Climate Resilience for Energy Security

International Energy Agency

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Abstract

Growing climate change is putting global energy security at risk, threatening the reliable supply of fuels and resources. Climate change directly affects every aspect of the energy system, from the extraction, processing and transport of fuels and minerals, to the potential, efficiency and reliability of power generation, to the physical resilience of energy infrastructure, as well as impacting energy demand patterns. According to most scenarios, climate change disruptions are likely to increase in magnitude in the coming decades. A comprehensive understanding of climate effects on energy supply and demand is crucial to strengthening the resilience of energy systems.

This report provides a comprehensive overview of the climate impacts and hazards facing energy systems, with projections up to the end of the 21st century. It also presents effective measures for energy suppliers, consumers and public authorities to enhance climate resilience, with cost-benefit analysis proving that investments in climate resilience bring long-term benefits.

Foreword

The global energy crisis prompted by Russia's invasion of Ukraine is a stark reminder of the importance of energy security. But there are many other threats to energy security, both old and new. These include climate change, which is already affecting the supply of fuels, minerals and electricity, as well as threatening the physical resilience of energy infrastructure. It is also altering energy demand for buildings, industry and transport. While these impacts vary significantly from country to country, no continent is immune to the consequences of climate change.

In November 2022, the United Nations COP27 Climate Change Conference in Egypt will work to strengthen global co-operation and collective action to tackle climate change. The focus will be just as much on adapting to the inevitable consequences of a warming planet as on how to accelerate mitigation to ensure that these consequences remain as manageable as possible.

We can understand, anticipate and therefore prepare for climate impacts to some degree, though our knowledge is neither complete nor infallible. The IEA has worked for many years to increase awareness of climate impacts among energy policy makers and stakeholders, for example by examining the climate resilience of power systems and the effects of climate change on hydropower. In the process, we have developed energy-focused *Climate Resilience Policy Indicators* for IEA member countries.

This publication provides an important reference point for those wanting a better understanding of the links between climate change and the supply and demand of energy. It synthesises existing literature and provides climate risk analysis for all fuels and key technologies, answering pressing questions: How does a changing climate affect energy supply and demand? How much greater will the impacts be if the world fails to reduce emissions? What will be the implications and added costs if energy systems are not sufficiently resilient? The IEA will continue to build on this work in future years in order to best support policy makers in their efforts to address climate impacts and to enhance the resilience of energy systems.

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Table of contents

Executive summary

Growing climate change impacts put global energy security at risk

Climate change is putting global energy security at risk. It affects the extraction, processing and transport of fuels and minerals, and alters power generation potential, efficiency and reliability. Some of the major energy-sector disruptions seen in 2022 were due to extreme climatic conditions, which are becoming more frequent and intense because of climate change. These range from heatwaves in Europe, Hurricane Ian in the United States and Cuba and record flooding in Pakistan. Severe droughts in Chile and flooding in South Africa also disrupted the global supply of copper and cobalt. The global mean surface temperature will continue to increase until at least mid-century, extending summer, bringing more heatwaves and triggering early snowmelt and even permafrost thawing. Climate change also leads to larger geographical and temporal variability in precipitation, increasing the likelihood of heavy rainfall, flooding and droughts. Tropical cyclones have become more intense, and the trend is expected to continue. Sea level will also continue to rise, threatening coastal areas with coastal erosion, flooding with storm surges, and saltwater intrusion.

Climate change impacts on energy are likely to grow in the coming decades. The mean surface temperature in the locations of refineries, mines, power plants and grids is expected to reach over 2.1°C in 2080-2100 compared to the pre-industrial period in a low-emissions scenario, while recording 6.5-16.8 more hot days (maximum temperature above 35°C). In a high-emissions scenario, it will exceed 5.5°C with additional 27.7-54.4 hot days. Higher temperatures could lead to more frequent heatwaves and early snowmelt, greater variability in rainfall with an increasing likelihood of flooding and droughts, and more intense tropical cyclones. For instance, in a higher emissions scenario, more than 80% of production sites of fossil fuel, critical minerals, electricity and grids are projected to see an over 10% increase in one-day maximum precipitation. Climate tipping points that could lead to hard-to-reverse impacts, such as permafrost thawing and greater sea-level rise, could be crossed in higher-emissions scenarios.

Unabated emissions could trigger more adverse impacts on energy system resilience. If global warming is limited to below 2°C, tropical cyclones, wildfires and increasing precipitation with heavy rainfall and floods are the most critical climate risks to energy supply. More intense tropical cyclones pose particular risks to oil and gas production and wind power plants. Besides damaging assets, the smoke particulates of wildfires reduce solar power generation. A wetter climate with heavy rainfalls and flooding can suspend critical mineral and coal mining activities and reduce product quality, while disrupting hydropower generation.

Should global warming exceed 4°C, these impacts are compounded by higher temperatures, droughts and sea-level rise that would pose major risks to energy supply. Rising temperatures and heatwaves could thaw permafrost, adding stress to oil and natural gas production. They would also affect the availability of cooling water for thermal power plants and reduce the efficiency of wind power generation. More frequent and intense droughts in some regions could also interrupt critical minerals production, thermal plant cooling and hydropower generation. Sea-level rise could threaten energy infrastructure in coastal areas.

Comparison of significant climate risks to energy supply between a low-emissions and a high-emissions scenario, 2080-2100

	Temperature	Precipitation (dry)	Precipitation (wet)	Sea level	Wind (cyclones)	Wildfires
Oil and natural gas	!			!	✓	✓
Coal			✓	-		
Critical minerals		✓	✓	-		
Fossil-fuelled thermal power	✓	!!	✓	!	✓	✓
Nuclear power	!!!	!	✓	-	✓	
Hydropower	!	!!	✓	-	✓	
Solar PV	✓	!	!	-	✓	✓
Wind	!			-	✓	
Electricity networks	✓		✓	-	✓	✓

Notes: This table shows the comparison of significant climate risks to energy supply in a low-emissions scenario (Shared Socioeconomic Pathway [SSP]1-2.6), associated with warming below 2°C, and a high-emissions scenario (SSP5-8.5), associated with warming of above 4°C, in 2080-2100. The check mark indicates that that part of the energy supply will face a significant level of climate risks even in a low-emissions scenario. The exclamation marks indicate that that part of energy supply will face a significant level of climate risks if GHG emissions are not mitigated, i.e. as in a high-emissions scenario. The number of exclamation marks indicates the level of risks in a high-emissions scenario, implying that a certain part of the energy supply would react more sensitively to an increased level of climate hazard. Blank cells indicate a low level of climate risks. Hyphens indicate no assessment results.

Climate change affects the entire energy supply chain, including fuel production, mining, power generation and grids

When it comes to fossil fuel production, our analysis of site exposure to climate hazards finds that 25% of today's refineries are exposed to risk of destructive cyclones, and around one-third of refineries are threatened by sea-level rise and storm surges. If GHG emissions are not mitigated, around 95% of refineries in low-lying areas could experience an over 0.6 m rise, and 10% could see an over 1 m sea-level rise. Around 80% of coal production sites are projected to be in a wetter condition in 2080-2100, with a more than 10% increase in one-day maximum precipitation. This could ease water stress in some areas but decrease quality and production in others due to heavy rainfall and floods.

Supply of critical minerals can be also threatened by climate change impacts. Although lithium requires more water than other minerals for production, over 50% of lithium production is currently concentrated in areas with high water stress, and over 80% of lithium mines will experience a drier climate in all future climate scenarios. In contrast, most nickel and cobalt production sites would see an increase in one-day maximum precipitation and face disruption risks from heavy rainfall and flooding. Impacts on copper production are mixed; regions in Chile and Australia are projected to face a drier climate, while those in Peru and China could face a wetter climate.

Electricity systems are witnessing increasing pressure from climate change impacts. Thermal plants would be affected by more extreme rainfall and associated floods that can make physical damage and disrupt power generation. Almost 80% of coal power plants, 65% of nuclear power plants and around 50% of gas and oil power plants are projected to see an over 10% increase in one-day maximum precipitation in 2080-2100 in all climate scenarios, compared to 1850-1900. Intensification of tropical cyclones would pose a risk to power generation, given that almost 30% of existing nuclear power plants are exposed to tropical cyclones. Limited or warm cooling water due to droughts and heatwaves could curtail the generation of thermal power plants that are using wet cooling systems. For nuclear plants, higher cooling water temperature is a major cause of climate-driven disruptions and reduced output. For some oil and gas power plants, reduced water availability due to climate change can become a concern. In a high-emissions future, 23% of oil power plants and 18% of gas power plants could see the number of consecutive dry days increase by ten in 2080-2100, compared to 1850-1900.

Increasing temperatures and associated dryer conditions will affect various renewable energy power generation sources. High temperatures would also decrease solar PV output and lead to higher wildfire risks at PV sites. Similarly, higher temperatures reduce wind power generation and increase damage to components; standard turbines stop functioning at temperatures above 45°C. Hydropower overall would experience greater variability in generation, with two-thirds of hydropower plants also seeing a notable increase (more than 10%) in one-day maximum precipitation, while approximately 6-20% of plants experience ten more consecutive dry days in 2080-2100, compared with 1850-1900. Tropical cyclones and associated floods and landslides damage and impair hydropower generation through increased sediment, debris and torrential streamflow. Tropical cyclones also lead to shutdown and damage to wind generation sites. Currently, 14% of hydropower installed capacity and 19% of wind power plants are exposed to tropical cyclones, and half of them are under the threat of major tropical cyclones (above Category 3). Decreased average wind speed is a less well studied but still a potential risk to wind power generation, especially in the northern hemisphere.

Electricity networks are highly vulnerable to various climate impacts. Around half of global electricity networks are currently exposed to fire weather for more than 50 days per year, while 18% are exposed to a high risk of wildfires, with more than 200 days of fire weather annually. The impact of more intense tropical cyclones and storms will also be damaging to electricity networks, as severe winds damage transmission and distribution lines, poles and transformers. Over 10% of networks are currently exposed to tropical cyclones, notably in North America, Australia and East Asia. Rising temperatures also reduce transmission capacity and lead to higher losses. Even with warming below 2°C, around 28% of electricity networks could experience 60 more days of maximum temperature above 35°C, compared with the 1850-1900 average.

Climate change will change energy demand patterns

Rising temperatures increase global electricity needs for cooling and can add strain on electricity grids during peak hours. At the same time, milder temperatures in winter can reduce energy demand for heating. Cooling degree days are projected to increase by 268 to 732 degree days globally in 2081-2100, compared to 1850-1900, while heating degree days could drop by 268 to 776 degree days. The net effect of these trends will vary across countries, with some experiencing overall reductions and others overall increases. Globally, these changes could trigger a 7-17% increase in energy consumption by 2050, depending on overall temperature increase. Combined with economic growth, this will increase electricity demand, particularly in emerging and developing economies.

Rising global temperatures and more frequent heatwaves could increase fuel consumption in aviation, curtailing the maximum allowable take-off weight and requiring more engine thrust for take-off. Higher average temperatures could also reduce the energy efficiency of road transport vehicles, particularly by reducing electric and hybrid vehicle battery efficiency.

