate investment are fundamental to accelerating action and minimising the impacts of climate change. Regulators have to examine whether the electricity market design is still fit for purpose, reviewing cost allocation frameworks and ensuring fair remuneration to system operators and investors. Policy makers should drive network operators **to develop climate-adaptation plans** that protect and upgrade their infrastructure through multi-year investment plans as well as in their operational regimes. **Identifying cost-effective resilience measures and creating an incentive mechanism** can stimulate utilities to adopt resilience measures, such as physical system hardening, improvements in system operation, recovery planning and capacity building.

Evaluating the effectiveness of the implemented resilience measures and adjusting them according to the results will enable a continuous improvement approach. Some countries have already started adopting guidelines to anticipate, absorb, accommodate and recover from present and projected climate impacts.

An example is represented by resilience in Italian regulation, where ad-hoc interventions are remunerated to DSOs in certain circumstances. The parameters considered include timelines, quantifying the advantages expected for a specific network portion, societal benefits, and continuity and quality of supply. Further details of this are included in case study 5.

There are still significant policy gaps in asserting climate resilience into mainstream long-term energy planning and electricity security. IEA analysis shows that around 25% of IEA member and association countries do not address climate resilience in their energy and climate plans and that most countries have scope to improve the level of their policy preparedness. This is further stressed in figure 11 below which shows the IEA Climate Resilience Policy Indicators.

Level according to the Climate Resilience Policy Indicator

Figure 11: Climate Resilience Policy Indicator, IEA member and association countries, May 2021

Key drivers of the need for a resilience investment prioritisation framework include:

- Increasing threat and climate adaptation
- Changing customer needs for energy-based services, and increasing utility and customer reliance on clean and distributed resources
- Lack of consensus around defining, assessing, valuing, and prioritising resilience investments

Scope considerations for resilience needs or improvement goals include threats or hazards of interest, what part of the system or type of impact is of interest, etc. The scope of planning activities will guide approaches to other aspects, with a decision support "framework" providing structure for how the relevant information fits together to guide decisions. Decision support frameworks rely on the ability to tie a value to the impacts of possible investments (i.e., costs and benefits), in order to weigh trade-offs of possibly diverse solutions or approaches during decision making.

An illustration the different timeframes that resilience solutions may target are described in Figure 12 below.[1],[2]

Resilience planning may weigh the ability of solutions to prepare for or mitigate impacts against support for adaptation of critical load and infrastructure during an outage and against improved system restoration times based on desired local and societal outcomes.

The value of energy may be captured as people's willingness to pay to maintain the critical levels of services that support individual and community economic activity, health, and safety. The value of a kilowatt-hour is its ability to support comfort, health, quality of life, and business continuity, and that depends on the service the kilowatt-hour provides, who is using the service, and how long they go without it.

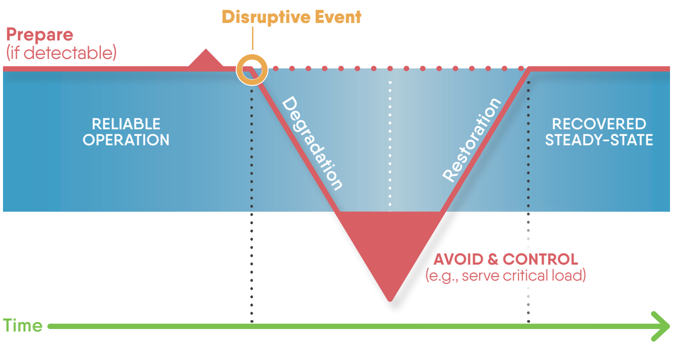


Figure 12: Illustration of resilience events as characterized by the North American Energy Reliability Corporation (NERC). *Reference: figure based on (IEEE, 2018a) (Moura, 2020)*

Key gaps and challenges in assessing the value of resilience[3]:

- Insufficient data to predict costs for sustained outages
- Difficulty modelling customer behaviour
- Incorporating uncertain climate futures into cost and benefit

Connecting system capabilities and performance to the customer and societal outcomes to be reduced or avoided rely on a defined role for metrics. For instance, how may a performance-based metric like unserved load translate to a customer or societal outcome?

An illustration of different approaches to estimating the cost of outages or the value of avoiding them is provided here.

