Climate Resilience

International Energy Agency

Electricity Security 2021

INTERNATIONAL ENERGY AGENCY

The IEA examines the full spectrum of energy issues including oil, gas and coal supply and demand, renewable energy technologies, electricity markets, energy efficiency, access to energy, demand side management and much more. Through its work, the IEA advocates policies that will enhance the reliability, affordability and sustainability of energy in its 30 member countries, 8 association countries and beyond.

IEA member countries:

Australia
Austria
Belgium
Canada
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Japan
Korea
Luxembourg
Mexico
Netherlands
New Zealand
Norway
Poland
Portugal
Slovak Republic
Spain
Sweden
Switzerland
Turkey
United Kingdom
United States

The European Commission also participates in the work of the IEA

IEA association countries:

Brazil
China
India
Indonesia
Morocco
Singapore
South Africa
Thailand

Abstract

Electricity is an integral part of all modern economies, supporting a range of critical services. Secure supply of electricity is of paramount importance. The power sector is going through fundamental changes with increasing pressure from climate change. Climate change directly affects every segment of the electricity system altering generation potential and efficiency, testing physical resilience of transmission and distribution networks, and changing demand patterns. Effective policy measures and co-ordinated action among key actors play a central role in building resilience to climate change. This report provides an overview of the climate impacts on electricity systems. It describes how climate change affects each segment of the electricity value chain – generation, transmission and distribution, and demand – with case studies around the world. It proposes a step-by-step application of measures for policy makers and key stakeholders to build the climate resilience of electricity systems.

Acknowledgements, contributors and credits

This report was prepared by a cross-agency group of experts from the Directorate of Energy Markets and Security, the Directorate of Sustainability, Technology and Outlooks and the Strategic Initiatives Office of the International Energy Agency (IEA). The study was led and co-ordinated by Edwin Haesen, former Head of the System Integration of Renewables (SIR) Unit, and César Alejandro Hernández Alva, Head of the Renewable Integration and Secure Electricity (RISE) Unit. Keisuke Sadamori, Director of Energy Markets and Security, provided expert guidance and advice.

The lead authors of this report were Craig Hart and Jinsun Lim. Other IEA colleagues also contributed to the analysis, including Jihyun Lee, Peerapat Vithayasrichareon, Keith Everhart, Kartik Veerakumar and Chiara D'Adamo (consultant) and Chiara Delmastro. Anna Kalista provided essential support.

Valuable input, comments and feedback were provided by IEA colleagues, including Dave Turk, Laszlo Varro, Paolo Frankl, Laura Cozzi, Peter Fraser, Tom Howes, Brian Motherway, Aad van Bohemen, Brent Wanner and Sara Moarif.

Justin French-Brooks was the editor of this report. Thanks go to the Communications and Digital Office (CDO) for its help in producing the report and website materials, particularly to Jad Mouawad, Head of CDO, and Astrid Dumond, Tanya Dyhin, Christopher Gully, Jethro Mullen, Isabelle Nonain-Semelin, Julie Puech and Therese Walsh.

A high-level workshop on Electricity Security was held in Paris on 28 January 2020. The participants offered valuable insights and feedback for this analysis. Further details are available at www.iea.org/events/iea-electricity-security-workshop.

The authors would like to thank the many external experts who provided valuable input, commented on the analysis and reviewed preliminary drafts of the report. They include: Francesca Gostinelli and Viviana Vitto (Enel); Hans Martin Füssel (European Environment Agency); Catherine Gamper (Organisation for Economic Co-operation and Development); Lwandle Mqadi (Eskom); Takashi Hongo (Global Strategic Studies Institute); Roberta Boscolo (World Meteorological Organization);

Sushil Kumar Soonee (Power System Operation Corporation Limited); Sylvie Parey (Électricité de France); Jean-Michel Glachant (Florence School of Regulation); James Falzon (European Bank for Reconstruction and Development), Juliet Mian (Arup); Manabu Nabeshima (Ministry of Foreign Affairs, Japan); and Russ Conklin, Fowad Muneer and Carolyn Gay (United States Department of Energy).

Comments and questions on this report are welcome and should be addressed to EMS-RISE@iea.org.

Executive summary

Climate change: An increasing threat

The electricity system is witnessing increasing pressure from climate change. Global warming, more variable precipitation patterns, rising sea levels and extreme weather events already pose a significant challenge to the resilience of electricity systems, increasing the likelihood of climate-driven disruption.

Climate change directly affects every segment of the electricity system. It impacts generation potential and efficiency, physical resilience of transmission and distribution networks, and demand patterns. In many countries the increasing frequency or intensity of extreme weather events such as heat waves and cold waves, wildfires, cyclones and floods are the dominant cause of large-scale outages. The recent outages due to heatwave in California, cold wave in Texas, and wildfires in Australia demonstrate that electricity systems are already exposed to and largely affected by climate hazards.

Higher global temperatures could lead to decreasing efficiency, changing generation potential and affecting demand for heating and cooling. Changes in precipitation patterns may alter generation output, potential, peak and variability while posing physical risks to transmission and distribution networks. Sea-level rise can limit further development of new assets and damage electricity systems near coastlines. In addition, electricity systems are also vulnerable to more intense or frequent extreme weather events which could lead to physical damage to energy assets and reduce efficiency.

Table 1 Overview of main potential impacts on the electricity system due to climate change

Climate impact	Generation	Transmission and distribution	Demand
Rising global temperatures	• Efficiency • Cooling efficiency • Generation potential • Need for additional generation	• Efficiency	• Cooling and heating
Changing precipitation patterns	• Output and potential • Peak and variability • Technology application	• Physical risks	• Cooling • Water supply
Sea-level rise	• Output • Physical risks • New asset development	• Physical risks • New asset development	• Water supply
Extreme weather events	• Physical risks • Efficiency	• Physical risks • Efficiency	• Cooling

Multiple benefits of climate resilience

A climate-resilient electricity system, which has the ability to anticipate, absorb, accommodate and recover from adverse climate impacts, brings multiple benefits to electricity security. **First, it reduces the potential damage and loss from climate impacts**. Recent studies suggest that the benefits of resilient electricity systems are much greater than the costs in most of the scenarios considering the growing impacts of climate change. For instance, in some vulnerable countries, underground transmission and distribution cables can significantly reduce potential damage from climate impacts and save recovery costs, although they may require higher upfront outlay than above-ground systems.

Moreover, adopting climate resilience measures contributes to improved electricity access. In Zambia, where only 30-40% of the population have access to electricity, a shorter rainy season and more frequent droughts significantly limit progress towards universal electricity access by reducing hydropower generation and prompting blackouts. The adoption of climate resilience measures, such as an improved system for monitoring climate hazards and a strategy for diversifying the electricity generating mix could help Zambia ensure reliable access to power networks.

Climate resilience also facilitates clean energy transitions, enabling more electrification solutions and accelerating the transition to renewable energy technologies, which are often sensitive to a changing climate. Adoption of measures to build climate resilience is vital, especially the case in countries whose electricity infrastructure is vulnerable to changes in climate and extreme weather events.

Effective policy measures

This report proposes a step-by-step application of measures for improving the climate resilience of electricity systems. It consists of six steps:

- **Assess climate change risks and impacts**: A comprehensive climate risk and impact assessment provides a strong scientific foundation for development of strategies and plans for climate resilience.
- **Mainstream climate resilience as a core element of energy and climate plans and regulations**: Integrating climate resilience into national strategies and plans sends a strong signal to utilities and investors to build a climate-resilient electricity system. However, the present level of commitment and progress varies considerably across countries. Only 24% of International Energy

Agency countries have developed concrete plans for the climate resilience of their entire electricity systems in national adaptation strategies.

- **Identify cost-effective resilience measures**: Plans and guidelines to enhance resilience to climate change can help utilities identify the most cost-effective measures at the planning stage. They encourage utilities to consider all available resilience measures over the entire life cycle of an asset, and estimate their cost-effectiveness based on the estimation of synergies with other business objectives and trade-offs.
- **Create appropriate incentives for utilities**: Although utilities have a direct interest in protecting their assets against adverse effects of climate change, appropriate incentives can encourage timely investment in resilient electricity systems. An incentivisation mechanism, such as performance-based rate making, catalyses investment in resilient electricity systems.
- **Implement resilience measures**: Physical system hardening, advanced system operation, better co-ordination of recovery efforts and capacity building enhance the climate resilience of electricity systems.
- **Evaluate effectiveness and adjust resilience measures**: Adjusting resilience measures based on an evaluation system and consultation with stakeholders enables the constant improvement of adopted resilience measures.

Introduction

Climate change poses an increasing threat to electricity security

Projections indicate that the world is very likely to experience greater climate hazards over the rest of this century. The continued increase in temperatures is expected to lead to sea level rise and a decline in snow cover and glaciers. Annual mean precipitation is projected to exhibit substantial regional variation, increasing in some countries while decreasing in others. Extreme weather events such as heatwaves, wildfire, tropical cyclones and floods are expected to become more frequent or intense in many countries.

Changing climate patterns and extreme weather events pose an increasing threat to electricity security. Climate change directly affects all domains of the entire electricity system. It impacts generation potential and efficiency, physical resilience of transmission and distribution networks, and demand patterns. Adverse climate impacts could lead to longer electricity outages, with negative effects on the economy and society. They may also hinder the energy transition towards low-carbon energy sources since renewable energy technologies are often sensitive to climate variability. The uncertainty and complexity of the earth's climate system makes it challenging to assess specific impacts of climate change on electricity systems and identify effective measures for electricity security.

Policy measures play a central role in addressing climate impacts and enhancing the resilience of electricity systems

To minimise the adverse impacts of climate change, effective policy measures have a central role to play in accelerating action by key actors. Although businesses have responsibility for and a direct interest in protecting their own assets and providing reliable services to their customers, there are several factors that may deter some from adopting resilience measures in practice. Consequently, it is the job of policy makers to collaborate with businesses and encourage them to build resilient electricity systems by adopting effective policy measures that can prevent potential "market failure".

Some countries have already introduced tools and guidelines to anticipate, absorb, accommodate and recover from present and projected climate impacts.

However, many others still have a significant policy gap in bringing climate resilience into the mainstream of long-term energy planning and electricity security.

Building a **clear assessment framework** for climate impacts and resilience is the first step to ensure all stakeholders properly understand projected changes in climate. After establishing a common assessment framework, policy makers need to **send appropriate signals** to essential service providers. They can encourage utilities to include climate resilience in their construction plans and operational regimes by emphasising climate resilience as a core element of their own long-term energy and climate policies. **Identifying cost-effective resilience measures** and **creating an incentive mechanism** also encourage utilities to adopt resilience measures. With supportive policy measures, businesses can **implement 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 the constant improvement of climate resilience.

This report supports policy makers and other key actors by providing step-by-step advice

This report aims to support policy makers and other relevant stakeholders in preparing for growing climate impacts on electricity systems. It provides an overview of climate observations and projections; assesses climate impacts on electricity systems with real-world examples; describes the benefits of climate resilience; and presents effective measures to mitigate the adverse effects of climate change. This report addresses the following questions:

- What types of climate hazards will we face?
- How does climate change impact electricity systems?
- What is “climate resilience” and what are the benefits of enhancing the resilience of electricity systems to climate change?
- Which policy measures can help to enhance climate resilience?

Discussing the questions above, this report introduces various terms and definitions. The following table describes the principal terms used in this report, aligned with the terminology of the United Nations Intergovernmental Panel on Climate Change. These terms align with the electricity security-related terms applied throughout this IEA report.

Table 2 Key terms and definitions

Term	Definition
Climate change	A change in the state of the climate that can be identified by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer.
Climate impact	The actual consequences of climate change.
Climate resilience	The ability to anticipate, absorb, accommodate and recover from adverse climate impacts.
Extreme weather events	Events that are rare at a particular place and time of year.
Climate change adaptation	The process of adjustment to actual or expected climate change and its effects.

Sources: IPCC (2012); IPCC (2015).

How the climate is changing

The world is already experiencing an increasing number of anomalies in climate patterns. More climate hazards are projected to manifest themselves during the rest of this century. The global mean temperature and sea level are likely to increase consistently as they have in the past few decades. Spatial variations in global precipitation are becoming more marked, and extreme weather events more frequent or intense in many countries.

The intensity and direction of the projected changes heavily depend on the trajectory of global greenhouse gas (GHG) concentrations. A future with more than 1 000 parts per million of CO_2-equivalent concentrations would be significantly different from a future with less than 500 ppm. To illustrate and compare future climate scenarios by the level of GHG concentrations, the IPCC Fifth Assessment Report defines a set of four Representative Concentration Pathways (RCPs).[1] Among these, RCP2.6 presents a low GHG concentration pathway that is aligned with the goals of the Paris Agreement, while RCP8.5 represents a high GHG concentration pathway.

Table 3 Overview of the RCPs

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Targeted radiative forcing in the year 2100 (W/m^2)	2.6	4.5	6.0	8.5
CO_2-equivalent concentrations (ppm)	430-480	580-720	720-1 000	> 1 000
Mean cumulative CO_2 emissions 2012 to 2100 ($GtCO_2$)	990	2 860	3 885	6 180

Notes: $GtCO_2$ = gigatonne of carbon dioxide. W/m_2 = watts per square metre.

Source: IPCC (2015).

Average temperatures continue to increase

The past decade (2010-19) was the hottest on record and the years 2016-20 were the warmest five-year period on record since modern temperature records began

[1] The RCPs show various representative GHG concentration trajectories and the impact of each level of GHG concentration on the future climate. The IPCC Fifth Assessment Report defines RCPs as scenarios that include time series of emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover (Moss et al., 2008). The word *representative* signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics.

in 1850. The global mean temperature in 2019 was around 1.1(±0.1)°C above pre-industrial levels (1850-1900).

A continuation of global warming in the 21st century is likely to be consistently observed under all RCP scenarios. Under the RCP2.6 scenario, the increase in global temperature is likely to stay below 2°C relative to the pre-industrial level (1850-1900) by the end of this century. In the RCP8.5 scenario, by comparison, the increase in global mean temperature is likely to exceed 4°C. The continued increase in temperature levels has already led to a general decline in snow cover, glaciers and permafrost in recent decades. This trend is projected to continue in almost all regions over the 21st century.

Table 4 Overview of the projected increase in the global temperature

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Global mean surface temperature change (°C) in 2081-2100 (relative to pre-industrial level, 1850-1900)	1.6 ±0.4	2.4 ±0.5	2.8 ±0.5	4.3 ±0.7
Likelihood of staying below a specific temperature level over the 21st century (relative to pre-industrial level, 1850-1900)	Likely to stay below 2°C	More unlikely than likely to stay below 2°C	More unlikely than likely to stay below 3°C	More unlikely than likely to stay below 4°C

Source: IPCC (2015).

Precipitation patterns will show substantial variation by region

Climate change is leading to increasing spatial variation in precipitation patterns, and is expected to make wet regions wetter and dry regions drier. Some regions are likely to experience increases in precipitation while others experience decreases. In fact, precipitation has increased since 1951 in the mid-latitude land areas of the Northern Hemisphere, while other areas such as Southeast Asia and some parts of Africa have observed a decrease in precipitation.

The variation is even more marked with a high GHG concentration. Under RCP8.5 high latitudes and equatorial Pacific are likely to experience an increase in annual mean precipitation for the rest of the century. In contrast, in many mid-latitude and dry subtropical regions, the mean precipitation is likely to decrease. The Mediterranean region, which has already observed an increase in droughts, may experience more drought years particularly with a high GHG concentration.

The global mean sea level continues to rise, driven by ocean warming and melting of glaciers and ice sheets

Over the period 1901-2010 the global mean sea level rose by 0.19 metres (m). Continuous increases in ocean heat content expanded the volume of sea water and accelerated the melting of ice sheets in Greenland and Antarctica. The global mean sea level reached its highest value in 2019 since the beginning of the high-precision record in 1993.

The global mean sea level is expected to continue to rise. According to research, by the end of the 21st century sea level rise will be observed in over 95% of the ocean area. About 70% of coastlines worldwide are projected to experience sea level change. Sea level rise will be affected by the pathway of CO_2 emissions and concentration. However, even under a low GHG concentration scenario (RCP2.6), the rate of sea level rise is likely to exceed the historical level of 2.0 millimetres per year. In the high GHG concentration scenario (RCP8.5) the rate of rise exceeds 8 millimetres per year during 2081-2100, leading to a more considerable and irreversible change in sea level.

Most countries are likely to experience more frequent or intense extreme weather events

Extreme weather events such as heatwaves, wildfires, tropical cyclones and floods are likely to become an increasing risk with further changes to the climate. However, it is often challenging to anticipate changes in the direction and magnitude of extreme weather events since it requires consideration of many factors, such as the type of events, geographical features, seasons and GHG concentration pathways.

The frequency of heatwaves has increased in large parts of Europe, Asia and Australia, and the length and intensity of heatwaves is likely to increase over most land areas. In 2019, for instance, two major heatwaves occurred in Western Europe in late June and late July, setting the record for highest temperature in France, Germany, the Netherlands, Belgium, Luxembourg and the United Kingdom.

The likelihood of wildfires is expected to increase with more frequent heatwaves and droughts in some regions. The duration of the fire weather season has increased by approximately 18-20% globally on average in recent decades.

The world is likely to experience more frequent occurrence of intense tropical cyclones that have higher peak wind intensity and precipitation than the historical average, although the total number of tropical cyclones should remain unchanged or even decrease. Records already show an increasing trend in intense tropical cyclone activity since 1970 in some regions. In 2019 cyclone Dorian and Idai resulted in widespread destruction in North America and Africa respectively.

The combination of projected changes in precipitation, temperature and frequency of intense tropical cyclones leads to possible changes in floods. For instance, increases in heavy rainfall and rapidly melting snow may contribute to increases in flooding in some regions, causing overflow or unusual accumulation of water.

Climate change is already affecting every segment of the electricity system in various ways

Policy makers and implementing agencies need to understand the impacts of climate change on infrastructure, society and the economy. The electricity sector deserves special attention, not only because of its high value to society, but also because of its specific features. The complexity of operations to balance supply and demand over a large area and population requires close consideration of climate risks.