Climate impacts could also indirectly affect energy consumption in industry and agriculture, although the links and implications require deeper investigation. The increased frequency or severity of extreme weather events could affect demand for energy-intensive construction materials for both adaptation (e.g. physical hardening) and reconstruction, potentially contributing to an increase in overall energy demand. Nitrogen loss due to rainfall and floods could increase demand for fertiliser and associated ammonia production. Last, prolonged droughts and impacts on water availability in some areas could increase energy demand through the use of energy-intensive seawater desalination.

Energy systems need to be resilient to be secure

Against the increasing impacts of climate change, resilient energy systems will bring more benefits than costs. A climate-resilient energy system that can anticipate, absorb, accommodate and recover from climate hazards, could prevent negative effects of climate change from spreading across the energy value chain. A climate-resilient energy system can prepare for changes in climate (readiness), adapt to and withstand the slow-onset changes in climate patterns (robustness), continue to operate under the immediate shocks from extreme weather events (resourcefulness) and restore the system's function after climate-driven disruptions (recovery). A cost-benefit analysis in this report finds that the net benefits of investing in resilience against floods in the power sector in Africa and Asia could reach almost USD 1 trillion to 2050, even in a low-emissions scenario. The return of investment in flood walls, advanced riprap, improved dike construction and extreme event flood design could be three to eight times higher than costs in Asia, and 11 to 15 times higher in Africa, depending on the scenario.

To capture these benefits, a range of actions are needed by all stakeholders (see Table below)**. Energy suppliers**, including generators and operators of transmission and distribution systems, play a key role in improving resilience across all four dimensions. Improving readiness through climate risk and impact assessments, and robustness through physical system hardening and improved production processes, are closely linked with protecting energy suppliers' own assets and providing reliable energy services to customers. Some aspects of improved recovery, namely better climate monitoring systems for early warning and emergency response, will also be required.

Energy authorities, which include national and sub-national governments and regulators, play a particularly important role in ensuring readiness by providing information and data for consumers and conducting risk assessments, and by establishing an enabling policy and market environment to catalyse actions by energy suppliers and consumers. These enable action by mainstreaming climate resilience into consumption, investment and operational decisions. Authorities also play an essential role in recovery by supporting insurance systems and emergency response and preparedness.

Energy consumers contribute to energy-sector climate resilience by adopting demand-side measures in main end-use sectors, such as buildings, industries and transport. Although demand-side measures can sometimes have only indirect impacts on the resilience of the energy system, some are already proving effective: climate-proofed infrastructure design; promotion of behavioural changes through greater awareness; improved energy efficiency; shift to smart and advanced technologies; nature-based solutions; and adoption of climate-resilient materials.

Measures to build climate resilience for energy security by stakeholder

Types	Measure	Readiness	Robustness	Resourcefulness	Recovery
Supply side	Conduct climate risk and impact assessment				
	Implement physical system improvement				
	Switch to water-efficient and heat-resilient production process				
	Diversify energy supply chain				
	Better monitor for early warning and emergency response				
Demand side	Ensure climate proofing in design and performance				
	Increase awareness and promote behavioural changes				
	Improve energy efficiency				
	Use smart and advanced technologies for better management				
	Adopt nature-based solutions				
	Switch to climate-resilient materials				
Authorities and governments	Enhance knowledge about climate risks and impacts				
	Establish appropriate policy frameworks				
	Mainstream climate resilience into relevant regulations				
	Mobilise financing and investment				
	Support adequate climate insurance				
	Ensure emergency preparedness				

Chapter 1. Introduction

Climate change is posing significant challenges to the resilience of energy systems across the world, increasing uncertainties as to the reliable supply of fuels and resources and raising the likelihood of climate-driven disruptions. The world has seen major disruptions in the energy sector due to climate change in 2022. Heatwaves in Europe raised electricity prices to a record-breaking level, with soaring energy demand for cooling. The Category 4 Hurricane Ian destroyed electricity networks in the United States and Cuba, leaving over 13 million people in the dark for hours to weeks. Massive floods from record monsoon rains and glacial melt in Pakistan damaged power stations and gas pipelines. Severe droughts in Chile and flooding in South Africa disrupted the global supply of copper and cobalt, critical minerals for energy systems.

Building climate resilience (the ability to anticipate, absorb, accommodate and recover from adverse climate impacts) is essential for future energy security and smooth energy transitions. To strengthen the resilience of energy systems against climate change, a comprehensive understanding of climate change impacts on energy supply and demand is crucial. Based on this information, energy sector stakeholders, including energy suppliers, consumers and authorities, can identify and implement appropriate measures for resilience against near-term and long-term climate risks.

Scope and structure

This report is designed to provide a comprehensive and scientific overview of the links between climate change and energy security. It highlights specific climate trends that are relevant to energy security and assesses future climate impacts through quantitative modelling using climate scenarios and geospatial analyses, as well as qualitative research. Based on the assessment results, it proposes effective measures for energy suppliers, energy consumers and public authorities that would bring more returns than investment.

Chapter 2 provides an overview of historical trends and projections of climate change in terms of temperature, precipitation, wind and sea-level rise. Chapter 3 comprehensively assesses climate change impacts on each segment of energy supply, from fuels and minerals to electricity grids, comparing three climate scenarios by 2100. Chapter 4 assess climate change impacts on energy demand, focusing on the three major end-use sectors: buildings, industry and transport. Chapter 5 provides a non-exhaustive overview of measures to build climate resilience for energy security, looking at supply, demand and cross-cutting actions from energy authorities. The final chapter presents a cost-benefit analysis for measures that build resilience against flooding in the power sector in Africa and Asia.

Chapter 2. Trends and projections of climate change

Climate change is already affecting every region of the globe. Extreme weather events are becoming more frequent or intense in many countries, while structural long-term changes, such as temperature rise and changing precipitation patterns, are becoming increasingly visible, affecting economic development and social welfare. Energy system risks associated with climate hazards are high, and the continued increase in extreme weather events and slow-onset impacts implies that such risks will increase in the future.

The direction and intensity of future climate change heavily depends on the trajectory of GHG concentrations, largely determined by human activities. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report defines five Shared Socioeconomic Pathways (SSPs) that explore possible evolutions of human societies and their implications for the climate.

Emissions scenarios considered in the IPCC's Sixth Assessment Report

Scenario	Description	Global warming estimate for 2100
SSP1-1.9	A very low-emissions reference scenario; implies net zero emissions by mid-century.*	Below 1.5°C
SSP1-2.6	A low-emissions reference scenario; implies net zero emissions in the second half of the century.**	Below 2°C
SSP2-4.5	An intermediate scenario, in line with the upper end of aggregate NDC emission levels by 2030.***	Below 3°C
SSP3-7.0	A medium to high reference scenario with no additional climate policy. Emissions almost double by 2100, compared to today's levels.	Above 3°C
SSP5-8.5	A high reference scenario with no additional climate policy. Emissions triple by 2100, compared to today's levels.	Above 4°C

* In the IEA *World Energy Outlook 2022*, the assumption of net zero emissions by mid-century of SSP1-1.9 is reflected in the IEA Net Zero Emissions by 2050 Scenario (NZE), a normative scenario that sets out a pathway for the global energy sector to achieve net zero CO_2 emissions by 2050. The NZE scenario also meets key energy-related United Nations Sustainable Development Goals, in particular by achieving universal energy access by 2030 and major improvements in air quality.

** SSP1-2.6 is in line with the IEA Stated Policies Scenario (STEPS), an exploratory scenario that reflects current policy settings and provides a benchmark to assess the potential achievements (and limitations) of recent developments in energy and climate policy.

*** SSP2-4.5 is broadly in line with the IEA Announced Policies Scenario (APS), another exploratory scenario that assumes that all climate commitments made by governments around the world, including NDCs and longer-term net zero targets, will be met in full and on time.

Notes: NDC = Nationally Determined Contribution.

Source: Based on IPCC (2021a).

The five Shared Socioeconomic Pathways cover a wide range of future pathways, including a scenario in which GHG emissions decline drastically to net zero by 2050 and are negative in the second half of the century (SSP1-1.9) and another in which emissions continue to rise sharply, doubling from today's levels by 2050 and more than tripling by 2100 (SSP5-8.5). SSP1-1.9 would limit global warming below 1.5°C in 2100 relative to pre-industrial levels, while SSP5-8.5 would lead to a climate that is warmer by above 4°C.

The latest IPCC Sixth Assessment Report shows that it will be more difficult to adapt to climate change when the global temperature increase gets close to or exceeds the 1.5°C threshold. Some adaptation measures will become less effective or ineffective above the 1.5°C threshold because many of the projected changes in the climate system will become significantly greater in this case. Prospects for climate-resilient energy systems (and climate-resilient development more broadly) are therefore fundamentally related to the level of climate change mitigation collectively achieved, in addition to progress in adaptation.

This chapter focuses on the changes in four key climate impact drivers that affect energy supply and demand: temperature, precipitation, wind and sea-level rise. For each of these variables, it discusses historic trends, projected changes until 2100, as well as the most important phenomena and risks resulting from these changes. The chapter also highlights interactions among various climate variables, recognising that climate impacts are often triggered by the combination of different hazards that occur at the same time (e.g. wildfires due to a combination of heatwaves and droughts or a storm surge in combination with sea-level rise and tropical cyclones) or in sequence (e.g. heavy rains following a dry season, which can trigger landslides).

Temperature

Global warming has accelerated in recent decades

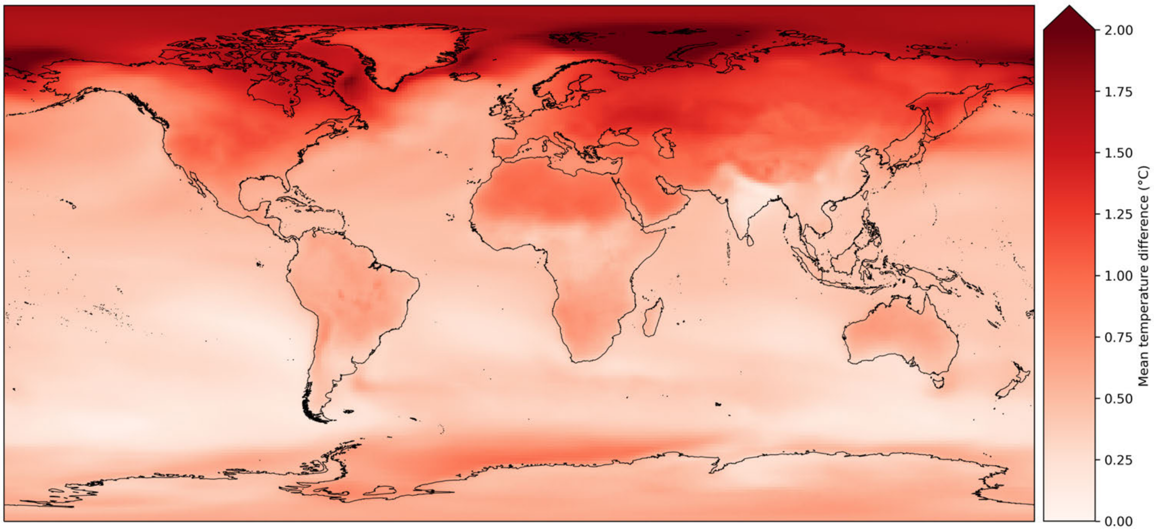
Increased global mean surface temperature, which is the average temperature at the surface of land and ocean areas, is the main impact of climate change. In addition to direct impacts such as hotter summers, rising temperatures affect precipitation, winds and sea-level rise (which are discussed in the sections below), all of which influence the frequency, intensity, extent and duration of extreme weather and climate events.