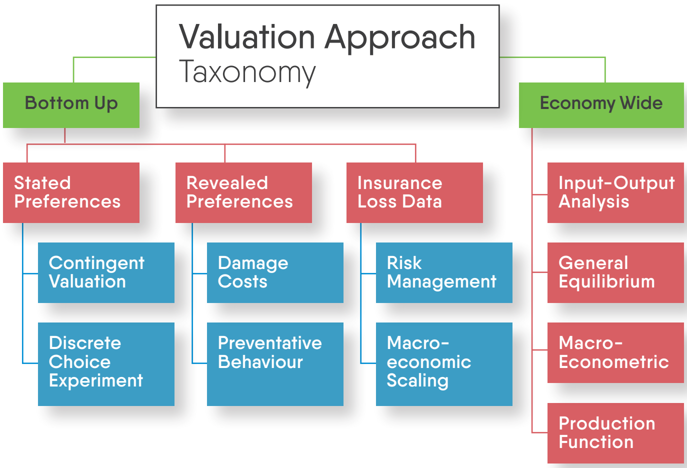
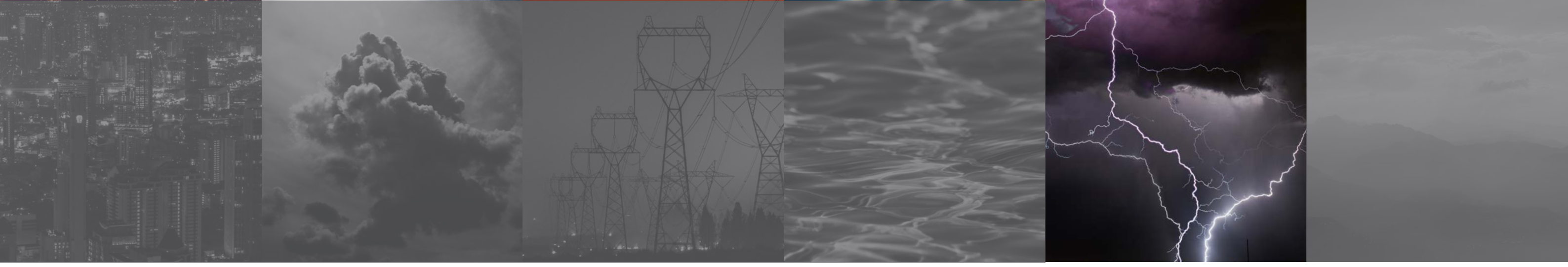


Figure 13: Illustration of different approaches to estimating outage costs to customers, businesses, and society. (Based on NARUC 2019)

The approach that's used depends on the level of threat, avoided outcomes, or planning activity being used.

Bottom up or microeconomic approaches often use people's or businesses' stated or revealed preferences to estimate the direct cost of outages, such as spoilage, lost wages, etc.

Economy-wide, top down, or macroeconomic approaches estimate direct plus indirect economic costs that ripple throughout the economy following an outage.

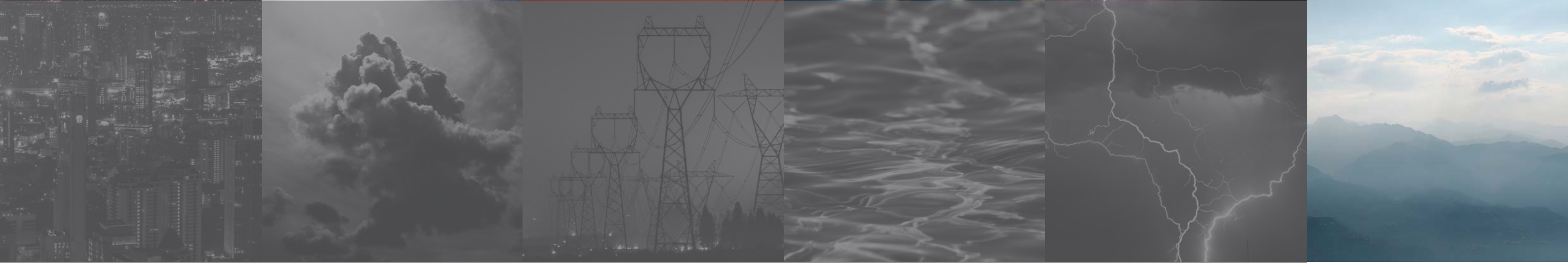


Gaps in valuation approaches:

- Existing bottom-up survey-based info detailing customer costs is dated, not statistically representative, and not well-suited for long duration/widespread interruptions.
- Economy-wide regional economic models estimate direct and indirect impacts of extended outages, but do not fully consider customer behaviour and may not produce results that may be easily used in planning.
- Regulators and utilities need simple and accessible tools to assess the value of investments to avoid short/long, local/widespread power interruptions.