An electricity system can be broadly categorised into three domains: 1) generation, 2) transmission and distribution (T&D), and 3) electricity demand. The impact of a rising global temperature, erratic patterns of precipitation, sea level rise and extreme weather events on any of these domains can have significant implications for electricity security. For generation, the impact of climate change can reduce the efficiency and alter the generation potential of thermal and renewable power plants. Climate change impacts on T&D networks often result in higher losses, changes in transfer capacity and particular physical damage. Electricity demand is also affected, particularly for cooling and heating, and water supply.

The table presents a summary of potential climate impacts on the electricity system, which are covered in more detail in the rest of the section.

Table 5 Overview of main potential impacts on the electricity system due to long-term climate trends and extreme weather events

<table>
<tr><th rowspan="2">Climate change trends</th><th rowspan="2">Specific parameter change</th><th colspan="3">Impact on electricity system domains</th></tr>
<tr><th>Generation</th><th>Transmission and distribution</th><th>Demand</th></tr>
<tr><td rowspan="2">Changing global temperature</td><td>Increase in air temperature</td><td>Generation efficiency
- Modest reduction in efficiency of solar PV modules and thermal power plants (derating)
Generation potential
- Decreasing hydropower potential due to increased evaporation losses from reservoirs
- Shift in hydrological flows due to changes in precipitation type (e.g. snow to rain) and glacial melt
Need for additional generation capacity due to higher demand
- Additional generation capacity in systems with annual peak in summer</td><td>Reduced network efficiency
- Modest increase in network losses and line sag reducing available capacity (also dependent on other variables such as wind)
- Derating of T&D equipment</td><td>Cooling and heating
- Increasing air-conditioning and refrigeration requirements
- Decreasing space heating demand</td></tr>
<tr><td>Increase in water temperature</td><td>Cooling efficiency
- Lower efficiency of thermal plant technologies with water-based cooling due to the increasing temperature of cooling water
Generation potential
- Lower generation potential due to ecological constraints on water temperature being fed back into water bodies</td><td></td><td></td></tr>
</table>

Climate change trends	Specific parameter change	Impact on electricity system domains		
		Generation	Transmission and distribution	Demand
Changing patterns of precipitation and humidity	Changing water availability	**Generation potential and output** - Changing hydropower potential due to changing patterns of precipitation - Partial output reduction or complete shutdown of thermal plants due to insufficient availability of cooling water **Peak and variability** - Increasing variations in hourly or seasonal peaks of hydropower generation as a result of increased anomalies in precipitation patterns **Technology application and development** - Constrained application of carbon capture, use and storage technologies where there is increased risk of water scarcity	**Physical risks to grids** - Damage to T&D assets due to direct or indirect impacts of heavy precipitation, such as intense rainfall, extreme snowfall, rock falls and landslides	**Cooling** - Increasing air-conditioning load due to a rising level of humidity in hot weather **Electricity for water supply** - Higher electricity demand to provide drinking and irrigation water in cases of drought
Sea level rise	Sea level rise	**Physical risks to generation assets** - Threats to existing generation facilities in coastal areas **Locations for new assets** - Limited availability of appropriate locations for new generation **Tidal generation output** - Change in generation output with a faster tidal current resulting from sea level rise	**Physical risks to grids** - Increasing vulnerability to coastal erosion and floods, linked to substations often located near main generation plants and load centres in coastal areas **Locations for new assets** - Limited availability of appropriate locations for grid development	**Electricity for water supply** - Increasing cases of adopting more energy-intensive methods (e.g. desalination) to provide water due to saltwater intrusion
Extreme weather events	Heat waves	**Generation efficiency** - Reduced efficiency of solar PV modules and thermal power plants	**Transmission efficiency** - Substantial reduction in line capacity due to increased sag or cable capacity due to heat dissipation limitations - Derating of capacity to prevent transformer overload - De-energising lines to prevent potential fires	**Cooling** - Substantial increase in demand due to air conditioning and refrigeration, intensified by thermal inertia of buildings

Climate change trends	Specific parameter change	Impact on electricity system domains		
		Generation	Transmission and distribution	Demand
	Cold spells	**Generator availability** - Equipment failure - Disruption of fuel supply	**Physical risks to grids** - Damage to T&D equipment due to direct or indirect impacts such as extreme snowfall	**Heating** Substantial increase in demand due to electric heating
	Wildfires	**Physical risks to generation assets** - Physical damage	**Physical risks to grids** - Damage to T&D equipment due to direct or indirect impacts **Multiple short circuits** - Loss of import/export of electricity	
	Cyclones	**Physical risks to generation assets** - Physical damage	**Physical risks to grids** - Damage to T&D lines due to flying debris, strong winds and corrosion due to saltwater - Faults caused by flooding of transformers and substations due to storm surges	
	Floods	**Physical risks to generation assets** - Physical damage - Hydropower turbine abrasions and efficiency decrease due to an increased sediment load after floods or landslides caused by storms	**Physical risks to grids** - Damage to T&D equipment due to direct or indirect impacts of flooding, such as undermining tower foundations, rock falls and landslides - Damage to T&D lines due to direct or indirect impacts	-

Sources: Adapted from IEA (2015); IEA (2016); IEA (2018) ; EEA (2019); World Bank (2019); IPCC (2018); AEMO (2020b); CPUC (2020); Ebinger et al. (2011); Bierkandt et al. (2015); and Moore (2010).

Long-term impacts on electricity systems

Higher temperatures lead to decreasing efficiency, derating of equipment and increased demand, with a significant impact on the electricity system

Increasing temperatures, both observed in recent years and projected over the coming century, have an impact across the entire electricity value chain.

On the supply side, increasing temperatures lead to a decrease in generation efficiency. This is true for a number of technologies, including thermal and solar PV generation. In the case of thermal power plants, efficiency losses result in a derating of capacity and reduction in total power output.

The impact on thermal generator efficiency from temperature rise is dependent on the principal technology (steam or gas turbine) and cooling technology. The cooling technology is particularly important for steam turbines, where the efficiency is linked either to ambient air temperature or water temperature. Different climatic impacts therefore affect them differently. Environmental constraints on water temperature (both freshwater and seawater, as appropriate) for once-through cooling plants further limit the operation of plants. This can be exacerbated by insufficient availability of water. This lower capacity availability can coincide with a rise in power demand for space cooling.

Renewable generation is also affected in various ways. The efficiency of solar PV panels degrades as the temperature increases, while wind turbines may also be derated under extreme heat. Hydropower generation is particularly affected, both in terms of seasonal and year-to-year availability of energy. Rising temperatures affect hydrological conditions due to changes in precipitation type (e.g. snowfall or rainfall) as well as snow and glacial melt. In many snow-covered regions the snowpack acts as storage of hydropower potential, prior to peak flows in the spring and summer. Therefore, changes in river runoff in snow-dominated and glacier-fed river basins may be significant in both amount and seasonality in response to snow cover and glacier decline, as projected. This would lead to a decline in peak spring and summer flows and, in the case of increased rainfall in place of snowfall, higher peak flows in the autumn and winter. This would disproportionately affect countries with glacier-fed river basins such as Nordic and Alpine regions, where the majority of European hydropower generation is concentrated.

Changes in temperature also affect the operational limits of transmission and distribution equipment. These are characterised by thermal ratings and hence higher ambient temperatures naturally reduce capacity while also leading to higher losses. Lines may be thermally rated according to worst-case assumptions (e.g. low wind speed, high ambient temperature and high solar radiation) or use dynamic line rating, which allows for additional capacity in less onerous conditions and derates with increasing temperatures. In the case that temperatures start to exceed worst-case assumptions, the thermal limits of lines may be inadvertently exceeded, leading to faults on the network, while dynamically rated lines will decrease in capacity.

Studies from the United States suggest that rising temperatures may decrease the average summertime transmission capacity by as much as 5.8% by the middle of the 21st century relative to a 1990-2010 reference period. This impact is aggravated as it coincides with summertime peak loads. In other regions a decline in snow cover, glacier and permafrost due to global warming is very likely to result in increasing landslides and floods, which could damage the transmission and distribution lines in particular areas.

Temperature rise also affects the demand side. As regions with traditionally cooler climates start to experience a large enough window of hotter days, the installation of individual air-conditioning units increases, especially in the residential sector. Depending on factors such as the prevailing load shape, this may have a significant impact on the instantaneous system peak demand, as well as the capacity for which residential distribution networks, in particular, are designed. Space cooling on the hottest days of the year is already significantly contributing to peak demand in urban networks, and even the system-wide peak demand in countries such as Singapore and those in the Middle East.

Conversely, increasing temperatures may also lead to a reduction in heating demand. Depending on the system, this may actually lead to a seasonal shift in peak demand and subsequent changes in grid operation and maintenance practices.

Box 1 Case study: Rising temperatures and demand for cooling will have a substantial impact on generation capacity requirements

The structure of future energy demand will play an important role in system planning. Electricity generation needs to meet demand at all times in a cost-effective and sustainable manner. Developments in energy-efficient appliances and building design will play a critical role in determining this demand.

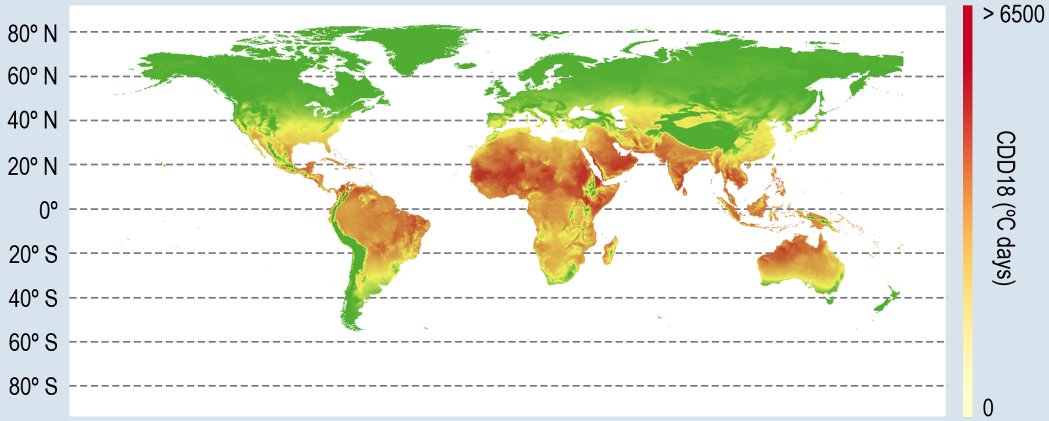
Recent IEA analysis looks at how future energy needs may evolve under two main IEA scenarios: the STEPS (Stated Policies Scenario), which looks at development of the global energy sector according to current and stated policies; and the SDS (Sustainable Development Scenario), which describes the broad evolution of the energy sector as required to reach the United Nations Sustainable Development Goals most closely related to energy, and consistent with reaching global net-zero CO_2 emissions from the energy sector in 2070.

The expected growth in space cooling demand is mainly driven by general cooling needs. These can be assessed by cooling degree days,[2] population growth and economic growth, which improves the standard of living and provides greater purchasing power. While growth in both the commercial and residential sectors is anticipated, it is expected that the residential sector will account for more than 70% of worldwide growth due very low air-conditioning ownership in hot and humid areas today. At the same time, other cooling demand is also expected to grow, such as refrigeration and cooling for data centres.

Global residential stocks of air conditioning could increase by another two-thirds by 2030. The rise in air-conditioning installations occurs predominantly in regions with both a warmer climate and higher economic growth, which in turn leads to improved standards of living and greater purchasing power. More than 80% of the growth in global residential air-conditioning stock to 2030 occurs in non-OECD countries where economic growth is highest through to 2030. Many of these countries also are in the warmer or more humid regions of the world, and hence experience relatively high numbers of cooling degree days (Figure 1). These regions are also expected to experience the largest change in cooling degree days under climate change projections (Figure 2).

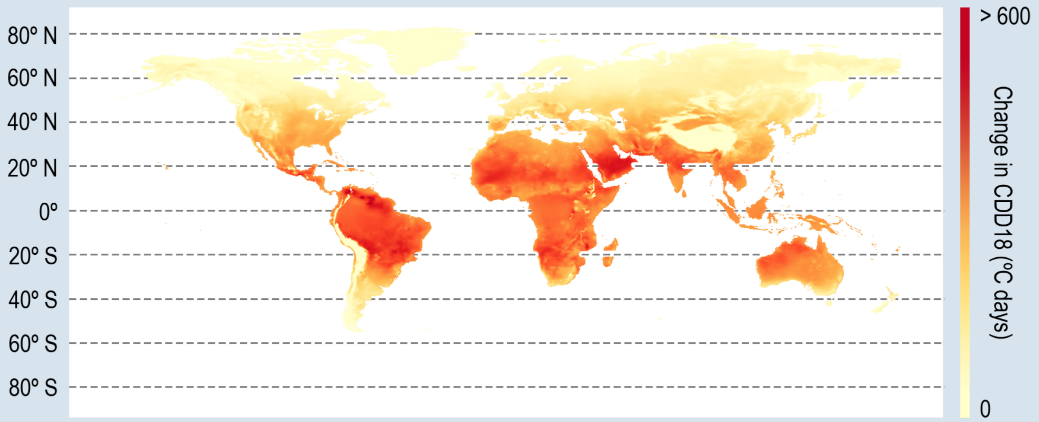
[2] These measure how much the mean temperature exceeds the standard temperature each day over a given period (e.g. a week in the summer or the entire year) and indicates space cooling requirements.

Figure 1 Cooling degree days across the world, 2019



Source: IEA (2020d).

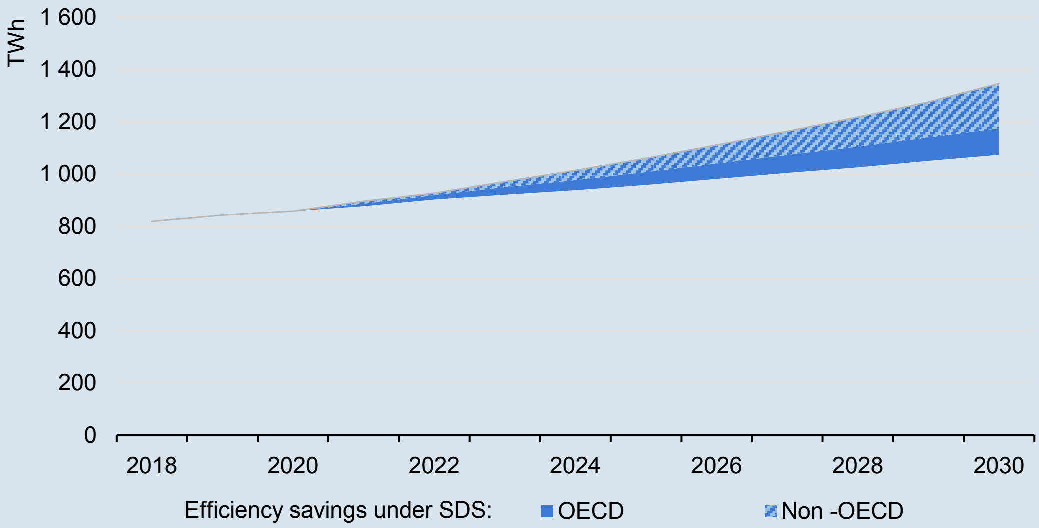
Figure 2 Change in cooling degree days across the world in 2070 under the STEPS scenario (RCP4.5 climate projections)



Source: IEA (2020d).

An increase in air-conditioning stocks will coincide with an increase in space cooling demand, in terms of both annual energy (TWh) and peak demand (GW). Both will be affected by the prevailing climate conditions. However, the level of increased demand can be mitigated by higher levels of energy efficiency in both cooling devices and building envelopes. Compared to 2018, global energy consumption for residential space cooling could increase by as much as 65% in 2030 (Figure 3). However, through a combination of more efficient devices, more resilient buildings and increased flexibility, this could be cut by one-fifth in the SDS, with the majority of these savings in non-OECD countries. This would correspond to a reduction of nearly 700 GWe in installed air-conditioning capacity through energy efficiency measures, directly benefiting the peak capacity requirements of the system. To put this in perspective, it is approximately equal to the combined peak demand of India and ENTSO-E in 2019.

Figure 3 Growth in residential space cooling demand under both STEPS and SDS to 2030



Source: IEA (2020a).

The projected increase in electricity demand for space cooling is especially important because, in general, the peak demand over the entire year (also known as the system peak) would be driven by seasonal heating and/or cooling needs. This system peak becomes the main driver for generation capacity requirements. Hence, as cooling demand grows and heat demand diminishes in many countries, this increase in cooling demand will become a driving factor for power capacity additions. Consequently, policies that support efficient and more responsive cooling technology and building design will become paramount in driving down capacity requirements for future electricity systems in many parts of both the developed and developing world.

Changing precipitation affects water availability, which increases stress on various electricity supply sources

The projected shift in global precipitation and its regional variations have implications for electricity supply – hydropower generation is evidently impacted. A shift in precipitation patterns, combined with changes in evapotranspiration caused by higher temperatures, leads to changes in hydropower generation. The increasing seasonal and multi-annual variability in this source of generation poses significant challenges to the operation and planning of the entire system.

As water availability changes at both seasonal and geographical levels, thermal generation that uses fresh water as a coolant is also affected. These thermal plants use water to cool the plant before either discharging it back into the source at a higher temperature (once-though cooling), or storing and evaporating it in cooling towers. While the latter requires less water, it actually consumes water as opposed to just withdrawing and discharging back.

Water shortages cause water-cooled thermal plants to reduce output capacity or to shut down completely, actions that may last for weeks if not months. This risk is substantial especially in cases where freshwater flows are heavily dependent on seasonal rainfall. If a wet season is delayed and a dry season is prolonged by a severe drought, thermal power plants will have difficulties in maintaining their generation level. The application of potential new technologies, such as carbon capture, use and storage, may also be constrained due to the additional water intensity they add to plants.

Changes in precipitation can also affect the demand for electricity to supply water to residential users and agriculture. The use of water pumps and desalination plants can increase during droughts to ensure the continuity of water supply to these users. This can structurally increase electricity demand. Some effects to load can also result from an increase in humidity during summer, with growth in electricity demand for air conditioning.

Box 2 Case study: Climate impacts on African hydropower

Hydropower currently accounts for 17% of electricity generation in Africa on average. In some countries, such as the Democratic Republic of the Congo, Ethiopia, Malawi, Mozambique, Uganda and Zambia, the share of hydropower in electricity generation exceeds 80%. The African average may increase to more than 23% by 2040 as part of the ongoing effort for a clean energy transition and universal energy access across the continent.