The global mean surface temperature has been increasing in all regions of the world since the end of the industrial revolution, accelerating in recent decades. Since 1970, the global mean surface temperature has increased faster than in any other 50-year period over at least the last 2 000 years. As a result, in the 2010s, the global mean surface temperature was about 1.1°C above pre-industrial levels

(1850-1900). The year 2021 was the seventh consecutive year (2015-2021) when the average global temperature was over 1°C above pre-industrial levels.

Although all regions are seeing an increase in surface temperatures**, some regions are experiencing a larger increase than others.** Global warming most strongly affects the polar regions, with the Arctic warming about twice as fast as the global average. Arid and inland regions, such as continental Asia, eastern Europe, the Arabian Peninsula and North Africa, are also warming at a faster pace. Among IEA member and association countries, the Republic of Türkiye (herafter "Türkiye"), central Europe (including the Slovak Republic, Austria, the Czech Republic and Hungary), Poland and the Baltic states recorded steeper temperature increases than the world average in the past two decades.

Change in mean surface temperature, 1961-1990 to 1995-2014



IEA. CC BY 4.0.

Source: IEA analysis based on IPCC (2021b).

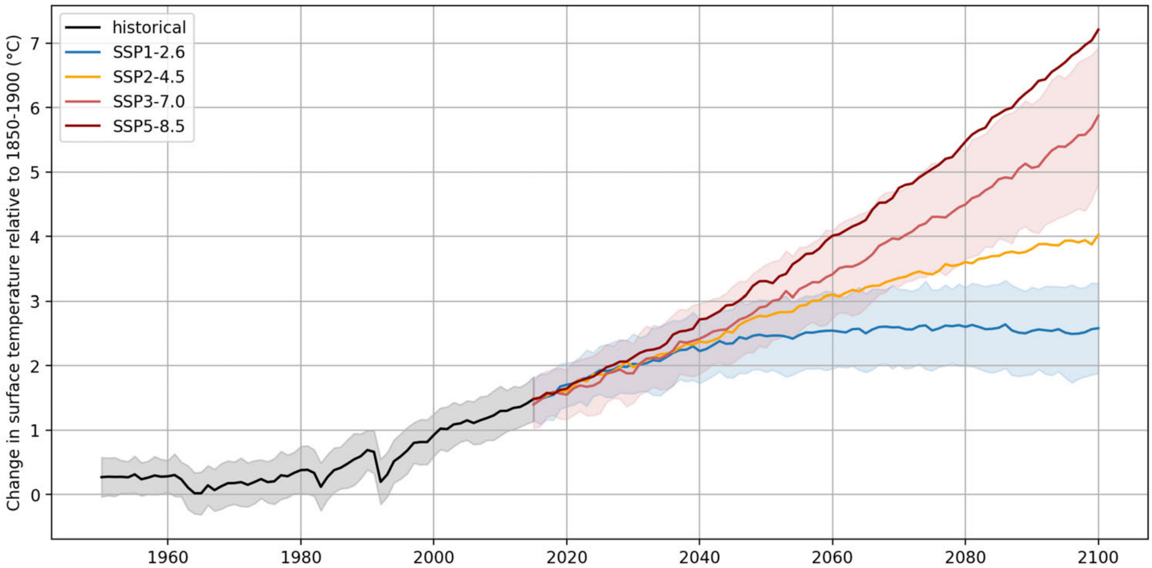
Global temperatures will keep rising until at least the mid-century

Global mean surface temperature will continue to increase until at least the mid-century in all five emissions scenarios considered in the IPCC Sixth Assessment Report. Even in the lowest-emissions scenario (SSP1-1.9), the IPCC projects that temperatures will overshoot +1.5°C at least temporarily (returning to temperatures below 1.5°C from the 2060s). In contrast, the very high-emissions scenario (SSP5-8.5) would lead to a temperature of 4.4°C above pre-industrial levels by 2100. Without immediate and deep GHG emission reductions in the coming decade, global warming of 1.5°C and 2°C by 2100 will be out of reach.

According to recent IEA analysis, the global temperature rise could be held to 1.8°C if the climate pledges made before the 2021 United Nations Climate Change Conference (COP26) are met fully and on time. If these pledges are not fully implemented and efforts remain at current levels, temperature rise could reach around 2.7°C by 2100.

There is still a possibility of increase in global temperature above 2.7°C due to carbon (and other GHG) cycle feedbacks and delayed implementation of climate actions. For example, higher mean surface temperatures will amplify permafrost thawing, which has increased over the past four decades. Depending on the scenario, the global permafrost area might decrease by 25% to 69% by 2100. As permafrost soils store a large amount of carbon and methane, permafrost thawing could release large amounts of GHGs into the atmosphere and thus accelerate global warming. This is just one example of irreversible climate impacts and potential climate tipping points – critical thresholds beyond which a small change could push fundamental parts of the Earth system to change dramatically and irreversibly.

Increase in the global mean surface temperature in each SSP scenario, relative to 1850-1900



Notes: The coloured lines indicate the mean of the CMIP6 climate models projections in global surface temperature change for the different scenarios, compared to the pre-industrial levels (1850-1900). The black line represents the simulated historical data. Shades show the standard deviation among the different models. The standard deviation is only displayed for scenarios SSP1-2.6 and SSP3-7.0 for greater clarity.

Source: IEA analysis based on IPCC (2021b).

Temperature impacts are relevant to energy

Changes in ambient temperatures directly influence energy supply and demand (see Chapter 3 and 4). In addition, the global temperature increase has a wide range of complex impacts on weather systems, including on extreme events. Three key temperature impacts with implications for energy production and use include changing seasonal length, extreme heatwaves and impacts on the hydrology of earlier snowmelt.

The continuous increase in global mean surface temperature has led to **changes in seasonal length**. On average, summers have become warmer while winters have become milder. In the northern hemisphere, the average summer length increased from 78 to 95 days between 1952 and 2011, while the lengths of winter, spring and summer decreased.[1] As global average surface temperatures continue to rise, seasonal durations are projected to change. In a high-emissions scenario, the summer in northern latitudes might last as long as six months in 2100. Even in lower-emissions scenarios, changing seasonal cycles can have serious impacts on economic activity and food production, e.g. by altering growing seasons.

Heatwaves have become longer, more frequent and more intense **in almost all regions of the world**.[2] According to the IPCC, hot temperature extremes occurred once on average every ten years in a pre-industrial climate, but now they occur three times every ten years and are intensified by more than 1.2°C.[3] In 2019, Europe experienced several record-breaking heatwaves, while North America experienced a severe heatwave as well. A few years later, in June and July 2022, much of continental Europe experienced heatwaves again, with many maximum temperatures records broken and the United Kingdom issuing the first ever Red warning for exceptional heat. That year was also among the hottest summers on record in the United States. While not likely to become more frequent, warming Arctic conditions may also lead to cold spells in some regions (see Box below).

Heatwaves will become more frequent and intense in the future. Even in the IPCC's lowest-emissions scenario (SSP1-1.9), hot temperature extremes that used to occur once in a decade in a pre-industrial climate will occur four times every ten years on average and will be 1.9°C more intense once global warming exceeds 1.5°C. Without adaptation, this could expose more than 350 million people to deadly heat stress by 2050. In the highest-emissions scenario

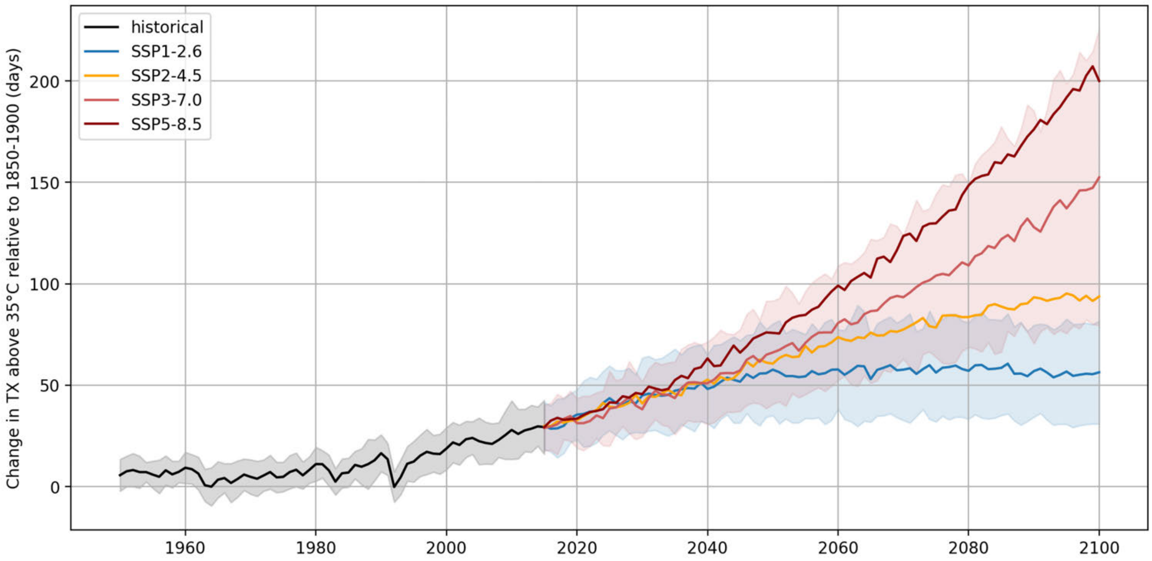
[1] The study defined the start of summer as the time when temperatures first surpassed the threshold set by the hottest 25% of days observed during the study period; the start of winter is defined as the time when temperatures dropped into the coldest 25% of the period; spring and fall are defined as the transition periods between the two other seasons.

[2] Heatwaves are defined as prolonged periods of excessive heat. Excessiveness is defined statistically in relation to historical temperatures at a given location and time of year.

[3] Hot temperature extremes are defined as the daily maximum temperatures over land that were exceeded on average once in a decade (ten-year event) during the 1850-1900 reference period.

(SSP5-8.5), heatwaves will occur nine times every ten years and will be 5°C more intense. Temperature increases will be higher in cities, given the structures and thermal inertia of buildings.

Increase in the number of days with maximum temperature above 35°C in each SSP scenario, relative to 1850-1900



Notes: The coloured lines indicate the mean of the CMIP6 climate models projections of the change in the number of days each year with maximum temperature above 35°C for the different scenarios, compared to the pre-industrial levels (1850-1900). The black line represents the simulated historical data. Shades show the standard deviation among the different models. The standard deviation is only displayed for scenarios SSP1-2.6 and SSP3-7.0 for greater clarity.
Source: IEA analysis based on IPCC (2021b).