EPRI's Climate READi approach to developing resilience and adaptation planning and prioritisation includes the following high-level tasks to arrive at a prioritisation framework:

- **Stakeholder Group Formation and Leadership:** This is a multi-dimension and complex problem to solve, and development of a "used and useful" framework necessitates inputs from and coordination among a wide range of subject matter expertise from many disciplines.
- **Development of Macro-Level Scenarios and Network Models for Analyses:** "Scenario" here refers to development of the future states of the grid for performing analyses across levels of infrastructure, and to be used for assessing societal impacts. Capturing climate change impacts requires projecting the future (2030+) conditions and adaptations of the system, and a robust integrated system planning process that can capture multiple objectives.
- **Extreme Event Definition:** "Extreme events" refer to high-impact low frequency (HILF) events which may be initiated by climate change, extreme weather or other natural or man-made causes; in particular extreme contingency events that could result in severe impacts on the power system and society.
- **Impact Quantification of Extreme Events:** It is critical to be able to quantify the impacts of extreme events across the power system and to customers/society in order to prioritise reinforcement decisions. Identifying and defining metrics that measure impact and improvement form the basis for any cost-benefit assessments, they in turn help identify the most effective decisions to improve the reliability and resilience of the system.
- **Cost-Benefit Assessment:** Fundamental to any resilience related investment decision is a full understanding of how the costs compare to the benefits, both from a systemic and socioeconomic perspective. Guidance on how to comprehensively combine varied metrics for a robust evaluation across potential mitigation and adaptation decisions is required.



Appendix I –
Further Detail of Climate Adaptation Legislation

Climate Change Adaptation in the Paris Agreement

Even if Europe and the world achieve their climate mitigation objectives, climate change will still have a major impact on society, the environment, and infrastructure. Mitigation must go hand in hand with adaptation when considering climate action. The Paris Agreement sets adaptation and resilience as one of its key objectives for addressing climate change. In Article 7, countries commit to ensuring their adaptation measures will take into account the impacts of global warming.

Taxonomy of Investments

Climate change adaptation is one of the six environmental objectives of the Taxonomy Regulation applicable since July 2020. The EU Taxonomy provides a methodology to define environmentally sustainable activities. Its main goal is to boost investment in green and viable enterprises to ensure the continuation of our society and environment. It thus gives a clear roadmap to companies, investors and policymakers to help Europe overcome climate challenges.

To be considered sustainable, an activity must contribute to at least one of the six objectives of the Taxonomy without doing significant harm to others which may jeopardise climate change mitigation. To offer a concrete process for existing and new activities to fit these two goals, a first delegated act on climate change mitigation and adaptation objectives entered into force in January 2022.

The document presents the screening criteria needed to consider that an activity contributes to climate change adaptation. Since quantitative baselines have not yet been developed on this topic, these principles are only qualitative:

1. The economic activity reduces all material physical climate risks to the extent possible and on a best-effort basis.
2. The economic activity does not adversely affect adaptation efforts by others.
3. The economic activity has adaptation-related outcomes that can be defined and measured using adequate indicators.

In terms of energy, climate change adaptation screening criteria are common to the whole sector, from generation to transmission to distribution, while economic activities related to climate change mitigation should always fit these same criteria. To contribute to climate change adaptation, an economic activity related to the energy sector should then meet the principles previously presented as well as the already existing regional and national adaptation plans and strategies. To comply with the first principle, a climate risk and vulnerability assessment identifying the physical climate risks that jeopardise the activity, their impacts on the given activity, and the related adaptation solutions should be conducted.

The mitigation and adaptation taxonomy delegated act distinguishes two types of contributions to climate change adaptation: adapted activities and activities. The decision tree below summarises the process of deciding whether an activity effectively contributes to climate change adaptation.