Changing precipitation patterns may have significant impacts on hydropower generation in Africa and, therefore, on electricity security. Southern Africa, where hydropower accounts for over 20% of the electricity in the regional power pool, is projected to experience electricity shortages due to the persistent occurrence of droughts in the coming decades. Indeed, last year some southern African countries received lower than normal amounts of precipitation. In East Africa, by contrast, a wetter climate with more frequent heavy precipitation is projected to pose a challenge to the management of hydropower systems, as it is likely to result in increasing inter-annual variability and uncertainty in generation. These regional variations in precipitation patterns would exacerbate the existing gap in water availability among African countries. Each country will require tailored measures to cope with these potential changes.

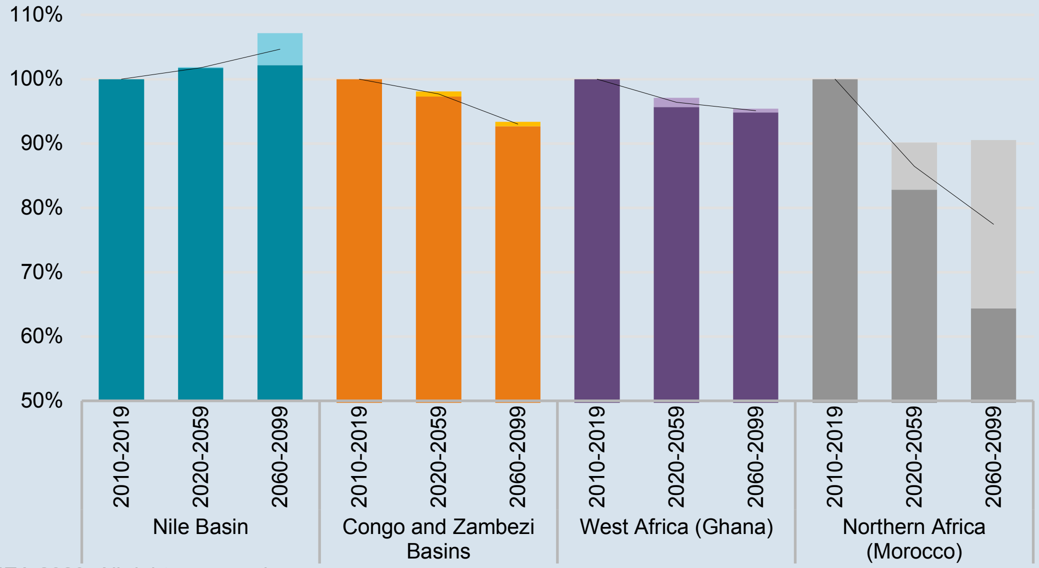
In a recent analysis, the IEA assesses climate impacts on African hydropower generation by comparing two different GHG concentration pathways (RCP2.6 and RCP6.0, which are associated with levels of global warming below 2°C and around 3°C by 2100, respectively).

The assessment covers 80% of the installed hydropower capacity in 13 African countries between 2020 and 2099, comparing projected results with values from the baseline period of 2010 to 2019.

The assessment shows climate change having significant impacts on most African countries, although the patterns of change may vary from one country to another. For example, the hydropower capacity factors of Morocco, Zambia, Zimbabwe, the Democratic Republic of the Congo and Mozambique are projected to decline considerably, while the decrease would be offset by an increase in the hydropower capacity of the Nile basin countries, notably Egypt, Sudan and Kenya.

This spatial variation in climate impacts on hydropower generation is likely to be starker with a higher GHG concentration. Under RCP2.6, countries in the Congo and Zambezi basins are likely to see a decrease of over 6.5%, while the Nile basin countries experience an increase of over 2% during 2060-99. In RCP6.0, the Congo and Zambezi basin countries may see a greater drop in hydropower capacity – over 7% on average. In contrast, the Nile basin countries are likely to see an increase of more than 7%.

Figure 4 Hydropower capacity factors in Africa, 2010-2099



Notes: 100% represents the baseline in 2010-19. Areas that are lightly coloured indicate the gap betaween the projections for RCP2 and RCP6.0.

Sources: IEA (2020c).

Box 3 Case study: Increasing water scarcity affects thermal power plants in water-stressed areas

Thermal plants continue to make up the bulk of installed capacity around the world, accounting for approximately 75% of generating capacity globally in 2018. While its share continues to decline with the steady rise of variable renewables and to some extent that of hydropower, thermal capacity remains a core component of many future electricity systems. IEA projections for 2040 show that thermal generation could still account for 56% of electricity generation in the STEPS, while this declines to 33% in the SDS.

Thermal power plants include a variety of fuel and technology types, such as nuclear, fossil fuels (coal, gas or oil), biofuels and geothermal. These plants require some form of cooling in order to operate, as follows:

Once-through (or open-loop) cooling: water is withdrawn from surface sources and returned to the source at a higher temperature, after it has passed through the condenser. Once-through systems typically withdraw up to 60 times more water than wet-tower systems, but the level of water consumption is much lower.[3]

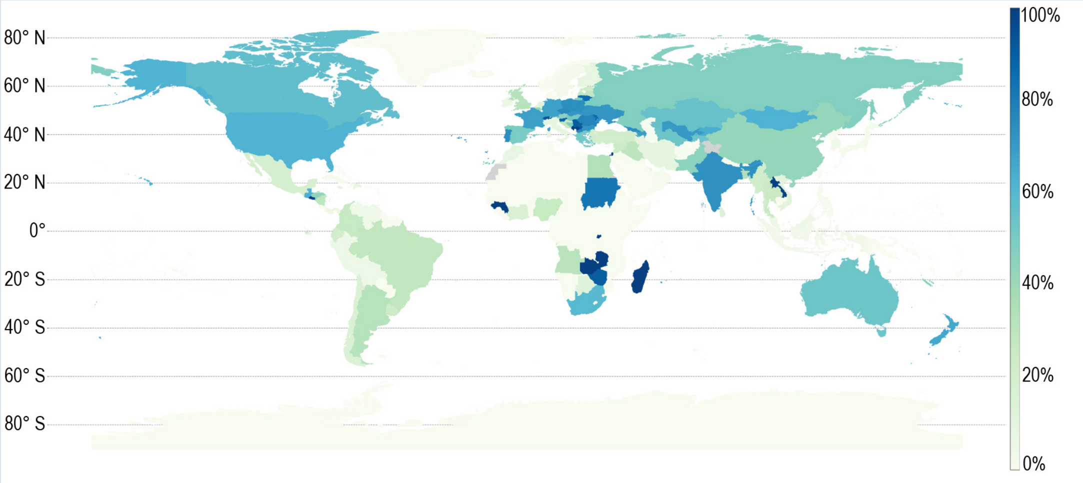
Wet-tower (or closed-loop) cooling: withdrawn water is managed in an internal reuse cycle, with water passing through the condenser being pumped to the top of a cooling tower and then collected at the bottom of the tower. While water withdrawals are lower than once-through cooling systems, the level of consumption is higher as some water is lost through evaporation. The capital cost is typically higher than once-through systems, while efficiency is lower.

Dry cooling: large volumes of air are passed over a heat exchanger and limited amounts of water are withdrawn and consumed. Dry-cooling systems use substantial amounts of electricity, effectively lowering the power output of the plant and its efficiency relative to once-through cooling systems. Dry-cooling systems usually require higher capital investment than other cooling systems.

Of the existing global thermal capacity, ~42% plants use freshwater cooling, with a further 22% using non-freshwater cooling and only ~7% using dry cooling. Of those plants using freshwater cooling, approximately 20% use once-through cooling while the remaining 80% use wet-tower or pond (closed-loop) cooling. Figure 5 shows the global share of thermal capacity using freshwater cooling. However the database is missing cooling information for certain plants. Figure 6 therefore presents the upper estimate of thermal plants with freshwater cooling, which also includes plants with an unknown cooling type.

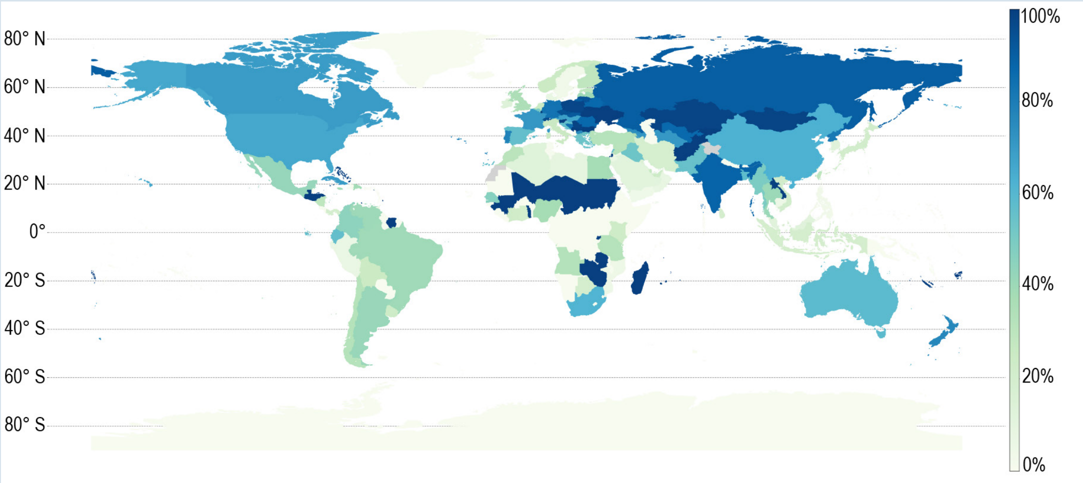
[3] Water withdrawals refers to the amount of fresh water that is withdrawn from local sources, such as lakes and rivers, and then returned to the local water basin. Water consumption refers to water that is withdrawn but not returned to the local water basin.

Figure 5 Share of existing thermal capacity using fresh water for cooling



Source: S&P Global Platts WEPP Database (2020).

Figure 6 Share of existing thermal capacity with freshwater cooling or an unknown cooling type



Source: S&P Global Platts WEPP Database (2020).

Climate change projections and hydrology models estimate that many regions around the world will undergo severe changes to their water tables towards the middle of the century. The World Resource Institute has developed a dataset with Utrecht University which looks at how changes in hydrology and potential water usage may increase water stress in certain regions. Water stress in the definition of the Aqueduct 3.0 dataset is the ratio of total water withdrawals over the total available surface and groundwater supplies.

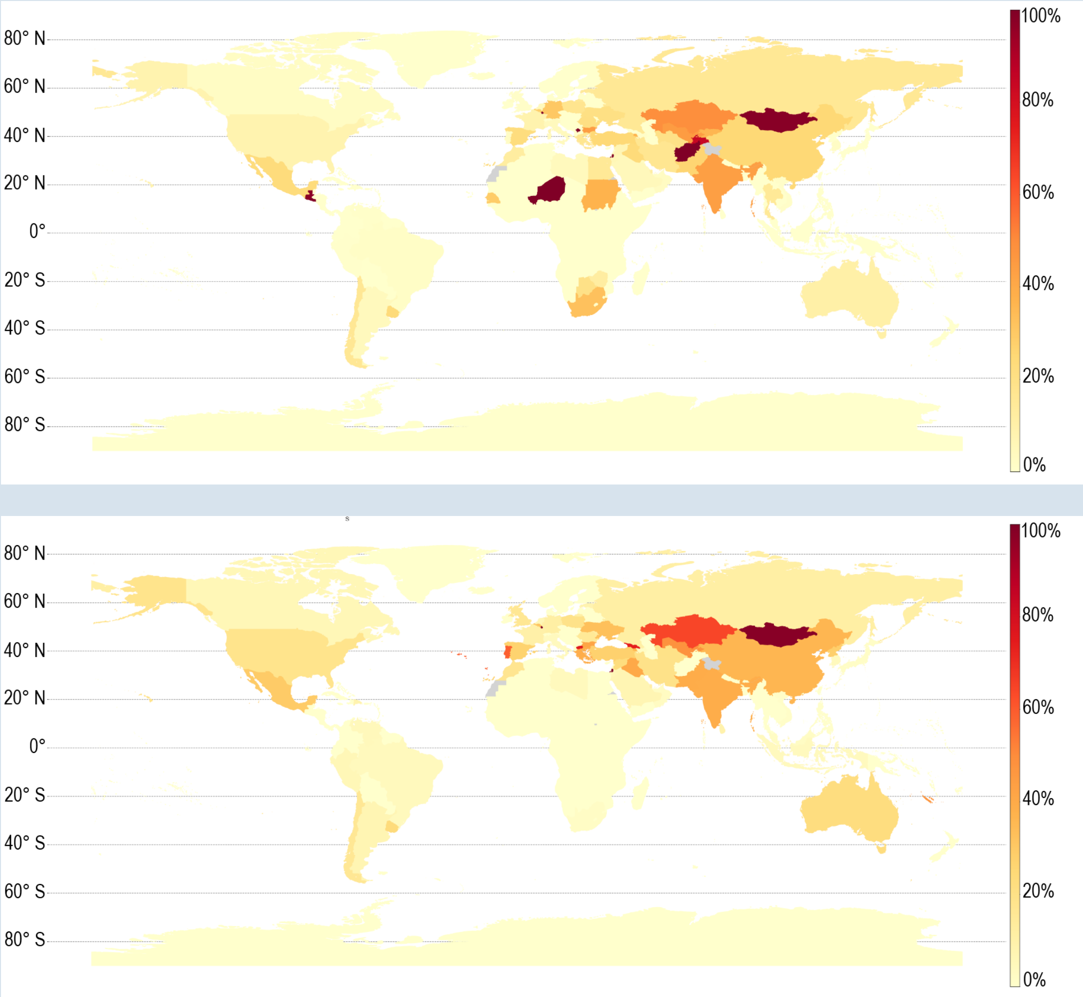
To assess how changing water stress may affect global thermal capacity, researchers analysed the existing thermal capacity according to the change in water stress using the

Aqueduct 3.0 dataset, taking into account a present day and future scenario (RCP4.5 climate change projection). They also took into account current and projected estimates of water withdrawals, including (inter alia) domestic, industrial, irrigation and agricultural uses. Water stress was then calculated as the ratio of water withdrawals to available renewable surface and groundwater supplies. In order to make the data more easily interpretable, several levels of water stress are designated: very low (< 20%), low (20% to 40%), high (40% to 80%) and very high (> 80%).

A geo-referenced global database of the global conventional generation fleet was used to analyse the change in water stress of the watershed at the site of each thermal plant which either uses freshwater cooling or has an unknown cooling type in the database. Figure 7 therefore shows the upper range of the share of global thermal capacity (on a national basis) that are freshwater-cooled and which, according to current and future (2040 under RCP4.5) projections, are or will be under high water stress (≥ 40%). While the water stress at existing thermal plant sites in some countries is projected to improve (e.g. South Africa, Botswana and Thailand), many more worsen. Figure 8 shows the sites that transition from a region of lower water stress (< 40%) to one that is considered high (≥ 40%) in 2040 under RCP4.5. Many countries across the world, including those in South America, Asia and Europe, appear to have a relatively high share of existing plants/sites that will operate in conditions of higher water stress in 2040 under RCP4.5 (Figure 8).

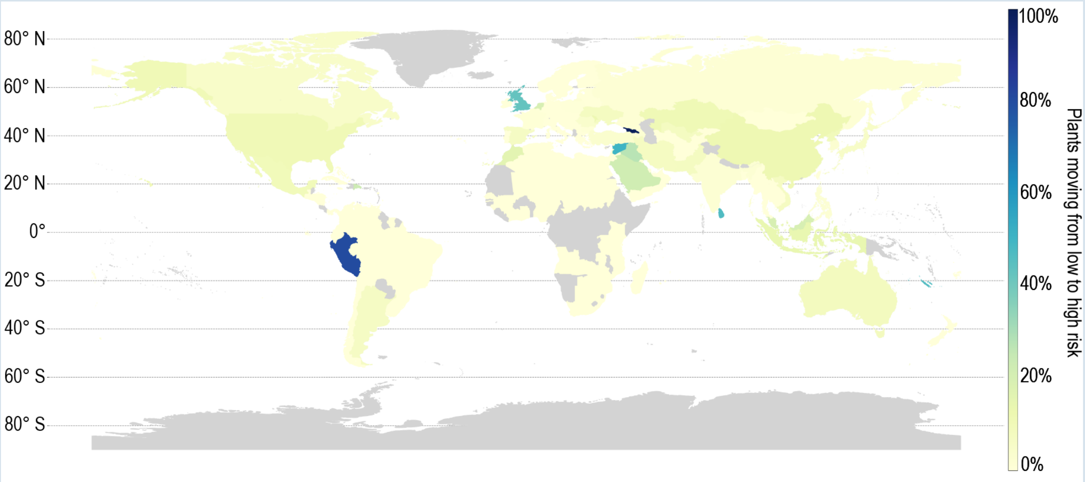
Many of these countries have generating capacity at sites that are currently under marginally good conditions (upper range of low stress classification), but which will transition to high water stress in 2040, as demonstrated in Figure 8. As a result, water availability will become increasingly important for maintaining electricity security in these regions. This highlights the importance of evaluating water availability (both current and future) when considering the development of new generation. This may be through the building of new plants with less water-intensive cooling systems (e.g. seawater/dry cooling), considering new sites for future plants or completely reconsidering whether the plant is part of an optimal generation mix. Additionally, this may also be relevant to existing plants, which may require adaptation through less water-intensive cooling systems.

Figure 7 Share of existing thermal capacity which are freshwater-cooled and in high water stress areas today and in 2040 following RCP4.



Sources: Hofste, R. et al. (2019); S&P Global Platts WEPP Database (2020).

Figure 8 Share of existing thermal capacity in countries that move from a low-risk to high-risk water region



Sources: Hofste, R. et al. (2019); S&P Global Platts WEPP Database (2020).