In snow-dominated regions, global warming will lead to an earlier onset of spring snowmelt **and permafrost thawing**. Earlier onset of spring snowmelt could lead to higher peak flows in rivers in spring at the expense of summer flows. In some watersheds, this will increase the risk of river floods in spring, while it could increase the risk of drought and wildfires in the summer.

Cold spells and climate change

With the increase in global temperatures, winters are generally becoming shorter and milder, and cold spells have become less frequent and severe globally. Climate projections indicate that this trend will continue in the future.

However, even in a warming world, warming in the Arctic contributes to extreme weather events and correlates with extreme cold weather events in some parts of the world. Some scientists suggest that changes in the Arctic due to climate change are key contributors to a chain of processes which ultimately results in periods of extreme cold in northern mid-latitudes. The United States and some regions of the northern hemisphere have experienced long, intense and increasingly frequent cold spells over the past four decades. In February 2021, cold conditions affected many parts of central United States, including Oklahoma City and Dallas, which experienced the lowest recorded temperatures since 1899 and 1949, respectively. Due to the cold spells, electricity transmission was severely disrupted, with power outages affecting nearly 10 million people.

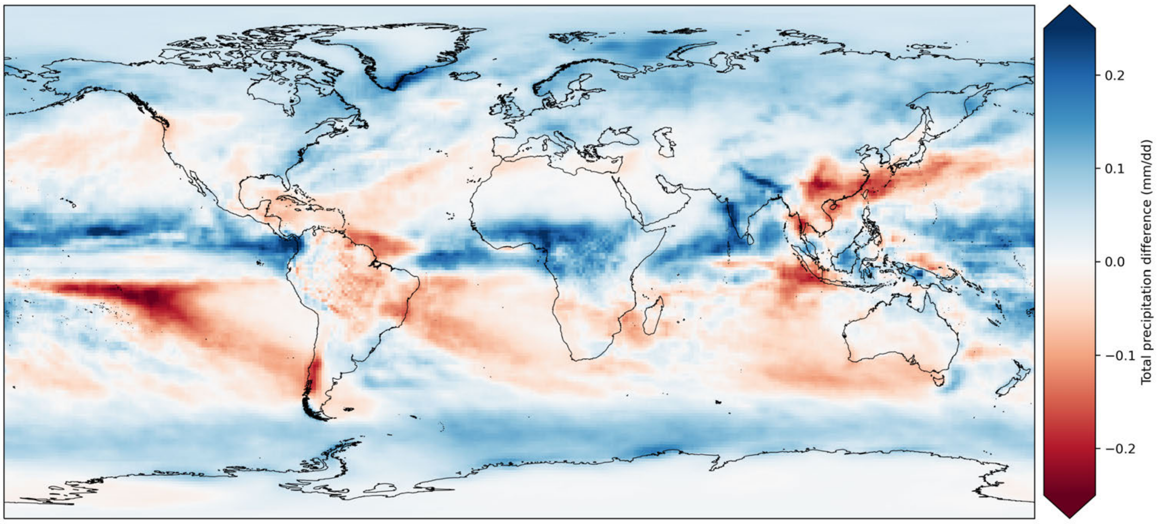
Precipitation

Changes in precipitation have widespread impacts on weather systems and will affect energy production and uses. Key impacts include increased variability and reduced predictability in overall precipitation patterns and an increase in extreme precipitation events.

Regional and temporal variabilities in precipitation have increased

Climate change has led to larger geographical and temporal variability in precipitation and has shifted precipitation patterns. Warmer air, which can store more water, has led to an increase in global annual mean precipitation since the 1950s (with a faster rate of increase since the 1980s). However, there have been notable regional differences, with some regions experiencing declining mean precipitation levels (e.g. central and southern Africa) and others seeing an increase (e.g. northern Europe). Even within a region, sub-regions often show notable spatial variations. For instance, over the past decades, mean precipitation decreased in north-eastern South America and increased in south-eastern South America. Temporal variability in precipitation has also increased significantly, leading to more frequent heavy precipitation events and droughts and affecting hydropower production in particular.

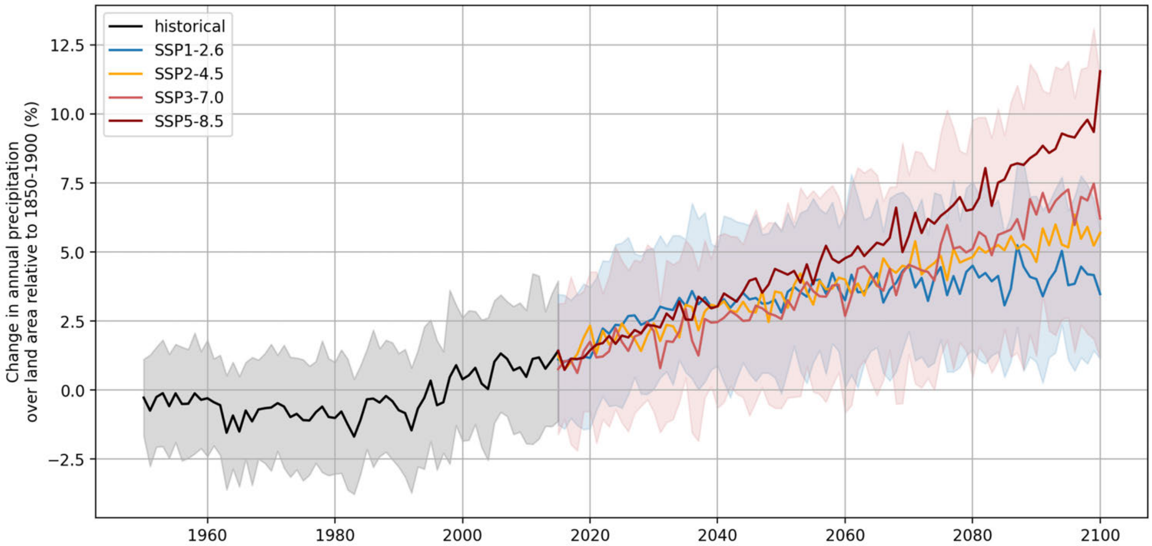
Change in total precipitation, 1961-1990 to 1995-2014



Source: IEA analysis based on IPCC (2021b).

Global annual mean precipitation will continue to increase with rising temperatures. In the lowest-emissions scenario (SSP1-1.9), global annual mean precipitation is projected to be around 3% above the recorded pre-industrial levels at the end of this century, while it would rise to around 8% in the highest-emissions scenario. Projected changes in the near term are, however, uncertain because of uncertainties in models and in forcings from natural and anthropogenic aerosols.

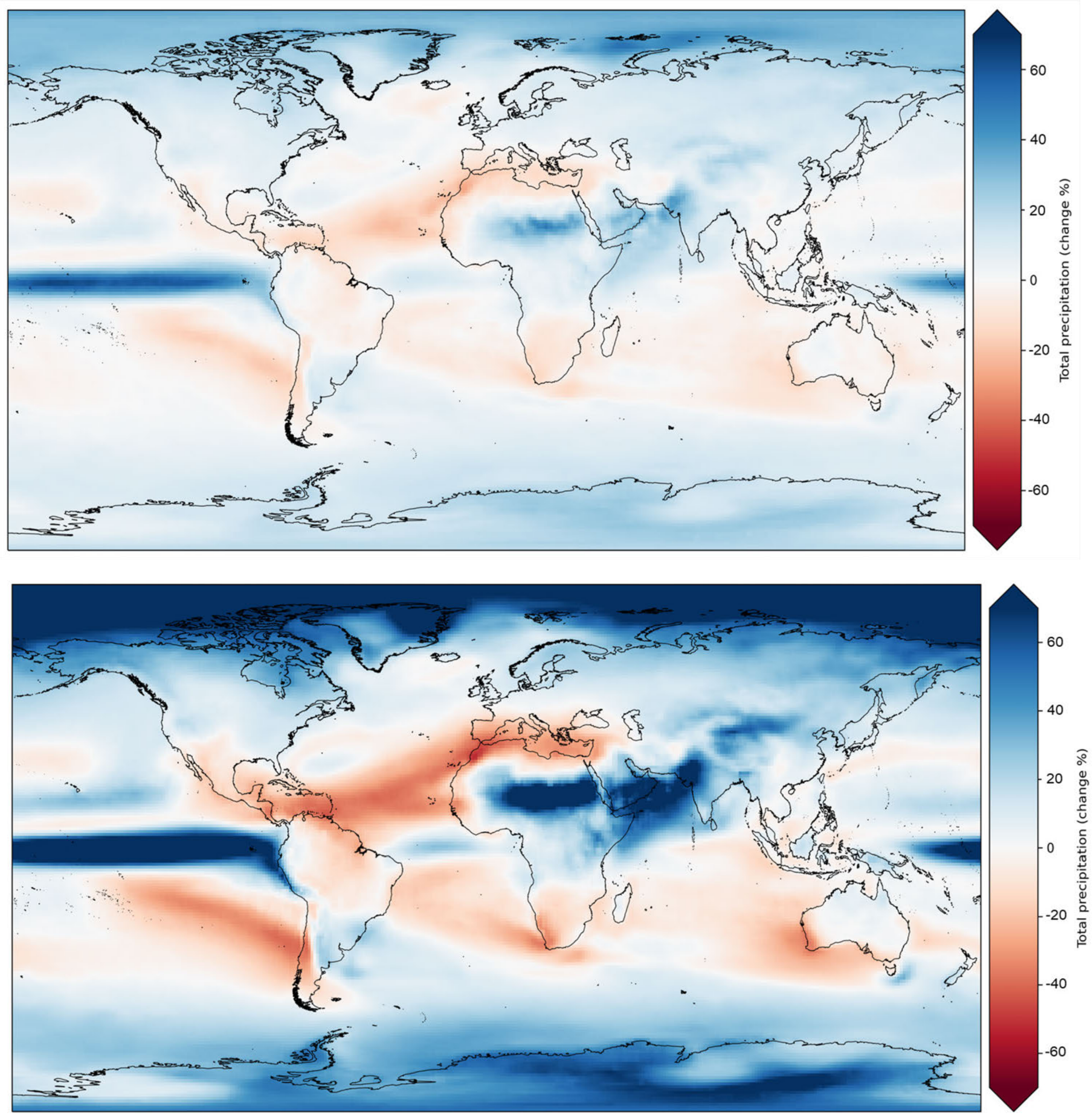
Annual mean precipitation change over land area in each SSP scenario, relative to 1850-1900



Notes: The coloured lines indicate the mean of the CMIP6 climate models projections of the change in annual total precipitation for the different scenarios, compared to the pre-industrial levels (1850-1900). The black line represents the simulated historical data. Shades show the standard deviation among the different models. The standard deviation is only displayed for scenarios SSP1-2.6 and SSP3-7.0 for greater clarity.
Sources: IPCC (2022); IEA analysis based on IPCC (2021b).

The overall increase in total precipitation does not mean that all regions will see an increase in precipitation. Changes in precipitation will show significant regional differences, with regional gaps in precipitation likely to grow under further global warming. High latitudes, the equatorial Pacific and monsoon regions (except the West Sahel) will likely see more annual precipitation, while average annual precipitation will likely decrease in several regions in Central and South America, southern Africa, the Mediterranean and Australia, for example. When downscaling projections of global models to higher-resolution regional models, results may be different for a given geographical area.