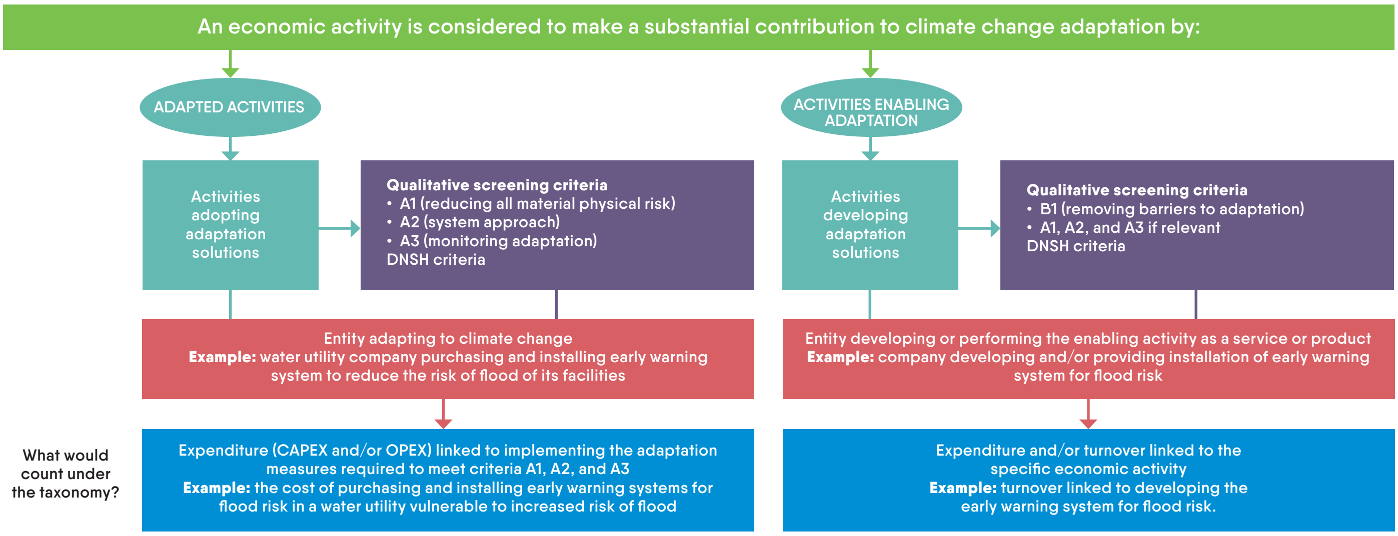
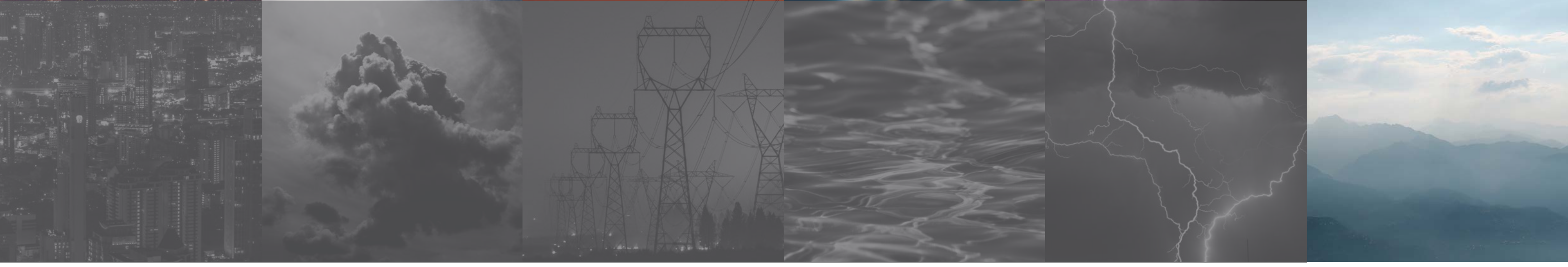


Figure 14: Taxonomy report: Technical Annex



Risk Preparedness Regulation

While the Taxonomy focuses on the EU's large-scale objectives, other texts refer to the expected disruptions or destructions in times of climate change. On June 5, 2019, the European institutions endorsed the Risk Preparedness Regulation to avert, adapt to and handle electricity crises, which can be caused by weather extremes. Under this multi-act Regulation, ENTSO-E submitted to ACER a methodology to identify regional electricity crisis scenarios. This approach thus enables countries to consider national specific circumstances. Each Member State must designate a competent authority to carry out tasks from the regulation.