Coastal floods increasingly jeopardise coastal infrastructure

Global sea levels are rising at an accelerated pace – by at least 3 mm per year in recent decades, almost double the pace observed during the 20th century. Sea level rise can cause coastal floods and erosion. This affects generation assets, transmission and distribution lines and substations located near the coast. While the risk of permanent inundation is only relevant to very specific low-lying coastal jurisdictions, other coastal infrastructure may be at higher risk of flooding from tides and storm surges in the absence of additional protection measures. Natural barriers to waves and storm surges may be eroded away, leaving previously unexposed infrastructure vulnerable to the force of the ocean without appropriate adaptation measures. While coastal infrastructure, including generators and substations, will have protection measures such as levees, these would need to be designed for the appropriate new 1-in-100 year flood levels.

Box 4 Case study: Impact of sea-level rise on coastal flooding of generation assets

We quantified the impact of potential sea level rise on the existing global generation fleet by using a geo-referenced global database of conventional power plants (i.e. thermal and hydro). Of the ~5 840 GW of installed capacity, 25% is considered coastal, i.e. within 10 km of the coast, accounting for ~1 480 GW of capacity.

To assess what proportion of this capacity is at risk of coastal flooding, we used a global tide and surge reanalysis dataset, which identifies the current coastal flood risk to each plant. We then applied several sea level rise scenarios based on projected RCP snapshots at different points during the 21st century. Here, we employed a simplification whereby we added the potential sea level rise to the height of the storm surge or tide.

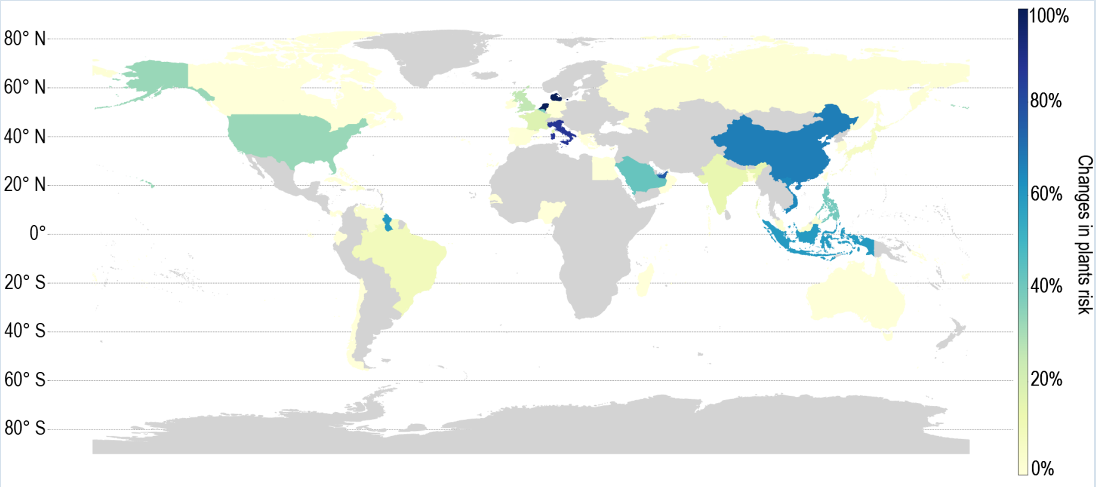
We identified the elevation of each plant using its co-ordinates and a digital elevation model. This in itself is also a simplification as plants can have fairly large footprints spread over a wide elevation profile.

From this analysis, we found 11% (or 163 GW) of existing coastal plants to be at risk of 1-in-100 year coastal floods, without any sea level rise relative to 2015 levels. These plants would, of course, be expected to have necessary protection considering the known potential for such floods.

Considering 0.59 m of sea level rise, at the upper end of the range for sea level rise expected at the end of the century under the RCP2.6 scenario, this increases to ~12.5% (or 174 GW). At the upper end of the range of sea level rise in 2100 under RCP4.5 (0.72 m), 189 GW (12.8%) are left exposed, and at 1.1 m of sea level rise, which is the upper end of sea level rise expected at the end of the century under RCP8.5, 205.1 GW (or 13.9% of coastal plants) are exposed.

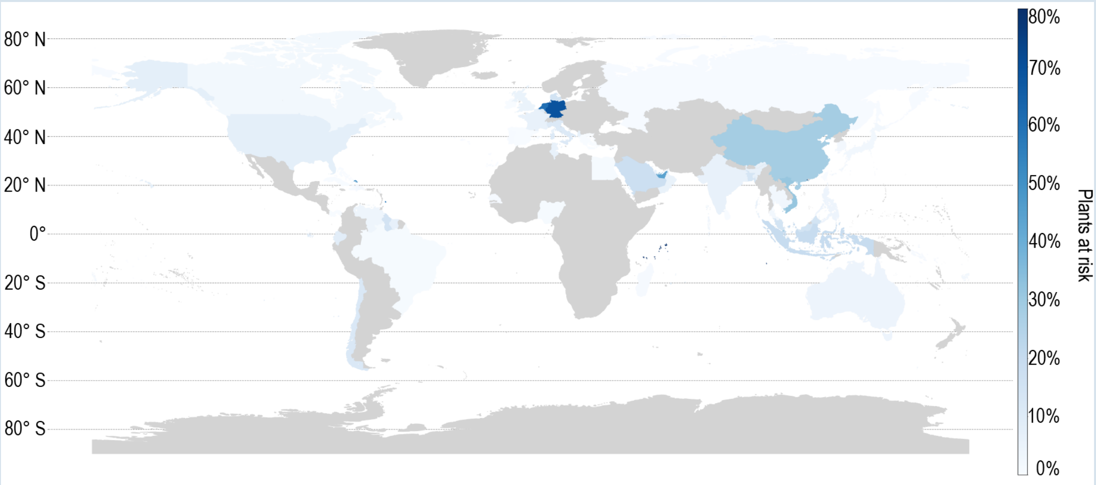
On the basis that existing plants should have appropriate resilience measures to protect against existing flood risk, regions with newly exposed plants are potentially at greatest risk. Figure 9 presents the share of coastal plants that are at risk of coastal flooding due to a sea level rise of 1.1 m, while Figure 10 shows the proportion of coastal plants at risk from 1.1 m sea level rise relative to a scenario with no sea level rise (i.e. same levels as 2015). It should be noted that this only considers existing sites, and so this analysis only highlights the risk to plants in regions in a "business-as-usual" scenario. It should also be noted that the dataset on power plants is not exhaustive and does not include renewable plants (i.e. wind, solar, bioenergy and geothermal). Additionally, it may be missing smaller plants such as diesel gensets and mini hydro plants which comprise a significant portion of generation capacity for many island nations, and which could also be at high risk.

Figure 9 Share of plants at country level at risk of 1-in-100 year floods due to sea level rise of 1.1 m (RCP8.5)



Sources: S&P Global Platts WEPP Database (2020); CGIAR – SRTM 90m DEM (2020); Muis, S. et al. (2016).

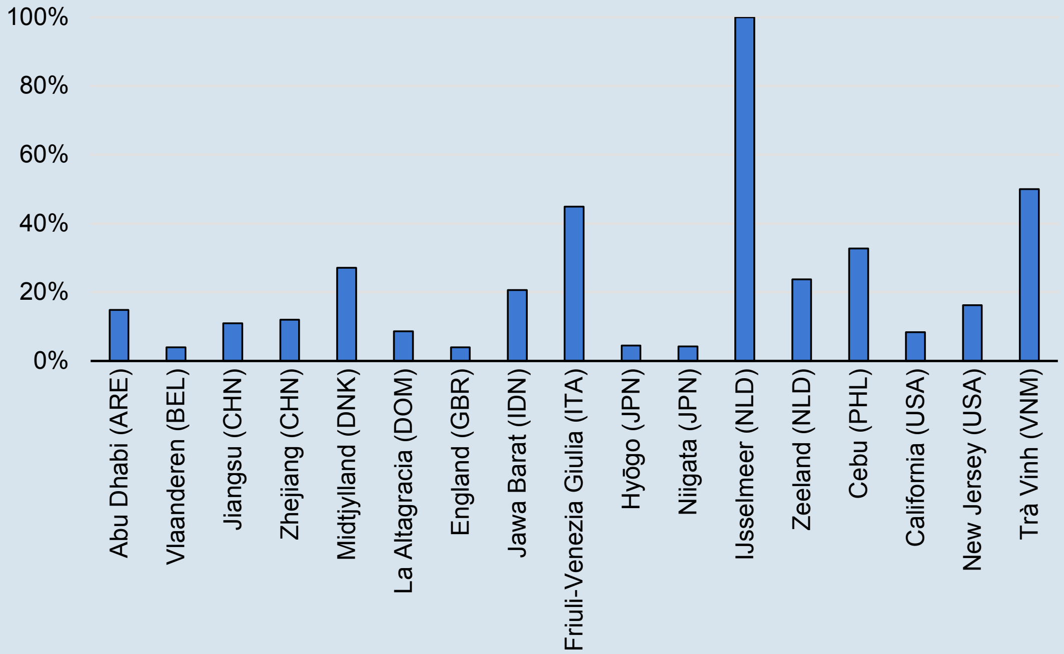
Figure 10 Change in share of plants at country level at risk of floods from 1.1 m sea level rise relative to 2015 levels



Sources: S&P Global Platts WEPP Database (2020); CGIAR – SRTM 90m DEM (2020); Muis, S. et al. (2016).

The risk of sea level rise is highly disparate, affecting only countries with particular geographies (coastal, low-lying). They are therefore relatively few in number. Additionally, sea level rise typically affects certain regions within a country more than others, as shown Figure 11. In some cases, the electricity systems in these regions may only be very loosely interconnected with other parts of the country's network, therefore making the impact of flooding on generation capacity and consequently the electricity system much more severe. Figure 11 presents those regions (provinces, states, regions, constituent countries or islands) that see a change, relative to no sea level rise, of at least 3% in their coastal plant capacity becoming at risk of flooding due to 1.1 m sea level rise.

Figure 11 Subnational divisions in which at least 1% of additional generation capacity becomes at risk of 1-in-100 year floods with 1.1 m sea level rise



Sources: S&P Global Platts WEPP Database (2020); CGIAR – SRTM 90m DEM (2020); Muis, S. et al. (2016).

Impacts of extreme weather events

As opposed to the previously discussed systemic changes to the climate, which gradually change the operational context of electricity systems, extreme weather events provide immediate shocks to the system with multiple impacts. However, climate change is also altering the general climatic conditions that lead to these shocks, with long-term changes to the climate implying changes in the frequency, duration and/or magnitude of these extreme events.

Extreme temperature events can severely strain the electricity system over large areas

While increasing temperatures represent a systemic problem for electricity systems, both heatwaves and cold spells pose a highly intense problem over a relatively short period of time. Definitions of a heatwave differ across the world. It is generally characterised as unusually high temperatures in a certain location over consecutive days (usually at least two to three days). It can affect a large area and may last for up to a few weeks. Similarly, intense cold spells, such as those seen across the northern hemisphere in winter 2020/21, also pose a similar challenge of sustained and intense low temperatures across large regions.

Due to the prolonged nature of both heatwaves and cold spells, and the often large area affected, they can have significant, and often compounded, temperature-related impacts across the electricity value chain. While the discussion below focuses on the impacts due to heatwaves, a notable example of the impact of cold spells, and especially those propagated by climate change, occurred in February 2021 in Texas, where large parts of the state were left without power for a number of days.[4]

During heatwaves in warmer climates, peak demands are observed as air-conditioning units operate closer to their maximum capacity. As average temperatures increase and the uptake of air conditioning increases in cooler climates, the dynamic of seasonal peaks may also shift, making heatwaves a major contributor to system peak demand. Transmission and distribution networks, if dynamically rated, will also be derated. Simultaneously, heatwaves can also lead to a number of generators derating over a large area due to

[4] Details on the latest findings around the blackout events in Texas at the time of publication can be found in the following IEA commentary from 18 February 2021.

decreasing efficiency. Generators may be shut down due to constraints on the discharge temperature of cooling water.

As heatwaves typically affect large areas, the impacts can stretch into neighbouring systems, putting at risk the availability of imports. This occurred in California in August 2020, when a heatwave affected large parts of the western United States, including Nevada and Arizona, on which California would normally rely for up to 10 GW of imports. Simultaneously, spikes in consumer demand, lower wind output than the day-ahead forecast and the unexpected outage of a 475 MW gas-fired plant resulted in involuntary load shedding across CAISO, the Californian balancing region. Three weeks later a similar heatwave occurred, but involuntary load shedding was avoided thanks to consumers decreasing demand following a statewide call to action via social media.

The simultaneity of these different temperature-related factors, and the increasing likelihood of their occurrence due to climate change as mean temperatures increase globally, are an important consideration for the reliable planning of system operations, both today and in the future. In the last few years alone, there have been multiple high-profile power outages caused by heatwaves on both coasts of the United States, in Argentina and in Australia.

Wildfire poses a growing threat to multiple types of infrastructure

Wildfire, while not necessarily a weather event, is certainly an example of an extreme weather-related event. Wildfires have been in the spotlight in recent years due to their growing frequency and intensity in specific regions. Their risk of occurring is higher in particular regions, sometimes exposing unpreparedness and severe vulnerabilities in their electricity supply. Northern California has experienced several high-impact wildfires in recent years and is projected to have an even higher frequency of fires in its mountainous regions due to a changing climate. Population growth and expanding human development are also expected to further increase the risk to electricity security.

While wildfires can affect all electricity infrastructure, the large footprint of transmission and distribution grids leaves them particularly exposed. Wildfires can cause multiple faults on multiple parts of the grid simultaneously through fire and smoke. This results in the loss of the ability to import and export the generation that these lines connect, or demand users being cut off from supply. Indirect impacts include thermal derating of overhead lines due to the heat from fires burning directly underneath these corridors. Evidently it can also cause direct damage to components, which can include the line structures themselves or substation equipment. Wooden poles in distribution networks are particularly at risk.

The effects have been demonstrated by recent wildfires in New South Wales, Australia. Simultaneous faults on multiple lines and substations on both transmission and distribution networks led to the loss of imports from the neighbouring state of Victoria, the unavailability of more than 2 GW of generation and direct outages for customers supplied by the affected substations.

The impact of wildfires can be extensive as substations are taken completely out of service due to damage to transformers, switchgear, telecommunications and other auxiliary equipment. This is often ground-based and therefore highly exposed to the flames that infiltrate the substation. Bringing this equipment back online requires crews to be physically present for inspection and repairs as necessary. These repairs can be delayed due to inaccessibility as the fire progresses. The transmission assets can therefore remain out of service for several days.

The impact of fires on distribution grids, often in urban fringe areas in which both private property and other infrastructure are equally exposed, is exacerbated by a workforce that is stretched thin and whose focus is prioritised on the protection of private property and human lives. Hence, firefighting and the protection of electricity infrastructure in the event of these fires is only a priority for critical components of the system.

The impact on the transmission and distribution network is further complicated as it can both suffer from fires and initiate them, highlighting how policy makers need to address electricity security with other (stronger) security objectives in mind. In 2019 the California Public Utilities Commission found that investor-owned utility Pacific Gas & Electric was liable for the Camp Fire wildfire, one of the most deadly and costly fires in history and which led to the utility filing for bankruptcy. Since then, it has included a “public safety power shutoff program” as part of its wildfire mitigation plans, a measure in which the utility monitors conditions around its network and proactively de-energises parts of its network in periods of high fire risk.

While this is not a new measure – San Diego Gas & Electric first implemented it in 2008 – the extent of its impact on the PG&E grid during its rollout was massive. A decision taken in October 2019 to de-energise a large part of its network led to the disconnection of 700 000 customers, many of whom were without power for almost three days in the process.

Box 5 Case study: Impact of wildfires

The extent of the distribution network globally leaves it heavily exposed to high-impact, low-probability events such as wildfires. The risk of wildfires varies across the world both geographically and seasonally. While they are heavily influenced by the weather, both in how easily they ignite (moisture and temperature) and how they behave (wind speed and direction), they are also influenced by the type of vegetation in the region (fuel availability) and the topography. Therefore, it is essential to understand the effects of weather and terrain to understand the risk of wildfires to electricity networks.

We analysed the global fire risk to distribution networks by comparing an approximated geospatial database of global distribution networks against historical fire weather and vegetation. Historical fire weather is based on the fire weather index, a metric developed by the Canadian Forest Service that takes into account weather attributes that influence fire ignition and fire behaviour to assess the risk and severity of wildfires.

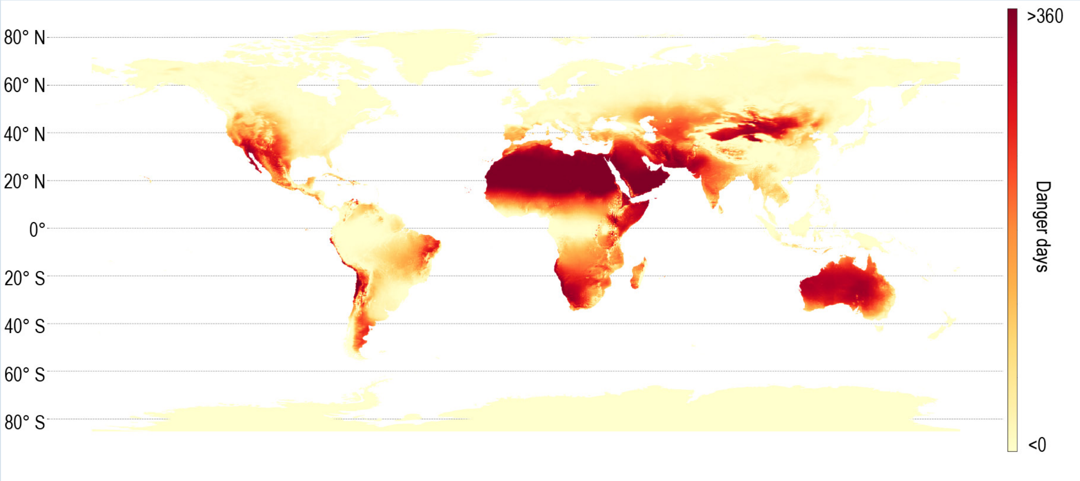
As the range of values of the fire weather index can vary greatly depending on climatic conditions, the European Forest Fire Information System adopted a danger index that ranks the risk of fire into classes, as shown in Table 6. Using these classes we derived a second metric, which indicates how many days per year a region experiences high danger of fire or worse – termed “danger days”. The global 20-year average (1999-2019) of fire danger days is shown in Figure 12. Well-publicised fire hotspots such as Australia and the west coast of the United States are evident, but other, much longer and more frequent fire seasons can be seen across Africa, the Middle East and Central Asia, as well as in parts of South America. However, without knowledge of fuel availability (i.e. vegetation), it tells an incomplete story.