Annual mean precipitation change (%) by climate scenario (SSP1-2.6 and SSP5-8.5), relative to 1850-1900

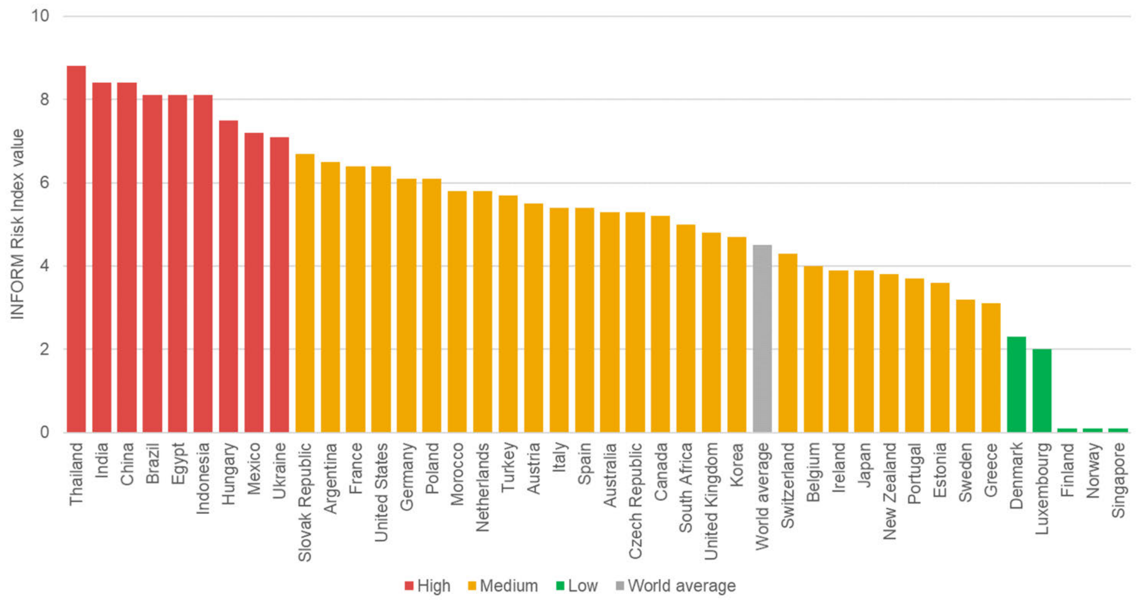


Note: Annual mean precipitation change (%) for 2081-2100 relative to 1850-1900 for scenarios SSP1-2.6 (top) and SSP5-8.5 (bottom).
Sources: IPCC (2022); IEA analysis based on IPCC (2021b).

Extreme precipitation events will continue to increase, leading to more floods and droughts

Globally, today's world is 30% more likely to experience a heavy precipitation event than it was in the pre-industrial period, and the event is on average 7% more intense. Heavy precipitation and associated flooding have become an increasing risk in several parts of the world, including in central and northern Europe, central and western North America and large parts of Asia. Nearly all IEA member and association countries (88%) have a medium or high level of flood risks. In Europe, an increasing share of annual precipitation has occurred during heavy rainfalls, leading to floods that have caused over 5 000 fatalities and cost more than EUR 20 billion between 1980 and 2020. In 2021, Europe experienced one of its most severe flooding events on record, with western Germany and eastern Belgium particularly affected.

Level of flood for IEA member and association countries, 2022



IEA. CC BY 4.0.

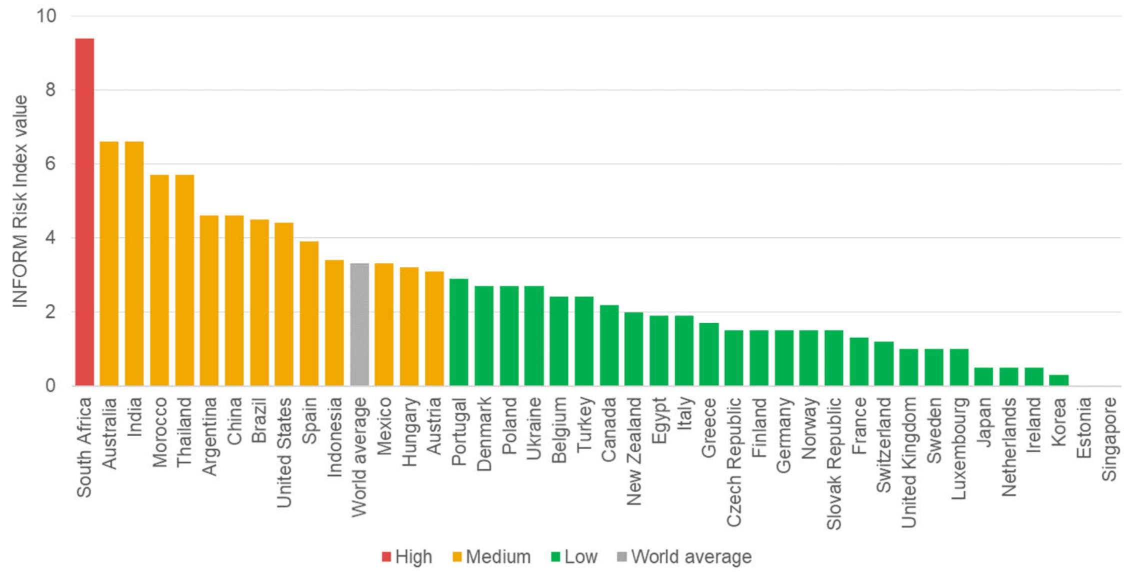
Notes: The level of climate hazard is assessed based on the indicator "Physical exposure to flood" developed by the INFORM Risk Index using the historical data of riverine floods from the United Nations Office for Disaster Risk Reduction. The minimum value is given 0 on the scale, while the maximum value is given 10. A detailed methodology of the indicator is described on the INFORM Risk Index page. In this report, the risk is defined as Low (0-2.99), Medium: (3-6.99) and High (7-10).
Source: European Commission (2022).

At the same time, changes in precipitation have increased the occurrence of hydrological droughts[4] in some regions (e.g. the Mediterranean, East Asia, West

[4] The IPCC Sixth Assessment Report distinguishes meteorological droughts (precipitation deficits), hydrological droughts (streamflow deficits) and agricultural and ecological droughts that result from a combined shortage of precipitation and excess evapotranspiration.

Africa and southern Australia) and agricultural and ecological droughts in a broader area (e.g. western and central Europe, a large part of Africa, the western part of the United States and Central Asia). Overall, the percentage of the planet affected by drought has more than doubled in the last 40 years, and half of the world's population currently experiences severe water scarcity for at least some part of the year. Nearly 35% of IEA member and association countries are estimated to have a medium to high risk of droughts. In Chile, long-term drought has persisted for over a decade.

Level of drought for IEA member and association countries, 2022



Notes: The level of climate hazard is assessed based on the indicator "Droughts probability and historical impact" developed by the INFORM Risk Index using the historical data from the Food and Agriculture Organization, the Centre for Research on the Epidemiology of Disasters and the EM-DAT database. The minimum value is given 0 on the scale, while the maximum value is given 10. A detailed methodology of the indicator is described on the INFORM Risk Index page. In this report, the risk is defined as Low (0-2.99), Medium (3-6.99) and High (7-10).

Source: European Commission (2022).

Heavy precipitation events and associated floods are projected to intensify and become more frequent in most regions in Europe, North America, Africa and Asia. The intensity and frequency of heavy precipitation events will increase with every additional degree of global warming, which, combined with soil artificialisation and waterproofing due to human activities, will increase the risk and societal costs of local flooding. For example, global warming of 3°C (as projected in SSP2-4.5) could double the risk of flooding, compared to the very low-emissions scenario (SSP1-1.9), and increase associated GDP losses by 20% to 80%. In Europe, global warming above 3°C could cause economic losses in the order of EUR 50 billion per year due to river flooding (more than six times the losses occurring today), while nearly three times as many people would be exposed. Limiting global warming to 1.5°C would halve the economic losses and population exposure to river flooding relative to unmitigated climate change.

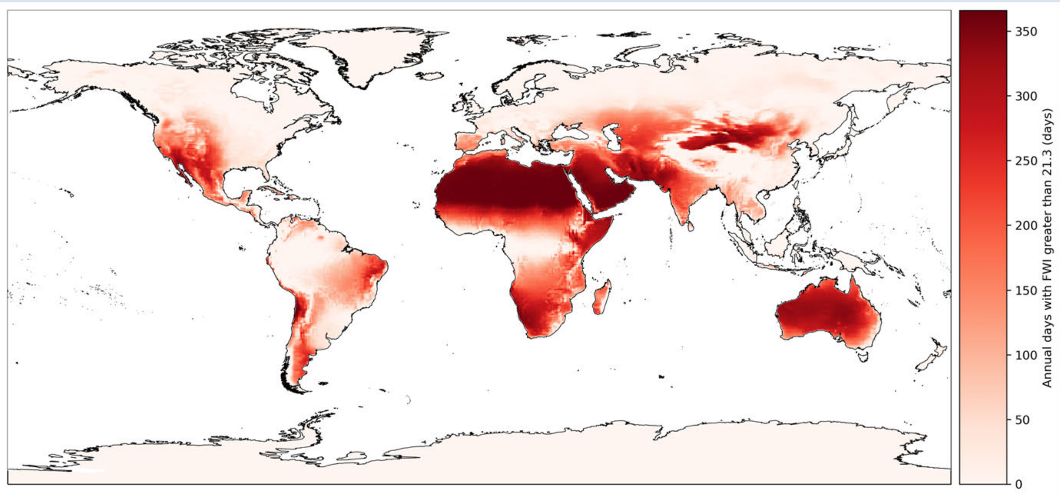
Droughts are also projected to become more frequent and/or severe in some regions with each additional degree of global warming, affecting energy generation and increasing risks of water scarcity. In the Mediterranean, western North America, southern Africa and southern Australia, hydrological droughts will become more frequent. Globally, each additional degree of global warming increases by 75% the probability of occurrence of severe drought, which occurred once per decade in pre-industrial times.

Some regions, such as western and central Europe and east southern Africa, could see an increase in both floods and droughts in the coming decades, depending on the season. The increasing seasonal gap in precipitation will require some regions to adapt to both extremes.

Wildfires: Cross-cutting issue of temperature, precipitation and wind

The combination of rising temperature, aridity and wind can lead to an increase in fire weather, which refers to weather conditions conducive to triggering and sustaining wildfires. In particular, when droughts overlap with heatwaves, the risk of wildfires increases. For example, the exceptional heatwaves that affected western North America in mid-2021, coupled with extreme drought, triggered wildfires that lasted for months. Similarly, drought and exceptional heat prompted wildfires in numerous European countries in June and July 2022. If climate change is not mitigated, wildfires are likely to become an increasing threat, with longer duration and higher frequency, intensity and spread rate.

Global 20-year average of fire danger days with the fire weather index greater than 21.3, 2001-2021



IEA. CC BY 4.0.

Source: Copernicus Climate Change Service (2022).