Based on ENTSO-E's methodology and consultations with all stakeholders, each competent authority must set up a national risk-preparedness plan. This plan establishes measures to avoid or deal with regional or national electricity crises focusing on the highest ranked scenarios. This way risk-preparedness plans help the power sector react to electricity crises in times of climate change.

Figure 15 below shows the countries for which crisis scenarios arising from the Risk Preparedness Regulation have been evaluated.

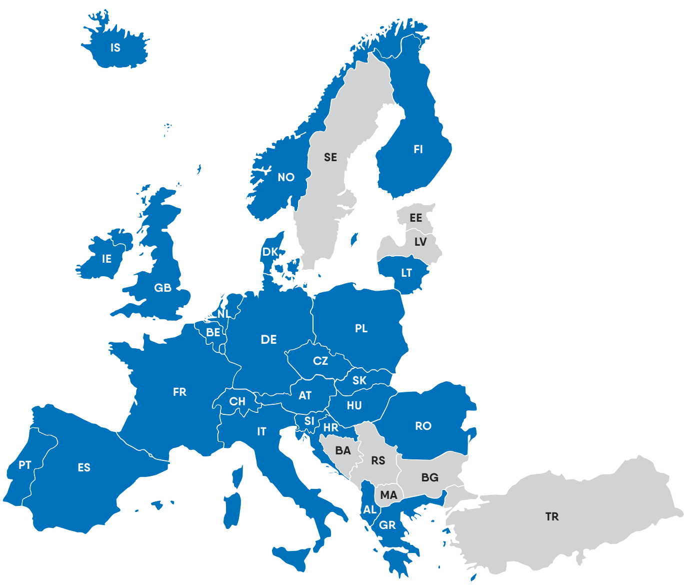
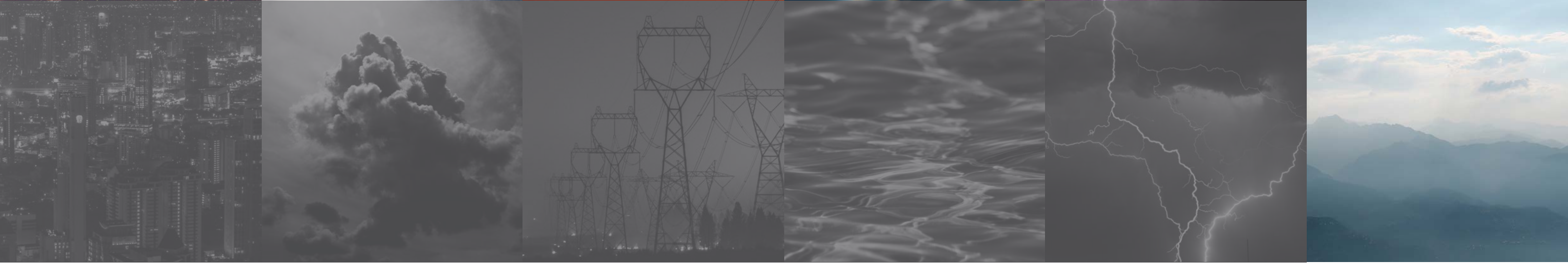


Figure 15: 26 Countries for which the likelihood and severity of regional electricity crisis scenarios were evaluated (ENTSO-E)

ENTSO-E has highlighted the top 15 scenarios with the highest likelihood and severity which include many scenarios related to attacks and cyber attacks. Extreme weather events however dominate the rankings as can be seen in Figure 16 below.

Topical groupings	Regional crisis scenario title
Cyber attack	Cyberattack - entities connected to electrical grid
Extreme weather	Heatwave
Attack	Physical attack - critical assets
Extreme weather	Storm
Extreme weather	Dry period
Fuel shortage	Fossil fuel shortage
Attack	Insider attack
Extreme weather	Cold spell
Extreme weather	Winter incident
Extreme weather	Multiple failures caused by extreme weather
Attack	Physical attack
Attack	Threat to key employees
Other	Pandemic
Technical failure	Loss of ICT systems for real-time operation
Cyber attack	Cyberattack - entities not connected to electrical grid

Figure 16: Rankings of Electricity Crisis Scenarios by ENTSO-E



CER Directive

In 2008, the European Union adopted the Critical Infrastructure Directive as part of its Programme for Critical Infrastructure Protection. This ensures the identification and protection of European critical energy and transport infrastructure, whose disruption could have major effects. A 2019 evaluation of this framework stressed the necessity to revise the directive to consider more assets and the latest risks such as the growing impacts of climate change.