Table 6 European Forest Fire Information System fire danger class levels

Fire danger class	Fire weather index value
Very low	FWI < 5.2
Low	5.2 ≤ FWI < 11.2
Moderate	11.2 ≤ FWI < 21.3
High	21.3 ≤ FWI < 38.0
Very high	38 ≤ FWI < 50.0
Extreme	FWI ≥ 50.0

Source: Fire danger indices historical data, C3S (2019).

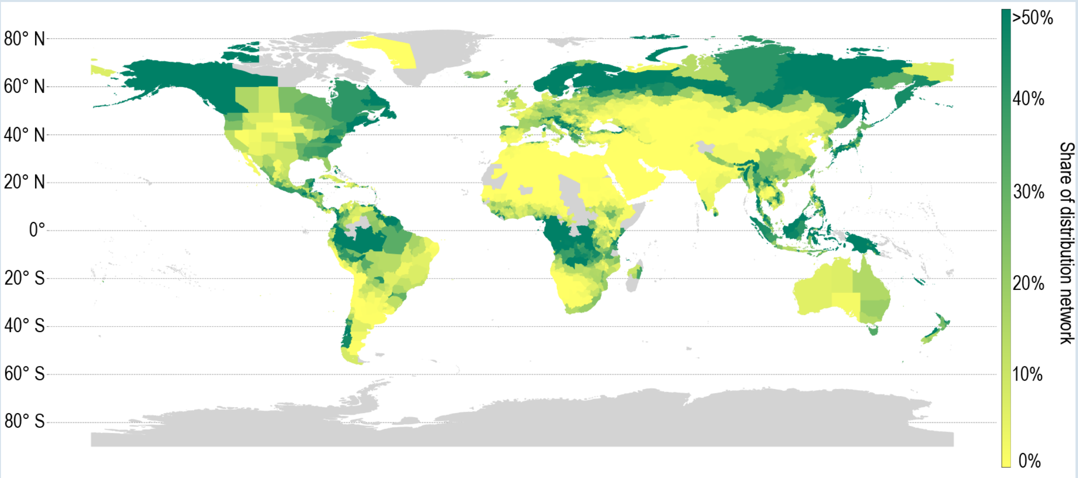
Figure 12 Global 20-year average (1999-2019) of fire danger days with fire weather index greater than 21.3



Sources: Fire danger indices historical data, C3S, 2019 (2019).

Wildfires can occur in different areas of vegetation, including grasslands, shrublands and forest, burning with different characteristics. While forested areas tend to have more intense fires due to a large amount of fuel, grassland fires can spread more quickly. Forested areas present a major challenge to utilities with networks in these areas due to the difficulty of overgrown vegetation coming close to large parts of the network. The failure to keep it clear can lead to ignition by lines, as demonstrated by recent legal outcomes against PG&E in California. We calculated the share of distribution networks that traverse forested regions using a dataset on global land cover. It is presented in Figure 13.

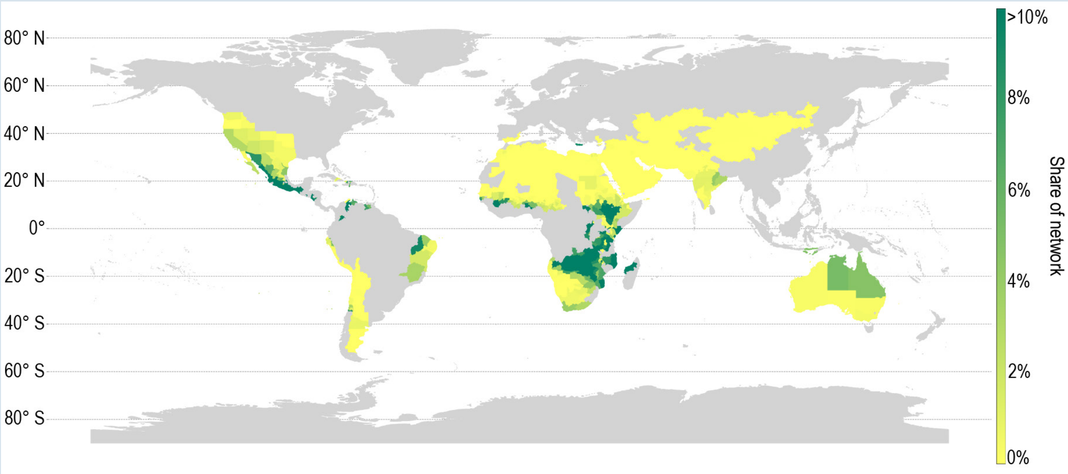
Figure 13 Share of distribution networks in forested areas by subnational division



Sources: Fire danger indices historical data, C3S (2019); Arderne et al. (2020); Land cover (GLCNMO), Geospatial Information Authority of Japan (2017).

Using the findings from both Figure 12 and Figure 13, we can look at the share of distribution networks that traverse through forested areas and specifically at regions that experience longer or more frequent windows of high fire danger risk – in this case those that experience an average of six months or more of danger days per year. Figure 14 indicates that certain regions, such as East Africa, California, Mexico, Brazil and Queensland, have a significant amount of their network at risk of forest fires due to both fire weather and fuel availability.

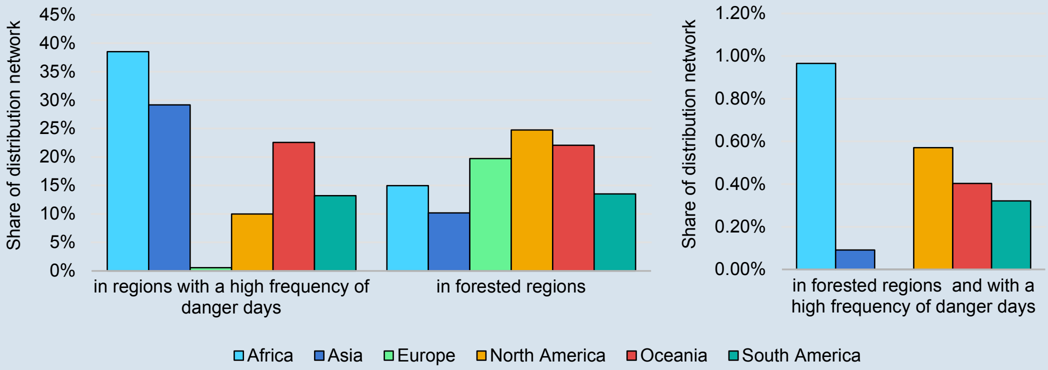
Figure 14 Share of distribution networks in forested areas by subnational division that experience an annual average of six months or more of fire danger days with fire weather index greater than 21.3



Sources: Fire danger indices historical data, C3S (2019); Arderne et al. (2020); Land cover (GLCNMO), Geospatial Information Authority of Japan (2017).

The regional share of networks that traverse forested regions, experience a high share of fire danger days (> 6 months) or the combination of both is presented in Figure 15 by continent. This highlights the significant regional disparity.

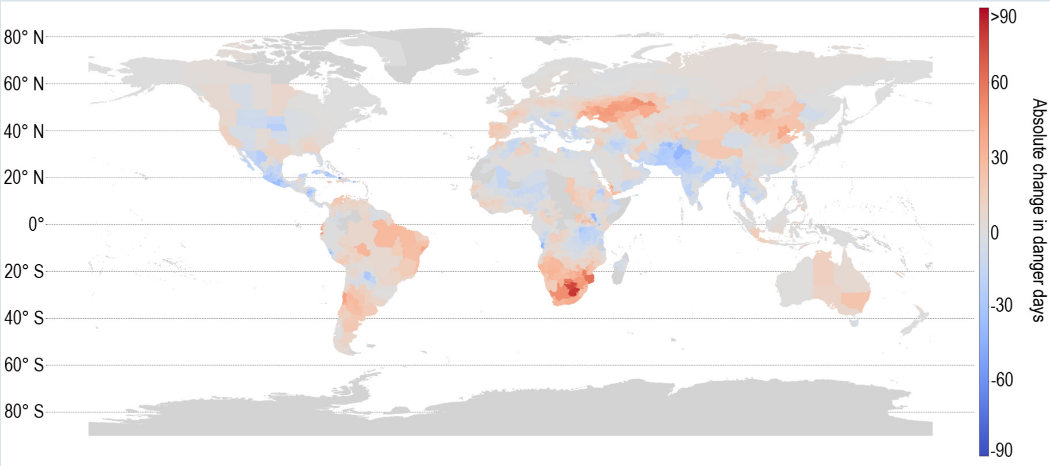
Figure 15 Regional share of distribution networks at fire risk due to both weather and fuel availability



Sources: Fire danger indices historical data, C3S (2019); Arderne et al. (2020); Land cover (GLCNMO), Geospatial Information Authority of Japan (2017).

Finally, climate change has also had an influence on global fire conditions. To see how the conditions are changing specifically around distribution infrastructure, we calculated the distribution network-weighted average of fire danger days by region. Figure 16 shows how the average annual frequency of fire danger days has changed from the beginning of the 21st century (1999-2004) until the end of the past decade (2015-19). Here, we see that many of the regions around the world are experiencing more frequent periods of severe fire weather conditions around grid-connected infrastructure. This upward trend in the number of danger days for certain regions, indicative of the widening of fire seasons, will necessitate an increase in appropriate adaptation measures. These include adopting fire mitigation plans, burying lines, co-ordinating vegetation management and making comprehensive emergency response plans.

Figure 16 Absolute change in the distribution network-weighted average of fire danger days by subnational region from 1999-2004 to 2015-2019



Sources: Fire danger indices historical data, C3S (2019); Arderne et al. (2020).

Cyclones with high-speed winds, flying debris and storm surges can affect many parts of coastal electricity infrastructure simultaneously

Similar to wildfire, violent storms and cyclones can have a major impact on the electricity system, due to both the large area that they affect and the extent of the transmission and distribution system. Coastal floods due to storm surges can severely affect coastal infrastructure such as the generation fleet and substations, while maritime infrastructure, including offshore wind plants, are particularly exposed. While offshore wind farm installations are currently located in less turbulent regions away from tropical storms and violent oceans, IEA projections from 2019 estimate growth of over 500 GW under the SDS in 2040, with huge growth in Asia and the United States. As the offshore wind market moves to regions with increasingly hostile meteorological conditions, new design standards for turbines and associated infrastructure, improved operational practices and customised insurance policies will become increasingly important to cope with more violent storm surges and cyclone-force winds.

The impact of these storms depends on both their strength and the resilience of the grid that they hit. Overhead distribution lines, in particular, are at risk from heavy storms. The stronger the storm is, the greater the possible impact on large infrastructure such as transmission lines and substations. With very strong storms transmission towers can be blown over directly by winds, and knocked over or lines short-circuited by debris. Meanwhile, salt deposits on electrical equipment can lead to their failure and contribute to outages. Due to the wide area that is affected, multiple outages will often occur simultaneously. There is also the risk of storm surges and coastal flooding, which can inundate critical ground-based equipment, such as transformers, and leave them inoperable.

2019 alone saw 39 tropical cyclones affect countries across Africa, Asia, Oceania and the Americas. This is in addition to other storm classifications such as extra-tropical and convective storms. All these collectively caused more than USD 1 billion in damage. Within the space of one month both Japan (September and October) and Mozambique (March and April) were each affected by two cyclones.

In Japan, Typhoon No. 15 led to outages for 930 000 households in the Kanto region (including the Greater Tokyo Area), with power only being fully restored more than 12 days later. One month later Typhoon No. 19 affected 520 000 households, with power fully restored 4 days later thanks to improved preparedness after the previous cyclone.

Mozambique was devastated by cyclones Idai and Kenneth. These damaged significant parts of the transmission network, several small hydro generators and off-grid solar PV plants, and affected 300 000 customers in Mozambique itself. Damage included an interconnector to South Africa, leading to the loss of 1 200 MW of hydro exports to South Africa. It was only fully restored six weeks later and exacerbated already-present supply constraints.

The amount of damage a storm inflicts will also depend on the topology of the grid, including, inter alia, whether the network is meshed and the concentration of load or generation centres. When Hurricane Sandy hit the US eastern seaboard (an area with a highly meshed grid but concentrated load) in 2012, the severe storm with larger than expected storm surge affected a large and densely populated region resulting in the loss of power to 8.35 million customers. When Hurricane Maria hit Puerto Rico in 2017, the eye of the storm remained over the island for eight hours, while most of the ageing grid infrastructure was not built to withstand a storm of its strength. Added to the existing poor interconnection between generation centres in the south and load centres in the north, it led to the loss of power to nearly all customers on the island. More than 80% of the transmission poles and lines were knocked out, with power only restored to the last affected neighbourhood 328 days after the storm hit. Policy makers need to take these conditions into account when incentivising utility preparedness and overseeing recovery plans.

Box 6 Case study: Impact of cyclones

Many countries around the world are affected by cyclones and tropical storms on an annual basis. These storms may differ from year to year and by location, but they can have a profound impact on electricity systems worldwide.

Due to the great extent of the transmission and distribution network, it remains a vulnerable part of the system, both to storm surges and high wind speeds. In addition, the large area that cyclones can affect in a short amount of time can lead to multiple simultaneous outages and extensively damaged equipment.

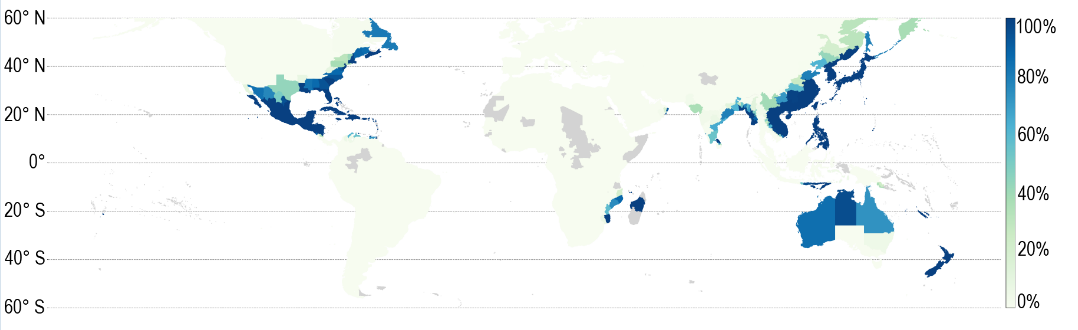
To analyse the global exposure of distribution networks to potential damage caused by high wind speeds from cyclones, we analysed an approximated geospatial database of global distribution networks against a database that assesses the global risk of high wind speeds and storm surges caused by tropical cyclones.

The database on high wind speed risk is based on a risk model that provides information on the expected peak wind speed (considering gusts that last for at least 3 seconds) over different return periods (50, 100, 250, 500 and 1 000 years). The database only includes tropical cyclones (within 60° latitude north and south) and therefore does not include extra-tropical storms such as those that occur in parts of Europe. According to the US National Oceanic and Atmospheric Administration, winds at or beyond 80 km/h start to become destructive to infrastructure. Hence, very high risk areas are those with winds exceeding 80 km/h with a return period of 50 years, with diminishing risk as the return period becomes larger.

Figure 17 shows the share of distribution networks by subnational division (province, state, etc.) that fall within regions at high risk (return period of 1-in-50 years) of winds capable of damaging infrastructure. Utilities in these regions should have appropriate adaptation measures in place to ensure that their supply of electricity is resilient to high-wind events.

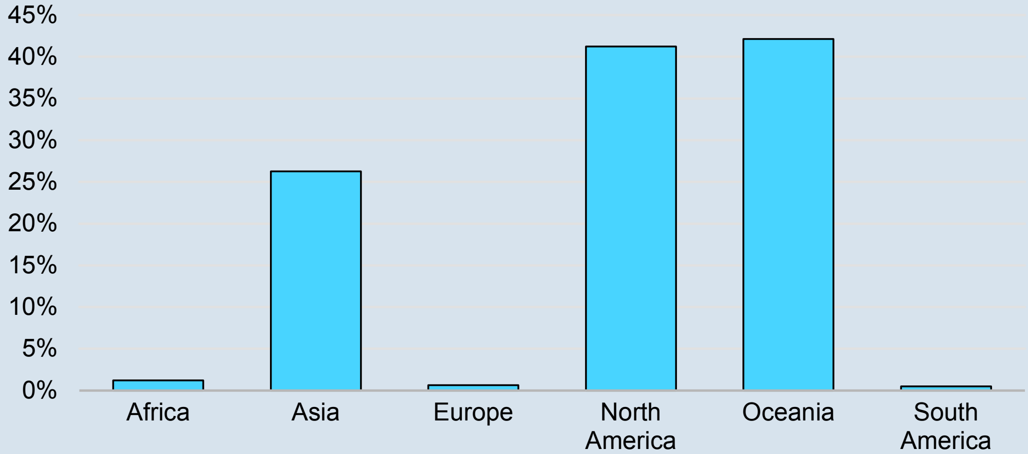
Cyclones are mostly limited to regions that are either coastal or close to the coast. Of all global distribution networks, 18% are estimated to be at very high risk of damaging winds (i.e. 1-in-50 year damaging winds), while the share at risk within OECD countries (26%) is almost double that of non-OECD countries (15%). Meanwhile, their distribution by continent is uneven, with notably increased risk in Asia, Oceania and North America (Figure 18).

Figure 17 Share of distribution networks at very high risk (1-in-50 years) of destructive cyclone winds



Sources: UNDRR (2015); Arderne et al. (2020).

Figure 18 Share of distribution networks at very high risk (1-in-50 years) of destructive cyclone winds by continent



Sources: UNDRR (2015); Arderne et al. (2020).

Floods put critical infrastructure at risk, with recurring patterns and consequences for erosion and landslides

Flood events can be categorised into three types: fluvial (river floods), pluvial (flash floods and surface water) and coastal (storm surges). The last of these is discussed in the previous subsection. They all have the potential to expose broad parts of the electricity system to damage, and are similar in that they can have a considerable impact on substations and thermal plants. Flash floods in Indonesia led to widespread outages in Jakarta on New Year's Day 2020, with over 5 000 substations affected and more than 2 500 shut down for more than 24 hours.