Wind

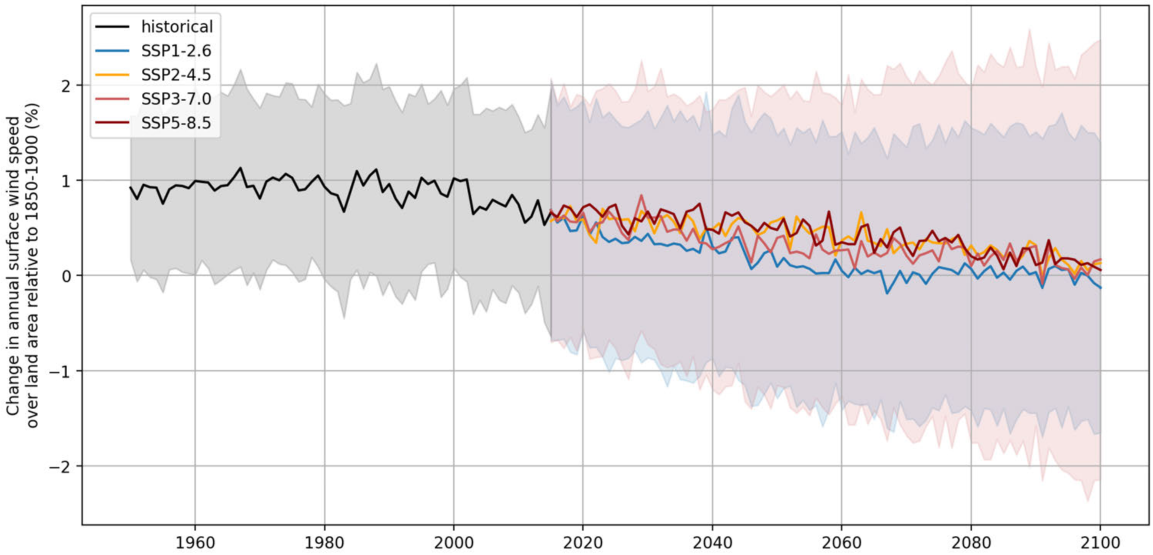
Global wind speeds are largely determined by the Earth's rotation and the temperature differential between the equator and the polar regions. Faster warming of the polar regions decreases the temperature differential between the poles and the equatorial region, weakening the wind speeds in most parts of North America and Eurasia. On a regional and local scale, winds are also strongly influenced by land use, relief and coastlines (the mere presence of a town can modify a storm's characteristics). Local disturbances can propagate to larger scales, creating strong variability. Changes in average surface wind speeds and increasing intensity of cyclones and storms due to climate change and other factors could affect energy systems.

Mean surface wind speeds are declining in North America and Eurasia

In general, mean surface wind speeds have decreased **over most land areas** with good observational coverage since the 1970s with weakening of the westerlies.[5] There are considerable uncertainties in the projection of wind patterns. Although changes in wind speed might not be significant with future climate change, wind speeds are expected to keep decreasing in some parts of the world, potentially reducing wind power generation (e.g. over a large part of Eurasia and western North America). However, some equatorial regions, such as the Amazon and West Africa, are expected to see increasing mean surface wind speeds. In addition, interannual and interdecadal fluctuations in wind speed can be significant.

[5] The westerlies are global mid-latitude winds from west to east (between 30 and 60 degrees north and south). They have an important role in the climate system, carrying the warm equatorial waters and winds to the western coasts of continents. The westerlies are more stable in the south because there are fewer continents to disturb the winds.

Change in annual surface wind speeds over land area in each SSP scenario, relative to 1850-1900



Notes: The coloured lines indicate the mean of the CMIP6 climate models projections in surface wind speed change over land area for the different scenarios, compared to the pre-industrial levels (1850-1900). The black line represents the simulated historical data. Shades show the standard deviation among the different models. The standard deviation is only displayed for scenarios SSP1-2.6 and SSP3-7.0 for greater clarity.
Source: IEA analysis based on IPCC (2021b).

Tropical cyclones and storms will become more intense

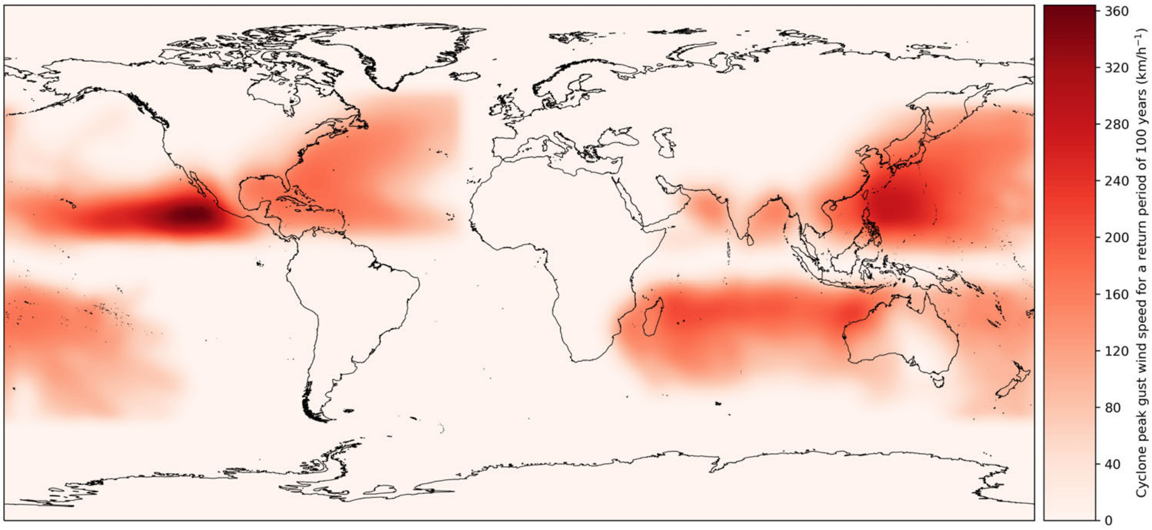
Despite the decline of mean surface wind speeds, **recent research suggests that the proportion of** intense tropical cyclones[6] **(Category 3-5) has increased,** despite a decrease in the number of tropical cyclones since pre-industrial times. Among IEA member and association countries, Japan, Korea, the People's Republic of China ("China" hereafter), the United States, Mexico, India and Australia are the most exposed to tropical cyclones. In 2021, the global tropical cyclone activity was close to average (1981-2010), but several regions experienced more intense cyclones than ever before. In the North Atlantic, Category 4 Cyclone Ida made the strongest landfall ever recorded in the state of Louisiana in August 2021, with damages leading to the death of 115 people and economic losses of at least USD 75 billion. In the southern hemisphere, Cyclone Seroja made the strongest landfall in western Australia since the 1950s, causing flooding and landslides resulting in the death of 226 people. In 2022, Hurricane Ian became one of the most powerful storms to strike the United States in

[6] Tropical cyclones are defined as cyclonic-scale storms that originate over tropical oceans. They are distinguished from tropical storms which have lower wind speeds. Extratropical cyclones are cyclonic-scale storms that are not tropical cyclones.

decades, causing widespread destruction and flooding, and knocking out power for more than 5 million households.

Even though some regions are not exposed to tropical cyclones, they often face severe windstorms. For instance, various parts of Europe experienced several severe storms, as seen in Belgium, France and Poland in June 2021. Storms were the costliest natural hazard in Europe in terms of insured losses.

Cyclone peak gust wind speed for a return period of 100 years



Note: The cyclone peak gust wind speed for a return period of 100 years is based on past observations. An 80 km/h threshold is applied to the dataset.
Source: IEA analysis based on UNDRR (2015).

The **proportion of intense cyclones is expected to increase**, although the total global number of tropical cyclones may decrease or remain unchanged. Globally, the IPCC projects that, in the late 21st century, the proportion of intense tropical cyclones will increase to 10% in a low-emissions scenario (SSP1-1.9) and to more than 30% in a high-emissions scenario (SSP5-8.5). Peak wind speeds and heavy precipitation associated with intense tropical cyclones are projected to increase at the global scale with rising global mean surface temperature.

In addition to tropical cyclones, severe storms are projected to increase in Europe and North America. Severe storms could increase heavy rainfall and flooding, while in areas where aridity increases, sand and dust storms could slightly increase.

Sea level

Rising temperatures have led to an increase in global mean sea levels, causing risks to millions of people and to infrastructure situated near coastlines. The thermal expansion of the oceans explained 50% of sea-level rise during 1971-2018, while ice loss from glaciers contributed 22%, ice loss from ice sheets 20% and changes in land water storage 8%. Since the early 2000s, however, ice loss was the dominant contributor to global sea-level rise. The largest loss of glacier ice occurred in Alaska, followed by the Andean glaciers and the Asian high mountain glaciers. Key hazards stemming from sea-level rise include damage to coastal infrastructure and the potential threat to water supply with saltwater intrusion.

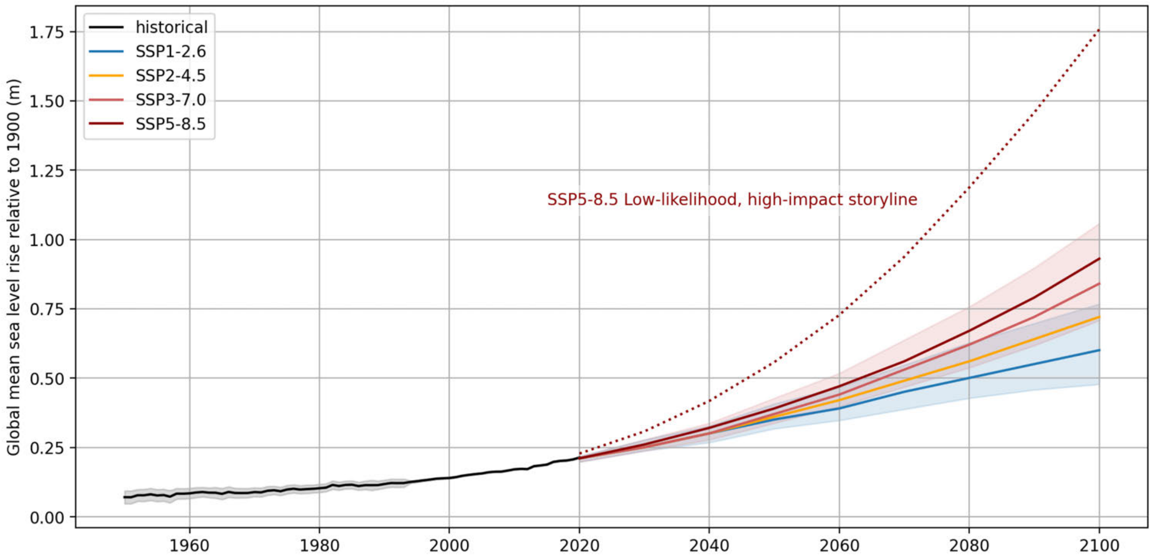
Sea levels have risen by 20 cm since 1900 at the fastest rate in the last 3 000 years

Since 1900, the sea level rose by about 0.2 m, faster than over any preceding century in at least the last 3 000 years. Sea-level rise accelerated over time, increasing from 1.3 mm per year on average in 1901-1971 to 1.9 mm in 1971-2006 and 3.7 mm in 2006-2018. In 2021, the global mean sea level reached a new record high. Regional patterns of sea level change are dominated by local changes in ocean heat content and salinity. The western tropical Pacific and the southwestern Indian ocean, for example, experience a substantially faster rate of sea-level rise than the global mean.