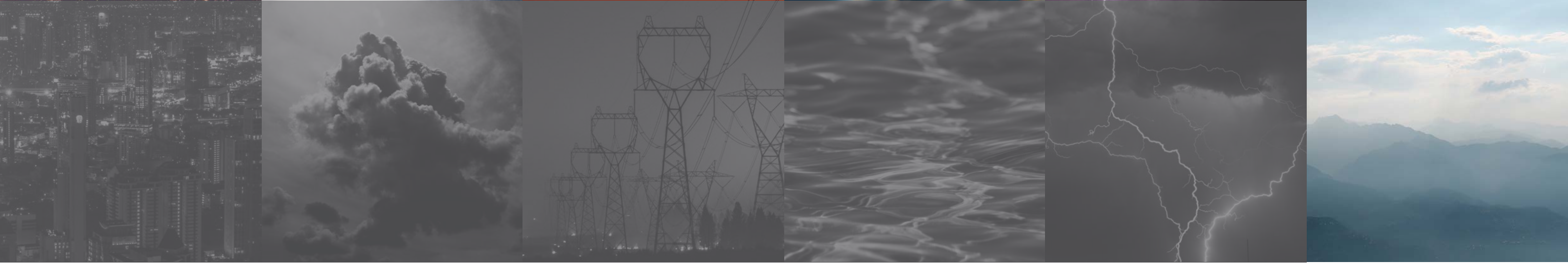
Hence, the European Commission's proposal published in December 2020 is now awaiting Parliament's decision in the first reading. The European Commission states the new Directive will "ensure that critical entities are able to prevent, resist, absorb and recover from disruptive incidents". In this respect, it first plans to enlarge the scale of the document from two to ten sectors, still including energy. Based on a national risk assessment they shall set up, it also requires Member States to identify their own critical entities, establish concrete measures to foster the resilience of such infrastructures and report every disruption to their national authorities.

Article 3 of the proposal acknowledges that the expected increase in the frequency and intensity of extreme weather events could threaten the efficiency or even the use of critical entities. The Article thus highlights that, in times of climate change, resilience and adaptation actions are fundamental in every sector.

Adaptation Strategy

These frameworks and laws are not the only European initiatives that will help the power sector withstand the huge impacts of climate change. Indeed, the European Union is currently revising its Adaptation Strategy. Adopted in 2013, the EU Strategy on Adaptation to climate change aims to strengthen Europe's resilience to its growing effects. Article 7 thus guarantees more resilient infrastructure, especially related to the power system. The strategy also led to the creation of Climate-ADAPT, the very reputed European platform for adaptation knowledge. Yet, in February 2021, following an evaluation of, and an open public consultation on the current framework, the Commission proposed to revise the strategy. While the existing one establishes guidelines to plan adaptation responses, this proposal intends to develop and implement solutions to the inevitable impacts of climate change.

At the same time, as part of its Horizon Europe programme, the Commission is currently conducting the five EU Missions which aim to make the continent greener, healthier, more inclusive and more resilient. One of them is specifically dedicated to adaptation to climate change. Based on a report published in 2019 by fifteen experts, the mission intends to demonstrate that our societies and infrastructure can adapt to the expected shocks by helping 150 European cities become climate-resilient by 2030.



Appendix II – Drafting Team Composition

A big thank you to the members of the drafting team and to EPRI colleagues for providing their time, expertise, and knowledge of the power sector's response to extreme weather events.