The impact of these floods can be amplified because they often cause soil erosion, rockfalls and landslides, which can physically damage infrastructure such as transmission towers. Changes to precipitation patterns and sea level rise will alter the intensity and location of these events. Hence, the current flood profiles of existing infrastructure may be inappropriate.

Fluvial floods can also have a large impact on hydropower plants, especially if their reservoirs are overtopped, which can damage not only the dams themselves, but also other downstream infrastructure and property. The spillways themselves can be damaged during these events, as occurred in Oroville, California, in 2017. This can have a compounding impact as the spillways then begin to carry debris, which can further damage downstream assets or the emergency spillways that are needed in such circumstances. Hydropower turbines can experience increased abrasion and loss of efficiency due to increased sediment in the water from flooding and landslides.

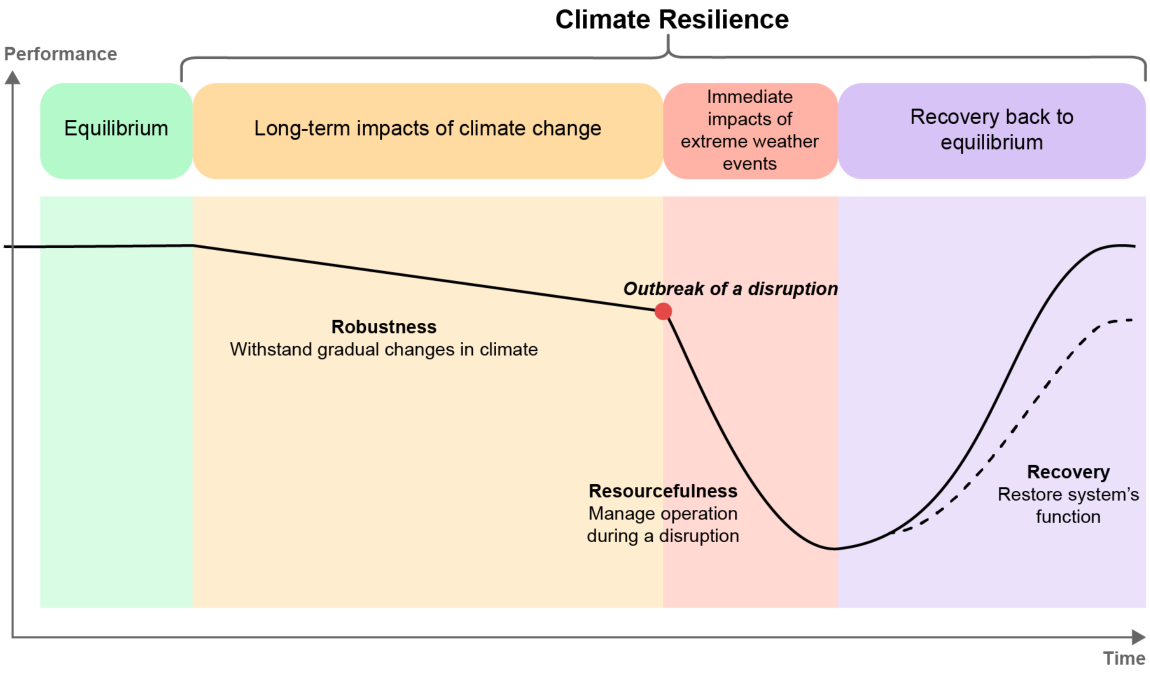
Benefits of building climate resilience

Increasing anomalies in climate patterns already pose a significant challenge to electricity systems and increase the likelihood of climate-driven disruption. Outages related to climate impacts, such as the 2019 wildfires in California, 2019 heatwaves in France and 2021 cold wave in Texas, demonstrate that electricity systems are already exposed to and largely affected by climate hazards. The increasingly adverse impacts of a changing climate on electricity systems highlight the urgent need for action by policy makers and other stakeholders to enhance their systems' resilience to climate change.

Climate resilience is the ability to anticipate, absorb, accommodate and recover from adverse climate impacts

Climate resilience in general is the ability to anticipate, absorb, accommodate and recover from the effects of a potentially hazardous event related to climate change. A conceptual framework for the climate resilience of the electricity system delineates the system's critical dimensions – robustness, resourcefulness and recovery.

Figure 18 Conceptual framework for climate resilience of the electricity system



Source: Argonne National Laboratory (2012), Resilience: Theory and Applications (ANL/DIS-12-1), as modified by International Energy Agency.

Robustness is the ability of an energy system to withstand the gradual, long-term changes in climate patterns and continue operation. For example, thermal power plants that use water from recirculation for cooling could be more resilient to increasing heat than those that use external sources such as rivers or lakes.

Resourcefulness is the ability to continue operation during immediate shocks such as extreme weather events. For example, a hydropower plant with a flood control reservoir is more resilient to potential floods than others.

Recovery is the ability to restore the system's function after an interruption resulting from climate hazards. For example, a more resilient electricity system with a well-coordinated contingency plan for communications, temporary assets and the workforce will recover faster from the interruptions caused by climate impacts.

Climate resilience is a cost-effective solution

Recent studies suggest that the benefits of resilient systems are much larger than the costs in most of the considered scenarios given the increasing impacts of climate change. It is estimated that for every dollar invested in climate-resilient infrastructure, six dollars are saved. According to the World Bank, if actions to build resilience are delayed by 10 years, the cost will almost double. In Bangladesh, for instance, a country highly prone to floods, USD 560 million for additional flood protection could save up to USD 1.6 billion. In California, where wildfires are a major threat, good forest maintenance can minimise the costs of wildfire on transmission and distribution lines.

Adopting climate resilience measures contributes to achieving universal electricity access

The projected increase in climate hazards poses a major threat to meeting universal electricity access, which is one of the objectives of Sustainable Development Goal (SDG) 7. According to the IEA World Energy Outlook 2020, about 770 million people around the world are still deprived of electricity access. Future changes in climate may significantly limit progress towards universal electricity access by restricting resource availability, reducing generation and transmission efficiency, and increasing the likelihood of outages.

Zambia's electricity system, for instance, where only 30-40% of the population has access to electricity, is already adversely affected by climate change. A shorter rainy season and more frequent droughts are posing a challenge for hydropower generation, which currently produces more than 80% of Zambia's electricity . In February 2016 the water levels of the Kariba Dam, the biggest electricity source in Zambia, dropped by 88%, prompting blackouts, power rationing and a slowdown in economic development. The disruption occurred again in August 2019, when the Kariba station needed to reduce output and impose daily blackouts. Adopting climate resilience measures – such as an improved system for monitoring climate hazards and a strategy for diversifying the electricity mix – would help Zambia ensure reliable access to electricity.

Climate-resilient electricity systems support the clean energy transition

Electricity plays a central role in the transition to a low-carbon energy system. But a lack of resilience in electricity systems can obstruct this transition, especially in regions whose electricity infrastructure is vulnerable to long-term changes in climate and more frequent extreme weather events.

The increasing electrification of heating, transport and other sectors means that a failure to manage climate impacts in the electricity sector could have widespread destructive consequences. For instance, the use of electric vehicles was greatly challenged when PG&E in California decided to cut the electricity supply to wide areas to prevent wildfires in October 2019. The incident drew much attention because California has the largest number of electric cars in the United States, and at the same time faced electricity reliability issues due to climate impacts. This case underscores the importance of ensuring climate resilience in the electricity sector to support further electrification and clean energy transitions in other sectors.

Measures for climate resilience

Effective policy measures and co-ordinated action among key actors prevent potential market failure in building up climate resilience

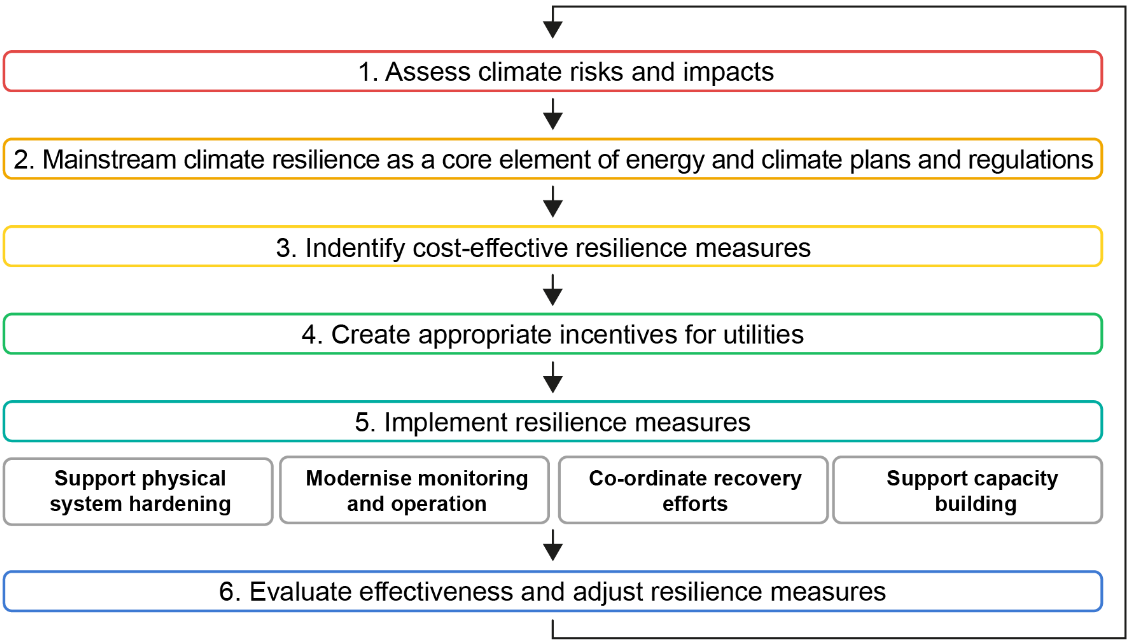
The benefits of climate resilience and the costs of climate impacts tend to be distributed unevenly across the electricity value chain. It inevitably raises the question of who should be responsible for delivering resilience measures and pay for them.

In principle, electricity sector businesses have responsibility for and direct interest in protecting their own assets and providing reliable services to their customers. While some utilities have taken measures to align their business interest with climate adaptation needs, several factors may be deterring others from adopting resilience measures in practice.

First, the benefits of investing in greater climate resilience are likely to become tangible only after a few years or even decades, while the capital cost of implementation is incurred immediately. Second, when climate impacts interrupt electricity supply and lead to large costs to society, generators and operators are expected to bear only a fraction of the entire social cost. Third, monopolistic market conditions and a lack of competition in some countries discourage service providers from investing in climate resilience measures to enhance the quality of electricity services.

Therefore, policy makers have a critical role to play in building resilient electricity systems by collaborating with business and adopting effective policy measures that can prevent potential market failure. Although there is no one-size-fits-all solution, policy makers and key actors in the electricity sector can enhance the climate resilience of electricity systems by assessing climate risks and impacts, making climate resilience central to energy and climate plans, identifying cost-effective measures, creating appropriate incentives for utilities, implementing resilience measures efficiently, and evaluating them for effectiveness. Step-by-step guidance for policy makers and other key actors can help to enhance climate resilience.

Figure 19 Sequential application of measures for climate resilience



1. Assess climate change risks and impacts

The first step in enhancing the climate resilience of any electricity system is to perform a comprehensive and systematic assessment of risks and impacts based on scientific evidence and geographical considerations. Climate risk refers to the factors that are associated with the potential consequences of climate change. It results from the interaction of hazard, exposure and vulnerability. Climate risk largely determines the actual consequences of climate change, which are referred to as climate impacts.

Various countries have already introduced guidelines and frameworks for climate risk and impact assessments. For instance, the US government has developed a guide for climate change vulnerability assessments as the initial step for climate resilience planning in the electricity sector. The United States also provides diverse tools for exploring climate hazards and assessing vulnerability and risks in the US Climate Resilience Toolkit. Similarly, the Canadian Electric Association has introduced a risk-based framework as part of its planning guide on managing climate risks. These assessments can help with the further development of strategies and plans for climate resilience, and allow countries to identify effective measures based on a strong scientific foundation.

In the European Union baseline requirements for climate adaptation assessments are set for EU member states. However, the depth and coverage of assessments varies significantly between countries. Countries including Estonia, Finland, France, Germany, Italy, Portugal, Sweden and the Netherlands have performed a climate change impact, vulnerability and risk assessment of their energy systems, while others such as Slovenia, Malta and Bulgaria have not fully conducted these yet. Although this method of energy system assessment tends to cover electricity as a key part, the areas of focus differ considerably, ranging from resource availability for electricity generation to electricity demand.

It is essential that all countries assess climate risks and impacts on their electricity sector. Individual countries can benefit from collaboration with other countries, utilities or international organisations. For instance, the Lao People's Democratic Republic has conducted a comprehensive vulnerability assessment of its electricity sector in partnership with the US Agency for International Development. The IEA has also released a series of qualitative and quantitative analyses of climate risks and impacts for hydropower plants in Africa and Latin America in collaboration with regional and national stakeholders.

Box 7 Electricity sector vulnerability assessment of the Lao People's Democratic Republic

The US Agency for International Development supported a resilience planning process for the Lao People's Democratic Republic. This included a comprehensive vulnerability assessment based on an eight-step process:

1. Create an impacts framework using inputs from key stakeholders.
2. Select a vulnerability assessment methodology.
3. Identify climate hazards and their impacts.
4. Identify potential vulnerabilities.
5. Associate hazards with potential vulnerabilities.
6. Score likelihood of hazards.
7. Score consequences of vulnerabilities.
8. Score risk and create a final risk matrix.

The vulnerability assessment supports prioritising actions to increase the resilience of the electricity system. These include developing climate projections and geospatial data, and establishing standards and enforcement mechanisms to cope with expected climate hazards.

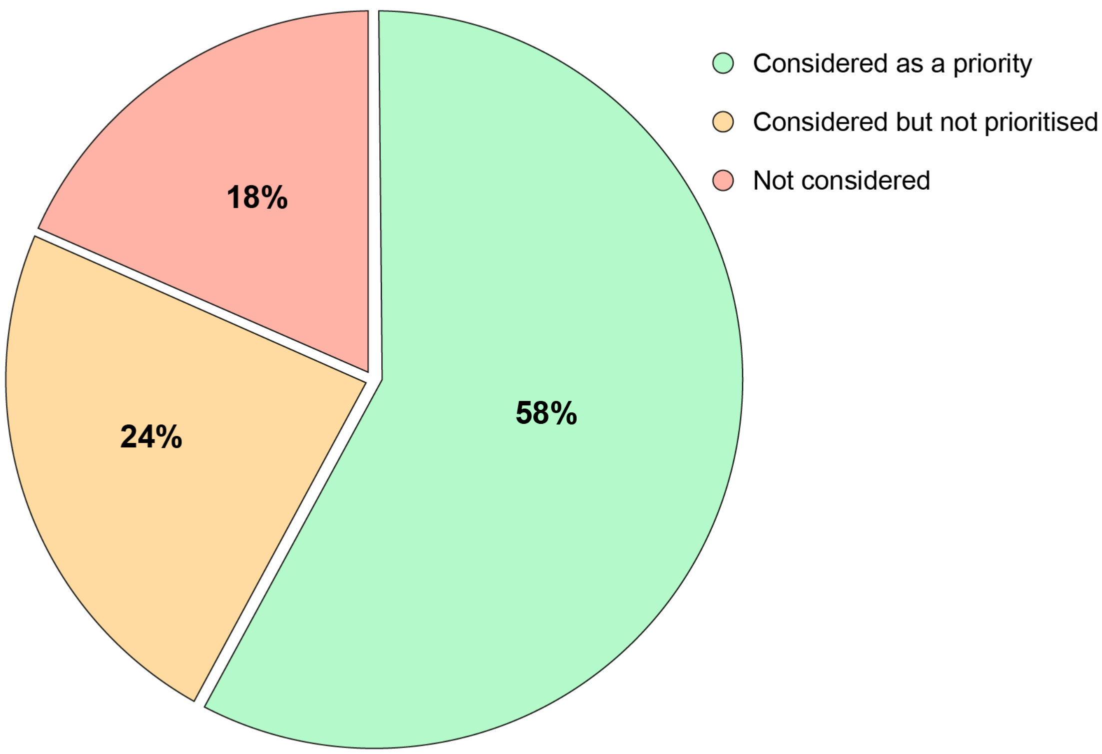
Source: NREL (2020).

2. Mainstream climate resilience as a core element of energy and climate plans and regulations

National plans and strategies that consider immediate and long-term impacts of climate change – and explicitly include climate resilience as a core element – send a strong signal to utilities and investors to strengthen the resilience of electricity systems in the design, operation and maintenance phases. Moves to integrate climate resilience into national energy and climate plans can be found worldwide in various forms. For instance, the European Union underlined climate resilience in the EU Adaptation Strategy, encouraging actions at a national level.

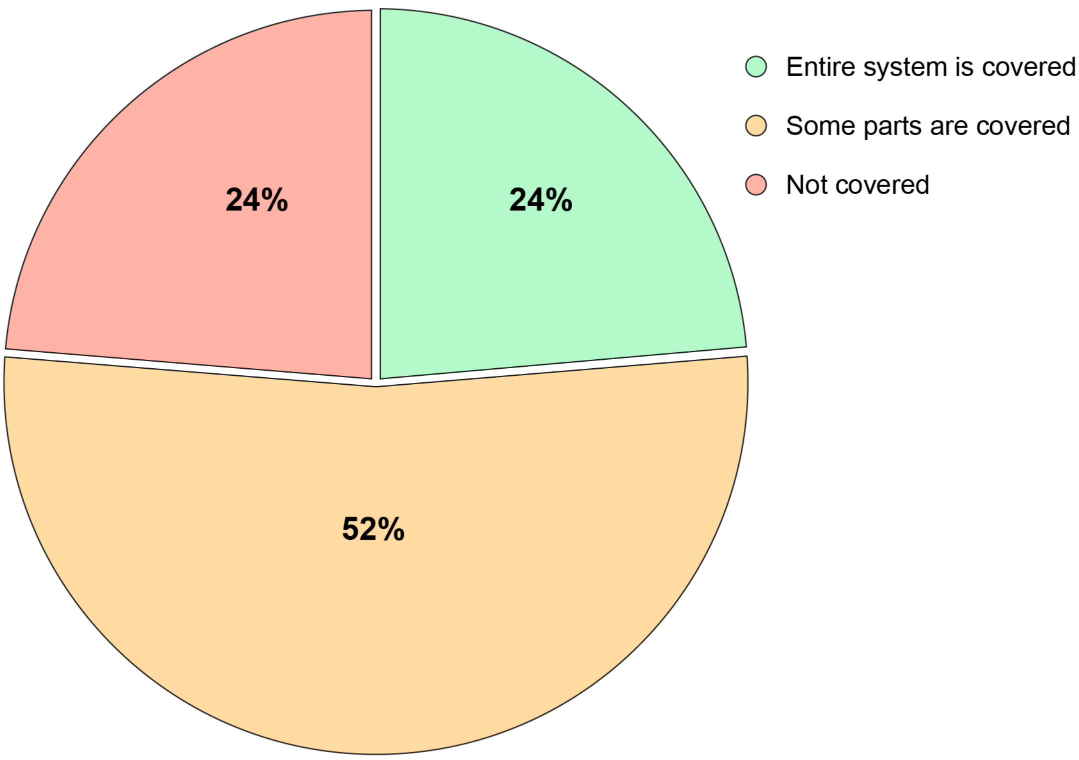
However, levels of commitment and progress vary considerably across the world. Although all IEA family countries have national strategies or plans for climate change adaptation, only 22 out of 38 countries consider the energy sector as one of the priorities in their strategies or plans.