Sea levels will continue to rise over the 21st century. As oceans are slow to respond to higher surface temperatures, ocean warming and the associated thermal expansion will continue due to accumulated GHG emissions, irrespective of future GHG emission levels and global surface temperatures. Because of its high inertia, sea-level rise will occur for several millennia and can be seen as an irreversible consequence of climate change. Mountain and polar glaciers will continue to melt for decades or centuries, and the Greenland and Antarctic ice sheets will continue to lose mass, leading to further sea-level rise.

In its low-emissions scenario (SSP1-1.9), the IPCC projects the sea level in 2100 to be 0.28 m to 0.55 m above 1995-2014 levels. In the highest-emissions scenario (SSP5-8.5), the range increases to 0.63 m to 1.01 m. The IPCC also considers a low-likelihood, high-impact scenario assuming instabilities of the Greenland and Antarctic ice sheets, which could lead to a more than 1.5 m sea-level rise by the end of the century, constituting a major risk to human systems.

Change in global mean sea level in each SSP scenario, relative to 1900



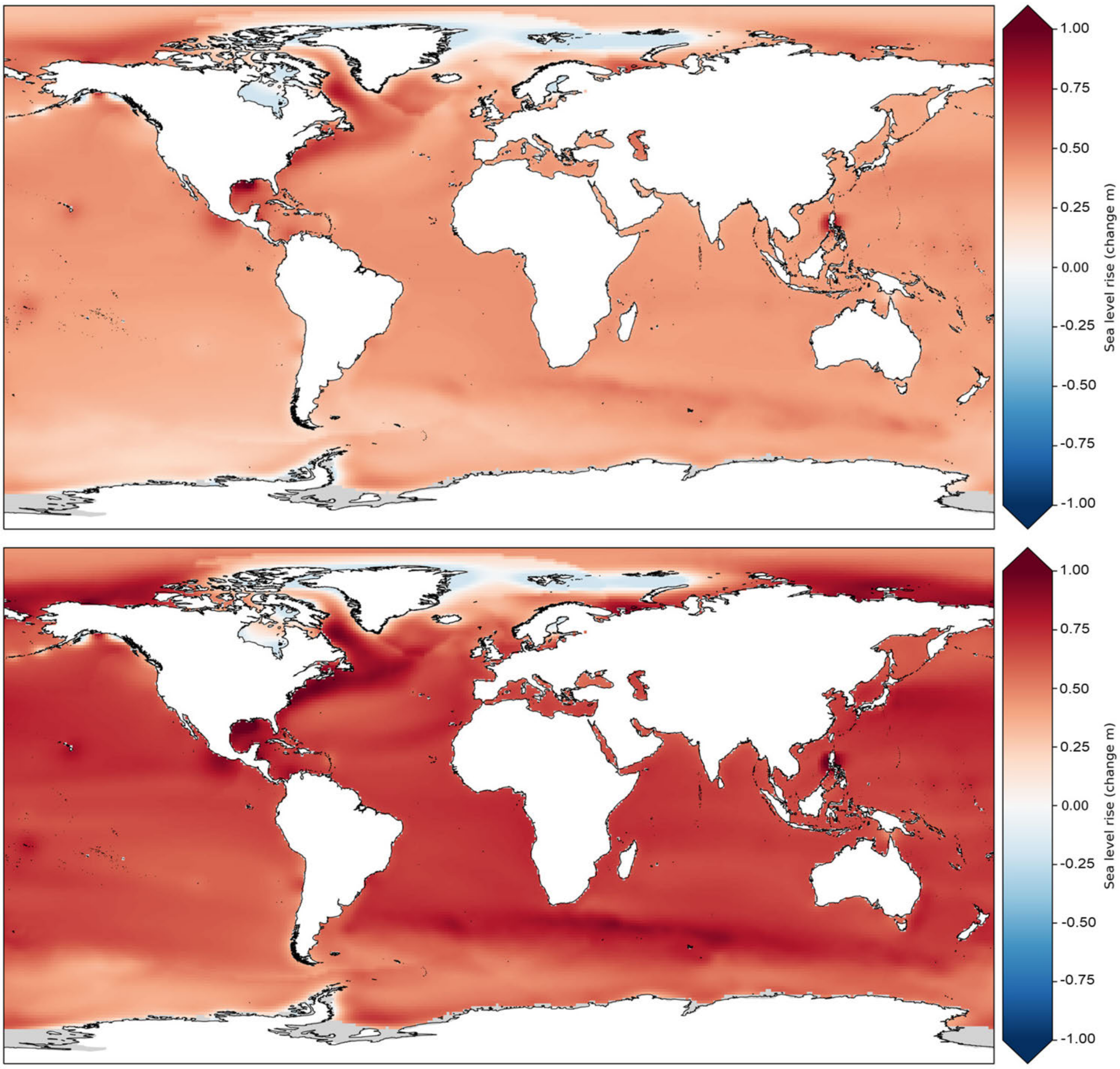
Notes: The coloured lines indicate the mean of the CMIP6 climate models projections in global mean sea level for the different scenarios, compared to the 1900 level. The black line represents the observed historical data based on tide gauges and altimetric satellites. Shades show the likely range of the observation and projection. The likely range, based on the IPCC definition, corresponds to a 17-83% probability. The range is only displayed for scenarios SSP1-2.6 and SSP3-7.0 for greater clarity. The decrease in the uncertainty range for the observed sea level is due to the development and use of altimetric satellites since January 1993.

Source: IEA analysis based on IPCC (2021b).

Coastal climatic hazards will continue to increase

Sea-level rise will affect almost all coastal regions of the world. In 2010, 11% of the world's population (about 760 million people) lived in coastal areas of below 10 m in elevation. This number is projected to exceed 1 billion by 2050. Besides being an existential threat for nearly all low-lying small islands, sea-level rise poses a serious threat to the entire world's coasts, except some sparsely populated areas where land is rising faster than sea level (within the Arctic Circle and parts of Canada and Scandinavia). Coastal infrastructure is particularly threatened by the combination of sea-level rise and increasing risks of storms and tropical cyclones (see Box below), which can occur even with sea-level rise consistent with relatively low GHG emissions scenarios. In addition, rising sea levels can lead to salinisation of soils and increased intrusion of seawater in freshwater aquifers, which in turn can increase water stress and competition for freshwater resources.

Sea-level rise by climate scenario (SSP1-2.6 and SSP5-8.5), relative to 1995-2014



Note: Sea-level rise (in metres) for 2081-2100 relative to 1995-2014 for scenarios SSP1-2.6 (top) and SSP5-8.5 (bottom).
Sources: IPCC (2022); IEA analysis based on IPCC (2021b).

Coastal flooding and storm surges: Cross-cutting issue of wind and sea-level rise

Coupled with the increasing intensity of storms and tropical cyclones, rising sea levels are likely to increase the frequency and severity of coastal erosion and flooding, with storm surges and strong waves. In the short to mid term (2021-2040), sea level rise accelerates coastal erosion along most sandy coasts. In the mid to long term (2040-2100), sea-level rise greatly amplifies the risks arising from coastal climatic hazards. The 100-year coastal flood risk increases by 20% (compared to today) when sea level rises by 0.15 m, by 40% for a rise of 0.75 m and by 60% for a rise of 1.4 m. On top of the rising sea levels, stronger winds could cause higher waves, increasing the risks of coastal flooding and erosion. These changes could add stresses to infrastructure in coastal regions, especially in the southern hemisphere and north Atlantic. In Europe, storm surge levels are projected to increase along the northern European Atlantic coastline. The number of people affected by sea-level rise and flooding from storm surges will likely increase in many regions. In India, for example, the population exposure to a storm surge of the scale of Cyclone Amphan (which hit the Bay of Bengal in May 2020) will increase by 50% to 200%, depending on the scenario.

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Chapter 3. Climate change impacts on energy supply

Fuels and critical minerals

Climate change impacts can affect the extraction, processing and transport of fuels and minerals essential to energy production and use, industry and agriculture. Temperature rise exacerbates the frequency and magnitude of wildfires that can damage oil and gas production and affect production sites in Arctic regions due to ice melting and permafrost thawing. Heatwaves could add stress to hydrogen liquefaction, which requires low temperatures, and to fuel pipelines, potentially leading to their expansion and increasing the risk of rupture. Precipitation-related hazards like floods and droughts are especially problematic for shale resources, coal mining, minerals extraction, biofuel production and river transport. Tropical cyclones, coupled with sea-level rise, could be a risk to coastal oil and gas production and transport facilities due to storm surge, coastal flooding and erosion.

The magnitude of climate change impacts on fuels and minerals is closely linked to climate pathways. If GHG emissions are reduced, the impacts can be limited to certain areas, e.g. tropical cyclones and wildfires for refineries, and heavy precipitation and associated floods for coal and nickel mines. If GHG emissions are not mitigated, climate change impacts can be extended further, adding concerns such as severe water shortage for mines and sea-level rise and rapid permafrost melting for refineries.

Comparison of climate change risks to fuels and minerals in the low-emissions and high-emissions scenarios, 2080-2100

Notes: These tables show climate change risks to refineries and mines at a global scale. SSP1-2.6 and SSP5-8.5 are used for the low-emissions and high-emissions scenarios, respectively. The levels of climate risks are divided into five categories, from dark green for low risks to red for high risks. Grey dots indicate no information. The levels are determined based on the combination of hazard, exposure and vulnerability. Hazard and exposure are calculated through geographic information system (GIS) analysis, while vulnerability is determined through qualitative research. For temperature, the level of exposure of refineries and mines to the increase in mean temperature and the number of days with maximum temperature above 35°C data is used. For precipitation (dry), the level of exposure of refineries and mines to a drier climate based on the Standard Precipitation Index and the number of consecutive dry days is used. For precipitation (wet), the level of exposure of refineries and mines to a wetter climate based on the Standard Precipitation Index and one-day maximum precipitation is used. For sea level, the level of exposure of refineries and mines to the projected rise of sea level is used. For wind, the level of exposure of refineries and mines to tropical cyclones based on the analysis of historical trends of tropical cyclones and major tropical cyclones (above Category 3) is used. For wildfires, the level of exposure of refineries and mines to wildfires based on the analysis of historical trends of fire weather is used.

Oil and natural gas

In 2021, oil and natural gas accounted for around 29% and 23% of total energy supply, respectively. In the IEA scenario examining the effects of current policy settings and ambitions (STEPS), oil demand reaches a high point in the mid-2030s at 103 million barrels per day (mb/d) and then declines very gently to 2050. Total oil production in the United States sees the biggest increase, rising by just under 4 mb/d to 2030. Concerning gas, demand rises by less than 5% between 2021 and 2030 and then remains flat at around 4 400 billion cubic metre (bcm) through to 2050. The shares of oil and natural gas in total energy supply remain stable until 2030, accounting for 29% and 22%, respectively, and then decline slightly to 27% and 20% in 2050.