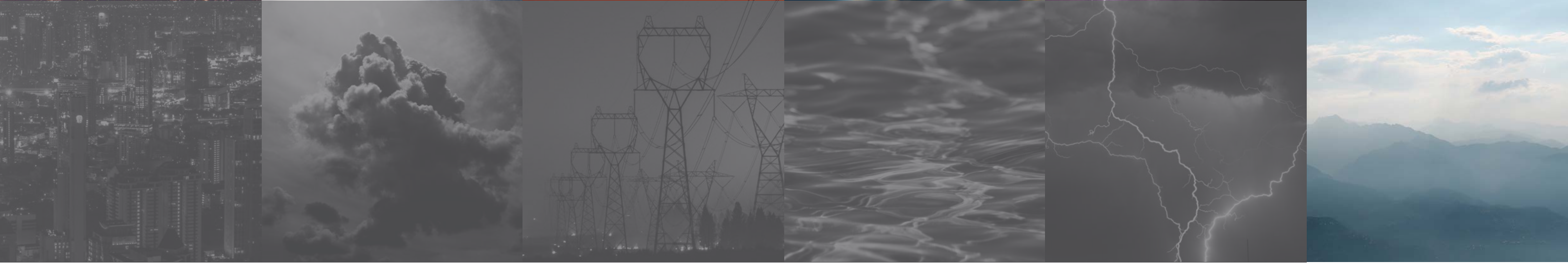
Eurelectric Secretariat & EPRI Leadership:

Caoimhín Ó Briain, *Distribution & Market Facilitation Team, Eurelectric – Project Manager*
Louise Rullaud, *Head of Distribution & Market Facilitation Team, Eurelectric*
Paul Wilczek, *Generation Head of Energy Policy, Climate & Sustainability team, Eurelectric*
Thibaut Arrat, *Trainee in the Distribution & Market Facilitation Team, Eurelectric*

Alexander Summe, *Chief Of Staff, EPRI*
Mark McGranaghan, *Fellow, EPRI*
Sara Mullen-Trento, *Senior Technical Leader, EPRI*
Markus Wolf, *Regional Manager for International Stakeholders & Germany, EPRI*
Laura Fischer, *Technical Leader, EPRI*
Morgan Scott, *Director – Climate READi, EPRI*

Drafting Team Members:

Alessio Pastore, *Market Strategy and Regulatory Analysis, Enel Grids*
Anna Lisa Frau, *Network Development, Enel Grids*
Anna Zvolikevych, *Brussels Representative, DTEK*
François Rondeau du Noyer, *Senior Advisor Energy, EDF*
Gundula Konrad, *Senior Advisor, VERBUND Hydro Power*
Mark Dunk, *Head of Engineering, ENA*
Marie Picut, *European Affairs Policy Manager, Enedis*
Włodzimierz Lewandowski, *Expert, PGE*
Richard Scharff, *Hydro, Vattenfall*
Stavros Saouros, *EAC*
Tzeni Varfi, *Policy and Legal Director, EDSO*



Appendix III –
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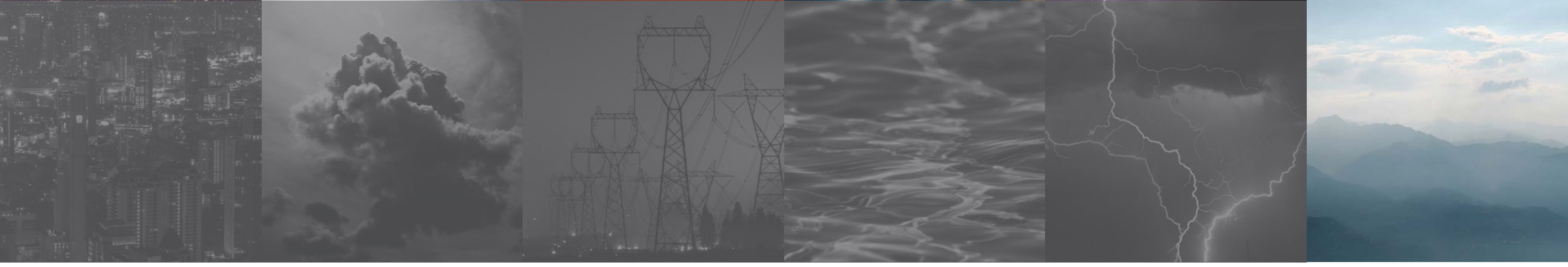

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Boulevard de l'Impératrice, 66 – bte 2 - 1000 Brussels, Belgium
Tel: + 32 2 515 10 00 - VAT: BE 0462 679 112 • www.eurelectric.org
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