Figure 20 Consideration of the energy sector in national adaptation strategies and plans, IEA family countries



If the scope is narrowed down to the electricity sector, the variation among countries becomes more marked. Actions and plans to adapt to climate change in the electricity sector have been overlooked in many countries. Although over three-fourths of IEA family countries consider the climate impacts and resilience of electricity systems in their national adaptation strategies and plans, the actions for some domains of the electricity system are still missing. Only nine countries include concrete actions for every segment of electricity systems, covering generation, transmission and distribution, and demand. For instance, the Czech Republic's National Adaptation Action Plan on Climate Change, announced in 2017, includes "industry and energy" as one of its priority sectors, elaborating measures, tasks, responsibilities, timelines and sources of financing. Italy also has a specific section on energy in its National Adaptation Strategy, and plans to develop it further in its National Adaptation Plan, which is under development with a priority ranking of measures for electricity generation, transmission and distribution, and demand.

Figure 21 Coverage of climate resilience of electricity systems in national adaptation strategies and plans, IEA family countries



IEA. All rights reserved.

Countries yet to address climate resilience as a core element of their national climate adaptation strategies and plans need to act immediately. Policy makers can also encourage utilities to consider the climate resilience of energy systems by introducing relevant regulations and processes. For instance, policy makers and regulators can integrate resilience standards into construction codes and add regular assessment of climate risks to operation and maintenance rules.

3. Identify cost-effective resilience measures

It is often difficult to identify the most cost-effective measures at the initial stage because resilience measures may have synergies with other business objectives or show trade-offs. For example, deployment of smart meter technologies not only enables faster awareness of and response to extreme weather events, but also brings additional benefits such as reduced labour costs for meter reading, easier fraud detection and greater efficiency.

Recognising the importance of climate resilience in the planning, operation and maintenance of electricity systems leads utilities to consider all available resilience measures over the life cycle of an asset. Policy guidance, incentives and requirements can also support the timely identification and implementation of cost-effective resilience measures.

For instance, operational measures adopted as early actions can cost less than physical hardening at a later stage. According to a US government study, regular vegetation management from an early stage tends to be less expensive than undergrounding a transmission line. Although an objective comparison of such options over the life cycle of the asset may not always be possible, this example urges planners to consider the potential benefits of various resilience options over the entire life cycle.

4. Create appropriate incentives for utilities

Although utilities have a direct interest in protecting their assets, they may be reluctant to invest in climate resilience measures since the benefits of the investment may be difficult to measure, occur at uncertain future point and be allocated to other parties. Policy makers need to introduce an incentivisation mechanism to encourage timely investment in resilient electricity systems.

Performance-based ratemaking is a straightforward financial incentive to improve the resilience of the electricity system. Under this approach, regulators set metrics or targets related to desirable utility outcomes and link rate recovery to performance against these targets. Regulators already apply it widely to achieve various objectives. Using performance-based rates alters the risk model to one in which risk is shared between the ratepayers and utilities. In exchange for internalising greater risk, shareholders can enhance their returns by meeting the performance criteria.

Performance-based ratemaking has been introduced in a number of jurisdictions, with an emphasis on a variety of performance metrics. Examples include the United Kingdom (customer satisfaction), New York (distributed resources), Denmark (distribution system reliability), Mexico (reducing system losses) and South Africa (controlling coal costs).

Although performance-based rates have to date rarely been applied to climate resilience, policy makers and regulators could extend the concept to focus on addressing climate impacts. In this case, regulators need to choose the appropriate resilience standard that is acceptable to all sides, and then measure performance under the standard. Conventional indicators such as the system average interruption duration index (SAIDI), the system average interruption frequency index (SAIFI), or the time to restore after an outage can be used as standards. In many jurisdictions this is already monitored and incentivised, taking into account normal operating parameters. The regulator could use the climate risk and impact assessment, possibly complemented with past performance or peer comparisons, to set a fair benchmark for performance upon which to base the incentive.

5. Implement resilience measures

Support physical system hardening

Physical system hardening covers technical and structural improvements to power plants or transmission and distribution networks. It can significantly reduce the probability of damage from cyclones and floods at relatively low cost. For instance, physical system hardening of hydropower plants which may increase the cost by 3% could reduce the probability of damage from floods by 50%. Similarly, strengthening of wind farms with a 5% increase in the cost would halve the probability of damage from cyclones.

Physical hardening of generation assets can help them to withstand climate impacts and avoid critical damage on the supply side. For instance, relocation of generation assets from flood-prone areas to higher ground can reduce damage from flooding. Construction of dry-cooling systems for thermal power plants may increase resilience against droughts and water scarcity. If a hydropower plant is projected to experience increasingly volatile hydrological patterns, increased reservoir capacity can make it more resilient.

A transmission and distribution network with underground lines and upgraded towers will also be more resilient to strong winds and high storm surges than others. Strongly meshed networks also show lower probability of loss of load and enhanced resilience to extreme weather events thanks to redundancy in the network that helps to quickly switch loads and bypass the possible faults.

Although physical hardening is generally led by business, government can also support it by providing technical assistance in the development of concrete actions. For instance, Puerto Rico organised a working group on energy resilience with public authorities, utilities and research institutes to identify actions to withstand future storms, after Hurricane Irma struck its northern coastline in 2017. The working group's recommendations offer guidance to utilities, proposing specific actions for each part of the electricity system.

Box 8 Puerto Rico case study: System hardening measures

The report "Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico", developed by the Puerto Rico Energy Resiliency Working Group, proposes physical hardening to cope with future extreme weather events. It considers hardening measures over the entire electricity value chain, including generation, transmission, distribution and substations. Several types of measures are covered.

Generation: Relocate smaller coastal or river-located facilities

The majority of Puerto Rico's generating facilities are situated on the coastal lines of the island, making critical generation components and substations vulnerable to floods, coastal storm surges and runoff of rainwater. Relocation of these facilities further inland can help to avoid critical damage from flooding and storm surges.

Substations: Introduce a three-level approach for flood protection

A three-level approach to flood protection can help enhance the resilience of substations. This approach includes: 1) building a perimeter flood barrier; 2) installing high-capacity pumps and backup generators; and 3) improving the roof and walls to withstand the anticipated high winds.

Transmission: Build transmission lines with monopole steel poles, high-strength insulators and vertical construction

Transmission lines should be designed or upgraded with high-strength insulators, monopole steel poles and vertical construction designs to withstand stronger wind loading than the current design standard.

Distribution: Use galvanised steel poles or install underground lines

When Hurricane Maria hit, concrete and wooden poles experienced severe damage, while galvanised steel poles fared better during the storm. Increasing the use of the galvanised steel poles can reduce damage to distribution lines. In addition, in areas that are particularly susceptible to damage from high winds, the installation of underground lines is recommended.

Source: New York Power Authority et al. (2017).

Enhance visibility and controllability in system operation

The deployment of smart grid technologies provides system operators with increased visibility of real-time operation across a much larger part of the system, reaching to the grid edge. It can also enable increased remote and automated operation while reducing the risk of human loss, particularly in cases of extreme weather events.

Advanced metering infrastructure is one example of a smart grid concept becoming more commonly applied. It enables the capture and communication of energy usage and technical parameters across the distribution network close to real time. Distribution system operators benefit from extensive visibility into the condition of their system, allowing them to reduce the impact of outages on the distribution network through fast and cost-effective detection and restoration.

Accurate weather forecasting is a critical element of optimising system operations in the context of variable renewables and asset capacities. It is also a crucial tool for utilities and system operators to anticipate extreme weather events and take necessary pre-emptive measures. These measures include reducing the output of the power plants most likely to be affected, reconfiguring transmission and distribution topology, adaptive islanding, applying temporary stricter system operation protocols, and putting workforce and communication channels on high alert.

For example, the Australian Energy Market Operator applies a security-constrained dispatch approach across its system. This takes into account credible contingencies, which are likely events that, based on probabilistic analyses, could lead to certain system components experiencing faults or outages. Whether an event is considered credible is constantly re-evaluated using real-time inputs from weather forecasts. They are used to identify probable simultaneous faults in specific locations of the grid due to weather events such as lightning and bushfire. Pre-empting such credible events avoids the large impact that sudden disturbances could have on the system, such as the tripping of a power plant or interconnector line.

A complementary approach is applied in California where, in response to more frequent wildfires, private utilities have included operational protocols into their public safety power shutoff program. In this case certain lines are de-energised during periods of high fire risk (dry, hot and windy) in order to mitigate any risk of igniting fires by flashover of the lines.

In some regions the application of microgrids and adaptive islanding schemes enhances physical resilience of the electricity system, while in other places higher degrees of interconnectivity across larger areas improves system security. Adaptive islanding schemes are planned and managed for grid separation processes during significant and cascading outages. They entail identifying those portions of the grid that can be operated in a stable manner by matching local clusters of load and generation.

Microgrids are a related concept where the electrical grid island size is usually smaller and can detach itself from the main grid under normal operating conditions. They can be seen as an extension of critical facilities having back-up power generation on a larger scale and across multiple grid users. Under certain conditions, microgrids can reduce adverse climate impacts by isolating vulnerable parts of an electricity system in the event of outages and ensuring local reliability is met with local resources. Whether a microgrid is an advisable solution depends on the acceptable risk profile of local grid users, on the reliability of the transmission interconnection itself, and eventually on a complete cost–benefit appraisal of the available options.

Policy makers can support and incentivise operators in enhancing the visibility and controllability of the system by promoting supportive technologies and operating schemes.

Box 9 Microgrid designs to cope with extreme weather events

Microgrids are often applied in university campuses, industrial sites or critical infrastructure, such as hospitals, that need higher resilience and reliability standards. Wesleyan University in Connecticut created a microgrid on its campus, consisting of a 3.1 MW co-generation plant and a 750 kWh solar array, after suffering a 77-hour outage because of Hurricane Sandy in 2012. The system has the controls to island the system from the main grid and can be used by the Federal Emergency Management Agency as a regional emergency control centre.

Microgrids normally depend on small-scale thermal generation with local fuel storage, or, where solely variable renewables are used, the deployment of batteries. This allows the local system to maintain the supply–demand balance and ensure resilience to various hazards.

A microgrid concept based on a balanced mix of renewables, batteries and thermal generation was also suggested for Puerto Rico after the devastating effects of Hurricane Maria in 2017. This would improve overall system resilience and could defer some transmission corridor investments.

The concept of microgrids receives widespread attention in literature on infrastructure resilience. It is interesting how this contrasts with other expert views on operational security, where wider regional interconnectivity is usually acknowledged as improving reliability and lowering overall system costs. It shows that the value of microgrids is predominant when one of the following conditions are met: 1) the local value of lost load is very high and makes it beneficial to set up dedicated infrastructure; or 2) grid interconnections themselves are the weak element, as was the case in Puerto Rico.

Sources: New York Power Authority et al. (2017), NREL and US Agency for International Development (USAID) (2018).

Co-ordinate recovery efforts

An overarching authority should properly co-ordinate the recovery efforts of the electricity system's diverse actors to minimise the magnitude of interruptions and restore operation to normal as quickly as possible. The authority should also consider that recovery efforts will often need to be co-ordinated across multiple sectors, such as information and communications, and transport. Policy makers signal the importance of rapid and efficient recovery from climate impacts by institutionalising the co-ordination authority and providing clear guidance on which actors are responsible for what actions.

Policy makers and critical actors should minimise the impacts of disruption by prioritising recovery planning. In general, a rapid and effective recovery requires the involvement of a number of stakeholders. Therefore, governments need to build plans in consultation with all these relevant stakeholders in order to cope with future disruption caused by climate-related events. These plans can be developed through modelling and simulation of necessary emergency response measures and should be constantly revised to reflect lessons learnt from recent events. Based on the established plans, implementing entities will then prioritise recovery actions to avoid critical damage to key infrastructure and protect the most vulnerable groups.

To implement the established recovery plans, critical actors need to ensure that they have sufficient workforce in place. Recovery procedures rely on sufficient numbers of skilled workers. However, in practice their availability could be limited as a result of choices the utility made earlier or workforce constraints. Workforce shortage could lead to delays in recovery after disruption caused by extreme weather events, such as cyclones, floods and wildfires. For instance, a shortage of skilled labour in distribution companies and regulators is considered one of the reasons for the prolonged outages after the heavy rainfall and flash flooding in Sydney in February 2020. New technologies such as pre-inspection by drones may be a partial response to this or at least allow for more rapid initial action.

Support capacity building for implementation of resilience measures

Even where clear assessment frameworks are available, and supportive regulations and incentives are in place, their appropriate use and implementation require skills that are not always available. For instance, climate forecasting and early warning systems are often constrained in Africa due to the lack of capacity. Similarly, an expert mission of the World Meteorological Organization to Mozambique after Cyclone Idai identified the limited capacities of key central and local government authorities to respond to emergencies as one of the major weaknesses.

Managing the adverse impacts of climate change may become more challenging with the increasing variability of climate patterns and more frequent extreme weather events. A lack of appropriate regulatory regimes, low levels of planning, and the absence of disaster risk reduction strategies could exacerbate vulnerability to climate impacts. Several studies point to the importance of capacity building to improve access to quality climate data, analysis and knowledge. Policy makers and critical actors need to invest in capacity building for risk and impact assessments, forecasting and early-warning systems, emergency response and recovery. Moreover, joint capacity-building programmes for multiple entities could provide an opportunity to strengthen the communication of the latest climate information between stakeholders and learn from each other's experience.

Box 10 Example of capacity-building services for climate resilience: African Risk Capacity

The African Risk Capacity (ARC) is a specialised agency of the African Union. It comprises the African Risk Capacity Agency and the ARC Insurance Company Limited. It was established to help African governments improve their capacity to plan, prepare and respond to extreme weather events and natural disasters.

The ARC Capacity Building Programme, one of the ARC's services, aims to prepare African countries for effective disaster risk management through the introduction of tools and processes that enhance response to natural disasters. In this programme, technical experts from African governments are trained on how to define the country's climate risk profile using the ARC's software, *Africa RiskView*, and receive advisory support in developing a contingency plan.

Source: African Risk Capacity (2017).

6. Evaluate effectiveness and adjust resilience measures

After the implementation of resilience measures, each solution should be evaluated according to established criteria. Critical actors, including government, should establish a stakeholder group and develop the evaluation process in consultation. The evaluation criteria may include consideration of cost-effectiveness, technical feasibility, sustainability and consistency with other policies. The timing of implementation or the availability of funding can be also selected as criteria. Based on the criteria, stakeholders can score and rank resilience measures to determine whether they should continue to implement a specific measure, or revise it.

The process for evaluation and revision of resilience measures should solicit substantial input from various sources. It needs to evaluate outcomes at each step, from climate risk and impact assessment to implementation of resilience measures, receiving input from diverse stakeholders. The process also needs to consider recent developments in technology, methodology and procedures, and reflect lessons learnt from other cases.

References

AEMO (Australian Energy Market Operator) (2020a), *Quarterly Energy Dynamics Q4 2019: Market Insights and WA Market Operations*, Australian Energy Market Operator Limited, https://www.aemo.com.au/-/media/files/major-publications/qed/2019/qed-q4-2019.pdf.

AEMO (2020b), *Preliminary Report: New South Wales and Victoria Separation Event on 4 January 2020*, Australian Energy Market Operator Limited, https://aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2020/preliminary-report-nsw-and-victoria-separation-event-4-jan-2020.pdf.

AEMO (2019a), *New South Wales Bushfires on 15 April 2018: Reviewable Operating Incident Report under the National Electricity Rules*, Australian Energy Market Operator Limited, Melbourne, https://www.aemo.com.au/-/media/files/electricity/nem/market_notices_and_events/power_system_incident_reports/2018/nsw-bushfires-on-15-april-2018.pdf?la=en&hash=269CA445A026EC46A1D2967E7ED400DE/.

African Risk Capacity (2017), Capacity Building Programme Brochure.

Arderne, C. et al. (2020), “Predictive mapping of the global power system using open data”, *Scientific Data*, Vol. 7, Article 19, https://doi.org/10.1038/s41597-019-0347-4.

Argonne National Laboratory, (2012). *Resilience: Theory and Applications* (ANL/DIS-12-1).

Arheimer, B., C. Donnelly and G. Lindström (2017), “Regulation of snow-fed rivers affects flow regimes more than climate change”, *Nature Communications*, Vol. 8, Article 62, https://doi.org/10.1038/s41467-017-00092-8/.

Bierkandt, R., M. Auffhammer and A. Levermann (2015), “US power plant sites at risk of future sea-level rise”, *Environmental Research Letters*, Vol. 10, Number 12, IOP Publishing, https://doi.org/10.1088/1748-9326/10/12/124022.

Bradbury, J., M. Allen and R. Dell (2015), *Climate Change and Energy Infrastructure Exposure to Strom Surge and Sea level Rise*, US Department of Energy, Washington, DC, https://www.energy.gov/sites/prod/files/2015/07/f24/QER%20Analysis%20-%20Climate%20Change%20and%20Energy%20Infrastructure%20Exposure%20to%20Storm%20Surge%20and%20Sea-Level%20Rise_0.pdf.

Burke, K. (2020), *Sydney Weather: Ongoing Power Blackouts Blamed on Electricians' Shortage*, *7News*, https://7news.com.au/news/severe-weather/sydney-weather-shortage-of-electricians-keeps-power-switched-off-says-union-c-691544.

Campbell, A. F. (2018), “It took 11 months to restore power to Puerto Rico after Hurricane Maria. A similar crisis could happen again”, *Vox Media*, https://www.vox.com/identities/2018/8/15/17692414/puerto-rico-power-electricity-restored-hurricane-maria/.

CEA (Canadian Electric Association) (2019), *Adaptation Through Risk Management: Electricity Sector Climate Adaptation Planning Guide*, https://electricity.ca/wp-content/uploads/2019/09/Adaptation-Through-Risk-Management-Electricity-Sector-Climate-Adaptation-Planning-Guide.pdf.

CGIAR-CSI (Consortium for Spatial Information) (2018), *SRTM 90m DEM Digital Elevation Database*, CGIAR Platform for Big Data in Agriculture, https://bigdata.cgiar.org/srtm-90m-digital-elevation-database/.

Club of Mozambique (2019), "Cahora Bassa power lines to southern Mozambique, S. Africa 'fully restored' after cyclone Idai", https://clubofmozambique.com/news/cahora-bassa-power-lines-to-southern-mozambique-s-africa-fully-restored-after-cyclone-idai/.

C3S (Copernicus Climate Change Service) (2019), *Fire Danger Indices Historical Data from the Copernicus Emergency Management Service,* Climate Data Store, https://doi.org/10.24381/cds.0e89c522.

CPUC (California Public Utilities Commission) (2020), *Public Safety Power Shutoff (PSPS)/De-Energization*, State of California, San Francisco, https://www.cpuc.ca.gov/deenergization/.

CRED (Centre for Research on the Epidemiology of Disasters) (2020), *EM-DAT (Emergency Events Database) The International Disaster Database*, Louvain-la-Neuve, https://www.emdat.be/database.

Cronin, J., G. Anandarajah and O. Dessens (2018), "Climate change impacts on the energy system: a review of trends and gaps", *Climatic Change*, Vol. 151, pp. 79–93, https://doi.org/10.1007/s10584-018-2265-4.

Dale, L. et al. (2018), *Assessing the Impact of Wildfires on the California Electricity Grid*, California Energy Commission, Sacramento, https://www.energy.ca.gov/sites/default/files/2019-11/Energy_CCCA4-CEC-2018-002_ADA.pdf.

DOE (US Department of Energy) (2018), *Energy Resilience Solutions for the Puerto Rico Grid*, United States Department of Energy, Washington, DC, https://www.energy.gov/sites/prod/files/2018/06/f53/DOE%20Report_Energy%20Resilience%20Solutions%20for%20the%20PR%20Grid%20Final%20June%202018.pdf.

DOE (2016), *Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning*, https://www.energy.gov/sites/prod/files/2016/10/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf.

Ebinger, J. and W. Vergara (2011), "Key issues for energy sector adaptation", *Climate Impacts on Energy Systems*, The World Bank Group, https://doi.org/10.1596/978-0-8213-8697.

EEA (European Energy Agency) (2019), *Adaptation Challenges and Opportunities for the European Energy System*, https://www.eea.europa.eu/publications/adaptation-in-energy-system.

Farouk, N., L. Sheng and Q. Hayat (2013), "Effect of ambient temperature on the performance of gas turbines", *International Journal of Computer Science Issues*, Vol. 10, Number 3, pp. 439-442, https://www.ijcsi.org/papers/IJCSI-10-1-3-439-442.pdf.

Geospatial Information Authority of Japan (2017), *Global Land Cover by National Mapping Organizations: GLCNMO Version 3*. https://globalmaps.github.io/glcnmo.html.

Hill, M. and R. Ndlovu (2019), "Power-starved Zimbabwe, Zambia face further drought-induced blackouts", *Bloomberg*, https://www.bloomberg.com/news/articles/2019-08-05/power-starved-zimbabwe-zambia-face-further-drought-induced-dark/.

Hofste, R. et al. (2019), *Aqueduct 3.0: Updated Decision – Relevant Global Water Risk Indicators: Technical Note*, World Resources Institute, Washington D.C., https://wriorg.s3.amazonaws.com/s3fs-public/aqueduct-30-updated-decision-relevant-global-water-risk-indicators_1.pdf.

IDN Financials (2020), "PLN reactivates 2,524 distribution substations in aftermath of Greater Jakarta floods", South Jakarta, https://www.idnfinancials.com/news/31038/pln-reactivates-distribution-substations-aftermath-jakarta-floods.

IEA (International Energy Agency) (2021), *Climate Impacts on Latin American Hydropower*, IEA, Paris, https://www.iea.org/reports/climate-impacts-on-latin-american-hydropower.

IEA (2020a), *Energy Technology Perspectives*, IEA, Paris, https://www.iea.org/reports/energy-technology-perspectives-2020.

IEA (2020b), *World Energy Outlook*, IEA, Paris, https://www.iea.org/reports/world-energy-outlook-2020.

IEA (2020c), *Climate Impacts on African Hydropower*, IEA, Paris, https://www.iea.org/reports/climate-impacts-on-african-hydropower.

IEA (2020d), *Is cooling the future of heating?,* IEA, Paris, https://www.iea.org/commentaries/is-cooling-the-future-of-heating

IEA (2019a), *Energy Policies of IEA Countries: United States 2019 Review*, IEA, Paris, https://webstore.iea.org/download/direct/2829?fileName=United_States_2019_Review.pdf.

IEA (2019b), *Africa Energy Outlook*, IEA, Paris, https://www.iea.org/reports/africa-energy-outlook-2019.

IEA (2019c), *Offshore Wind Outlook 2019*, IEA, Paris, https://www.iea.org/reports/offshore-wind-outlook-2019.

IEA (2018), *The Future of Cooling*, IEA, Paris, https://www.iea.org/reports/the-future-of-cooling

IEA (2016), *Energy, Climate Change & Environment – 2016 Insights*, IEA, Paris, https://www.iea.org/reports/energy-climate-change-and-environment-2016-insights.

IEA (2015), *India Energy Outlook 2015*, IEA, Paris, https://www.iea.org/reports/india-energy-outlook-2015.

IHA (International Hydropower Association) (2017), *Hydropower Status Report 2016*, London.

IPCC (Intergovernmental Panel on Climate Change) (2019), *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, https://www.ipcc.ch/site/assets/uploads/sites/3/2019/12/SROCC_FullReport_FINAL.pdf.

IPCC (2018), *Global Warming of 1.5°C*, https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf.

IPCC (2015), *Climate Change 2014: Synthesis Report*, https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

IPCC (2014a), "Climate Change 2014: Mitigation of climate change" (Vol. 9780521880), https://www.ipcc.ch/report/ar5/wg3/.

IPCC (2014b), "Climate Change 2014: Impacts, adaptation, and vulnerability", in *Statewide Agricultural Land Use Baseline 2015* (Vol. 1), https://doi.org/10.1017/CBO9781107415324.004.

IPCC (2012), "Climate change: new dimensions in disaster risk, exposure, vulnerability, and resilience", in *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, Cambridge University Press, Cambridge, https://www.ipcc.ch/site/assets/uploads/2018/03/SREX-Chap1_FINAL-1.pdf.

IRENA (International Renewable Energy Agency) (2018), *Nurturing Offshore Wind Markets: Good Practices for International Standardisation*, IRENA, Abu Dhabi, https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/May/IRENA_Nurturing_offshore_wind_2018.pdf.

Jin, Y. et al. (2015), "Identification of two distinct fire regimes in Southern California: implications for economic impact and future change", *Environmental Research Letters*, Vol. 10, No. 9, IOP Publishing, https://doi.org/10.1088/1748-9326/10/9/094005/.

Jolly, W. M. et al. (2015), "Climate-induced variations in global wildfire danger from 1979 to 2013", *Nature Communications*, Vol. 6, Article 7537, pp. 1-11, https://doi.org/10.1038/ncomms8537/.

Karagiannis, G. M. et al. (2019), *Climate Change and Critical Infrastructure –Storms*, Publications Office of the European Union, Luxembourg, https://doi.org/10.2760/986436/.

Karagiannis, G. M. et al. (2017), *Power Grid Recovery After Natural Hazard Impact*, JRC (Joint Research Centre) Science for Policy Report, European Commission, Luxembourg, https://doi.org/10.2760/87402/.

Kuo, L. (2016), "Africa's biggest hydropower plant may soon run out of water", *Quartz Media*, https://qz.com/africa/862789/mozambiques-hydropower-dam-supplies-south-africa-and-zimbabwe-may-soon-run-out-of-water/#.

Lemperiere, F. et al. (2018), *Flood risk management for hydropower plants in France,* The European Climate Adaptation Platform Climate-ADAPT, CA, https://climate-adapt.eea.europa.eu/metadata/case-studies/fd/#challenges_anchor.

Luo, T., D. S. Krishnan and S. Sen (2018), *Parched Power: Water Demands, Risks, and Opportunities for India's Power Sector*, World Resources Institute, Washington, DC, https://www.wri.org/publication/parched-power/.

Macdonald-Smith, A. (2020), "Fires cut power link between NSW and Vic", *The Australian Financial Review*, https://www.afr.com/companies/energy/nsw-at-risk-of-blackouts-as-fires-cut-power-link-with-vic-20200104-p53ov4.

McArdle, P. (2020), "Extreme temperature effects on generation supply technology", *WattClarity*, http://www.wattclarity.com.au/articles/2020/02/extremes-temperature-effects-on-generation-supply-technology/.

Miyamoto International (2019), *Overview of Engineering Options for Increasing Infrastructure Resilience: Final Report*, World Bank Group, Washington, DC, http://documents.worldbank.org/curated/en/474111560527161937/pdf/Final-Report.pdf.

Moore, S. K. (2010), "The water cost of carbon capture", *IEEE Spectrum*, New York, https://spectrum.ieee.org/energy/environment/the-water-cost-of-carbon-capture/.

Moss, R. et. Al. (2008), "Towards new scenarios for analysis of emissions, climate change, impacts and response strategies", IPCC Expert Meeting Report, 19-21 September, 2007, Noordwijkerhout, Netherlands, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Muis, S. et al. (2016), "A global reanalysis of storm surges and extreme sea levels", *Nature Communications*, Vol. *7*, Article 11969, https://doi.org/10.1038/ncomms11969/.

NAP (The National Academies Press) (2017), *Enhancing the Resilience of the Nation's Electricity System*, The National Academies Press, Washington, DC, https://doi.org/10.17226/24836.

NERC (North American Electric Reliability Corporation) (2014), *Hurricane Sandy Event Analysis Report*, NERC, Atlanta, https://www.nerc.com/pa/rrm/ea/Oct2012HurricanSandyEvntAnlyssRprtDL/Hurricane_Sandy_EAR_20140312_Final.pdf.

New York Power Authority et al. (2017), *Build Back Better: Reimagining and Strengthening the Power Grid of Puerto Rico*, https://www.governor.ny.gov/sites/governor.ny.gov/files/atoms/files/PRERWG_Report_PR_Grid_Resiliency_Report.pdf.

Nicolas, C. et al. (2019), *Stronger Power: Improving Power Sector Resilience to Natural Hazards,* International Bank for Reconstruction and Development and the World Bank, Washington, DC, http://documents1.worldbank.org/curated/en/200771560790885170/pdf/Stronger-Power-Improving-Power-Sector-Resilience-to-Natural-Hazards.pdf.

Nqola, R. (2019), "*Mozambique cyclone to blame for Stage 4 load shedding, says Eskom"*, EWN (Eyewitness News), https://ewn.co.za/2019/03/16/mozambique-cyclone-to-blame-for-stage-4-load-shedding-says-eskom/.

NREL (National Renewable Energy Laboratory) (2020), *Lao Power Sector Vulnerability Assessment and Resilience Action Plan*, https://www.nrel.gov/docs/fy20osti/73069.pdf.

NREL (2017), *The Next-Generation Performance-Based Regulation*, https://www.nrel.gov/docs/fy17osti/68512.pdf.

NREL and US Agency for International Development (USAID) (2018), *Bridging Climate Change Resilience and Mitigation in the Electricity Sector Through Renewable Energy and Energy Efficiency*, https://www.nrel.gov/docs/fy18osti/67040.pdf.

OECD (Organisation for Economic Co-operation and Development) (2018), *Climate-Resilient Infrastructure*, http://www.oecd.org/environment/cc/policy-perspectives-climate-resilient-infrastructure.pdf.

Ogallo, Laban and Christopher Oludhe (2009), *Climate Information in Decision-Making in the Greater Horn of Africa: Lessons and Experiences*, World Meteorological Organization, https://public.wmo.int/en/bulletin/climate-information-decision-making-greater-horn-africa-lessons-and-experiences.

Oller, S. (2019), “California power outages threaten EV charging – Tesla owners urged to charge up as utility shuts off electricity to prevent wildfires, *CSP*, https://www.cspdailynews.com/fuels/california-power-outages-threaten-ev-charging/.

Onishi, N. (2016), “Climate change hits hard in Zambia, an African success story”, *The New York Times*, New York, https://www.nytimes.com/2016/04/13/world/africa/zambia-drought-climate-change-economy.html/.

Penn, I. and P. Eavis (2019), “Report detailing PG&E’s failures raises new hurdles for utility”, *The New York Times*, New York, https://www.nytimes.com/2019/12/03/business/energy-environment/pge-camp-fire-report.html/.

PG&E (Pacific Gas and Electric Company) (2019), *Pacific Gas and Electric Company Amended 2019 Wildfire Safety Plan*, PG&E, San Francisco, https://www.pge.com/pge_global/common/pdfs/safety/emergency-preparedness/natural-disaster/wildfires/Wildfire-Safety-Plan.pdf.

Procupez, V. (2016), “The perfect storm: Heat waves and power outages in Buenos Aires”, *Public Culture*, Vol. 28, No. 2(79), pp. 351-357, https://doi.org/10.1215/08992363-3427475.

Paul, S. (2019). Record-breaking heatwave triggers power cuts on Australia’s stressed grid, *Reuters*, https://www.reuters.com/article/us-australia-power-idUSKCN1PJ0AB

Romo, V. (2019), “With blackouts, California's electric car owners are finding new ways to charge up”, *NPR*, https://www.npr.org/2019/11/08/777752175/with-blackouts-californias-electric-car-owners-are-finding-new-ways-to-charge-up?t=1586805617320/.

S&P Global Platts, World Electric Power Plants Database, accessed 8 April 2020, https://www.spglobal.com/platts/en/ (Subscription).

Schaeffer, R. et al. (2012), “Energy sector vulnerability to climate change: A review”, *Energy*, Vol. 38, Issue 1, pp. 1-12, https://doi.org/10.1016/j.energy.2011.11.056/.

SDG&E (San Diego Gas & Electric Company) (2020), *2020 Wildfire Mitigation Plan*, SDG&E, San Diego, https://www.sdge.com/2020-wildfire-mitigation-plan/.

St. John, J. (2019), “PG&E outlines path to easing future power grid outages", *Greentech Media*, https://www.greentechmedia.com/articles/read/pge-points-to-grid-sectionalization-forecasting-and-microgrids-to-ease-outa.

Stavi, I. (2019), “Wildfires in grasslands and shrublands: A review of impacts on vegetation, soil, hydrology, and geomorphology”, *Water*, Vol. 11, Issue 5, p. 1042, https://doi.org/10.3390/w11051042.

UNDRR (UN Office for Disaster Risk Reduction) (2015), *Global Cyclone Hazard*, World Bank, Washington, DC, https://www.preventionweb.net/english/hyogo/gar/2015/en/gar-pdf/Annex1-GAR_Global_Risk_Assessment_Data_methodology_and_usage.pdf.

UN (United Nations) (2019), “ ‘For every dollar invested in climate-resilient infrastructure six dollars are saved’, Secretary-General says in message for Disaster Risk Reduction Day” (SG/SM/19807-IHA/1472-OBV/1927, 10 October 2019), https://www.un.org/press/en/2019/sgsm19807.doc.htm.

Watkins, A., and A. Southall (2019), “Amid heat wave in New York, 50,000 lose electricity”, *New York Times*, https://www.nytimes.com/2019/07/21/nyregion/nyc-heat-wave.html.

Wilbanks, T. et al. (2008), *Effects of Climate Change on Energy Production and Use in the United States*, US Department of Energy, Climate Change Science Program, Washington, DC, https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1005&context=usdoepub/.

WMO (World Meteorological Organization) (2020), “*Global partnership urges stronger preparation for hot weather during COVID-19”*, https://public.wmo.int/en/media/news/global-partnership-urges-stronger-preparation-hot-weather-during-covid-19/.

WMO (2019), “Reducing vulnerability to extreme hydro-meteorological hazards in Mozambique after Cyclone IDAI”, WMO mission report following tropical cyclone IDAI (29 April-7 May 2019), https://library.wmo.int/doc_num.php?explnum_id=6259.

WMO (2018), “Guidelines on the defintion and monitoring of extreme weather and climate events (Final Draft)”, WMO Commission for Climatology Task Team on the Definition of Extreme Weather and Climate Events, Geneva, http://www.wmo.int/pages/prog/wcp/ccl/documents/GUIDELINESONTHEDEFINTIONANDMONITORINGOFEXTREMEWEATHERANDCLIMATEEVENTS_09032018.pdf.

World Bank (2019), *Lifelines: The Resilient Infrastructure Opportunity*, http://hdl.handle.net/10986/31805.

"*This publication has been produced with the financial assistance of the European Union as part of the Clean Energy Transitions in Emerging Economies programme. This publication reflects the views of the International Energy Agency (IEA) Secretariat but does not necessarily reflect those of individual IEA member countries or the European Union (EU). Neither the IEA nor the EU make any representation or warranty, express or implied, in respect to the publication's contents (including its completeness or accuracy) and shall not be responsible for any use of, or reliance on, the publication.*"

The Clean Energy Transitions in Emerging Economies programme has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952363

IEA Publications

International Energy Agency

Website: www.iea.org

Contact information: www.iea.org/about/contact

Typeset in France by IEA – April 2021

Cover design: IEA

Photo credits: © Shutterstock