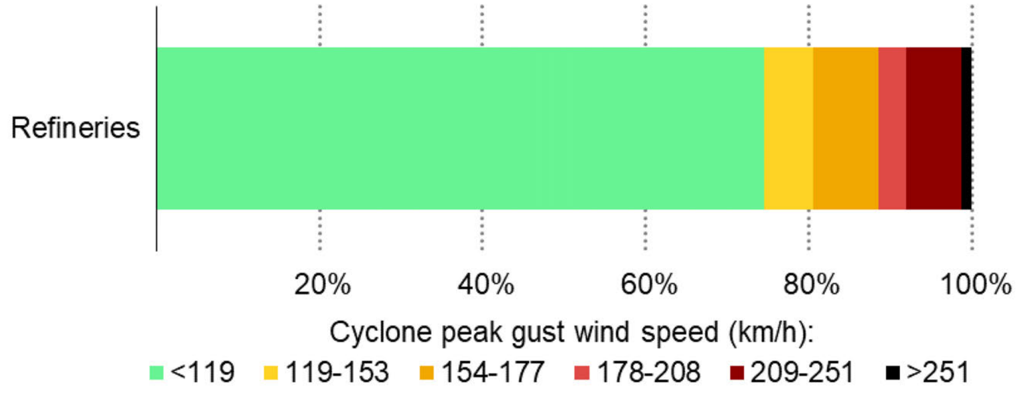
In a scenario to meet net zero emissions by the mid-21st century (NZE), the shares of oil and natural gas in total energy supply decline significantly both to 8% in 2050. The rapid drop in the roles of oil and natural gas means that no new oil and natural gas fields are required beyond those that have already been approved for development as of 2021. However, in the near term, oil and natural gas would account for around 45% of global energy supply by 2030.

While almost all regions consume oil and natural gas, production is concentrated in a limited number of countries. For oil, 15 countries account for more than 75% of the world's oil production and hold roughly 93% of its reserves, while for gas, 17 countries account for over three-quarters of gas production and hold around 85% of gas reserves. The major oil and gas producers are concentrated in North America (the United States and Canada), the Middle East (Saudi Arabia, Iran and Qatar), the Russian Federation ("Russia" hereafter) and China. These are also the countries which are expected to lead oil and natural gas production in the coming years. For instance, half of the projected growth in natural gas production in the next five years will come from North America and the Middle East. Due to the geographical concentration of oil and natural gas resources, a single critical climate hazard in a major supplier can threaten energy security.

Tropical cyclones, coupled with sea-level rise, can threaten coastal oil and natural gas production sites

Although not all major oil and gas production sites are at risk of destructive cyclones, currently, over 25% of refineries are exposed to tropical cyclones, and over 10% are estimated to be under threat of major tropical cyclones above Category 3, particularly in the United States and Australia. A destructive cyclone that hits major production areas can have a negative impact on the global oil market and related supply chains. This has been seen in the case of hurricanes that hit the Gulf of Mexico.

Share of refineries capacity exposed to tropical cyclones



Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.
Sources: IEA analysis based on S&P Global (2021a) and UNDRR (2015).

The Gulf of Mexico is the most prominent energy producing and processing region in the United States, accounting for 47% of total petroleum refining capacity and 51% of its natural gas processing capacity. In August 2021, Hurricane Ida shut down around 96% of crude oil production and 94% of natural gas production in the region. The strong winds, torrential rains and associated landfall of the hurricane prompted the evacuation of 288 offshore oil platforms and curtailed production from at least nine refineries. As a result, US crude oil production fell by 1.5 mb/d (around 14% of total daily production),[7] and exports fell by 698 000 b/d on the week of Hurricane Ida, raising oil prices to their highest levels in three years, with an increase of 10% in the following month alone.

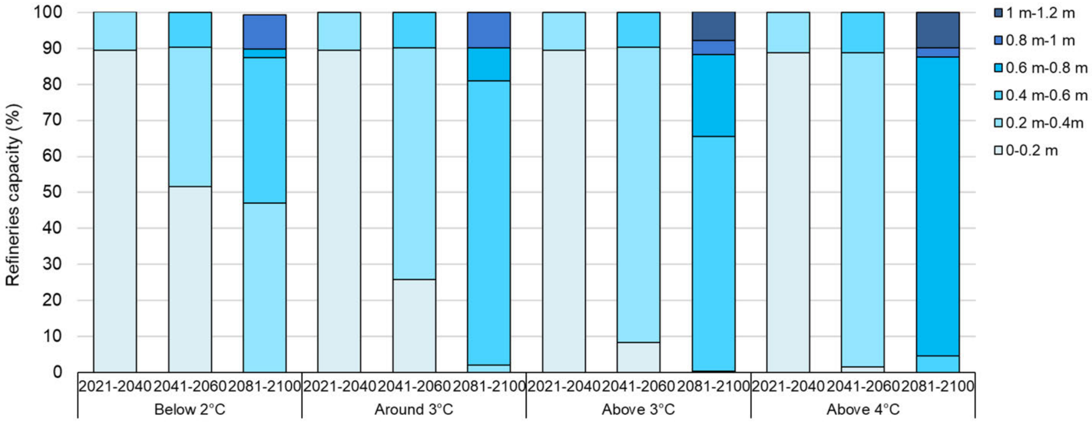
Similar disruptions in oil and gas supply from the Gulf of Mexico have occurred before, with adverse impacts on global fuel supply during Hurricane Harvey in 2017 (which reduced the country's crude oil refining capacity and production for over one month) and Hurricane Katrina in 2005 (shutting down about 30% of US refining capacity and disturbing oil production for up to two months). Given that the Gulf Coast is projected to see a greater number of the most intense tropical cyclones with higher rainfall potential, the destructive impacts of tropical cyclones may grow.

[7] As of EIA estimates of crude oil production in the United States for 2021 (11.254 million b/d).

The destructive impacts of tropical cyclones on pipelines and ports can also disrupt oil and gas supply. In Puerto Rico following Hurricanes Irma and Maria, port closures resulted in the loss of an estimated 1.2 mb of petroleum per day for 11 days, which directly affected the major generation stations that relied exclusively on imported fuel. Similar closures occurred in Texas in 2017, as well as in New Jersey and New York during Hurricane Sandy. Also in 2021, Hurricane Ida affected several oil and gas pipelines in Louisiana and caused widespread power outages. In the two weeks after Ida, the National Oceanic and Atmospheric Administration issued a total of 55 spill reports, demonstrating that the concentration of pipelines, platforms and wells in the area have become increasingly vulnerable to tropical cyclones. A 2021 report released by the US Government Accountability Office found that the roughly 14 000 km of active oil and gas pipelines were not being sufficiently monitored against extreme weather events.

Refineries and liquified natural gas (LNG) plants in low-lying coastal areas may experience greater risk from storm surges and coastal floods due to sea-level rise, coupled with more intense tropical cyclones. As of today, around one-third of refineries are located in low-elevation areas of below 10 m over the sea surface. More than half of them are projected to be exposed to over 0.4 m of sea-level rise in a low-emissions scenario (SSP1-2.6) in 2081-2100. In the highest-emissions scenario (SSP5-8.5), around 95% of refineries would be subject to over 0.6 m rise; among them, 10% could see over 1 m of sea-level rise.

Low-elevation refineries capacity exposed to sea-level rise by climate scenario, relative to 1995-2014



Note: The graph shows the exposure to sea-level rise of refineries located in low-elevation areas (i.e. located at a level below 10 m), representing 34% of the total refining capacity, which is equivalent to 34 825 mb/d.
Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

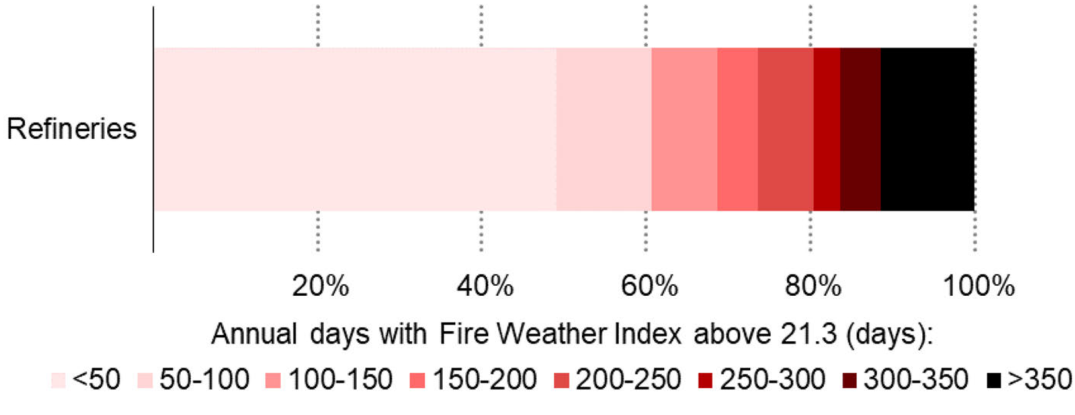
The Gulf of Mexico is also exposed to sea-level rise, with more than 18 000 km^2 of the Gulf Coast in low-lying areas of below 1.5 m in elevation. Rising sea levels could threaten refineries and other coastal energy infrastructure (e.g. transport terminals, transmission hubs, pipelines and storage facilities). The Gulf Coast is likely to see a sea-level rise of 0.35 m to 0.45 m in the next three decades, and major flooding is expected to occur five times as often in 2050 as it does today.

Storm surges could also increase in the Gulf Coast with the intensification of tropical cyclones and rising sea levels. According to a United States Department of Energy analysis, petroleum infrastructure facilities (refineries, pumping facilities and Strategic Petroleum Reserves facilities) will be among the most exposed to storm surges and flooding because they are densely located in proximity to shorelines in the Gulf of Mexico.

Higher wildfire risks in a drier climate may disrupt oil supply

A drier climate could increase the probability of wildfires in certain regions, with potential disruptions in oil supply, as has been seen in western North America and southern Australia. Northern Alberta's Fort McMurray wildfire in May 2016 halted production in the oil sands and cut Canada's daily oil production by as much as 1 mb/d, roughly 25-40% of total Canadian crude oil production, and only fully recovered in August. Spatial analysis of oil fields, oil wells and wildfire zones found that 160 out of 517 California oil fields (31%) were burned by encroaching wildfires in 1998-2018, with six oil fields burned by a massive wildfire in 2017. The state's highest risk zones for wildfires are located close to and within oil and gas fields. Vast wildfires have also broken out in Siberia in Russia, causing oil drilling on some sites in east Siberia to halt completely for several days in 2019.

Refineries exposed to wildfires



Note: The Fire Weather Index (FWI) is a meteorologically-based index used worldwide to estimate fire danger. The higher the FWI, the more favourable the meteorological conditions to trigger a wildfire. The FWI can be categorised into six classes of danger: Very low danger (FWI less than 5.2), Low danger (FWI between 5.2 and 11.2), Moderate danger (FWI between 11.2 and 21.3), High danger (FWI between 21.3 and 38.0), Very high danger (FWI between 38.0 and 50) and Extreme danger (FWI greater than 50).
Sources: IEA analysis based on S&P Global (2021a) and Copernicus Emergency Management Service (2022).

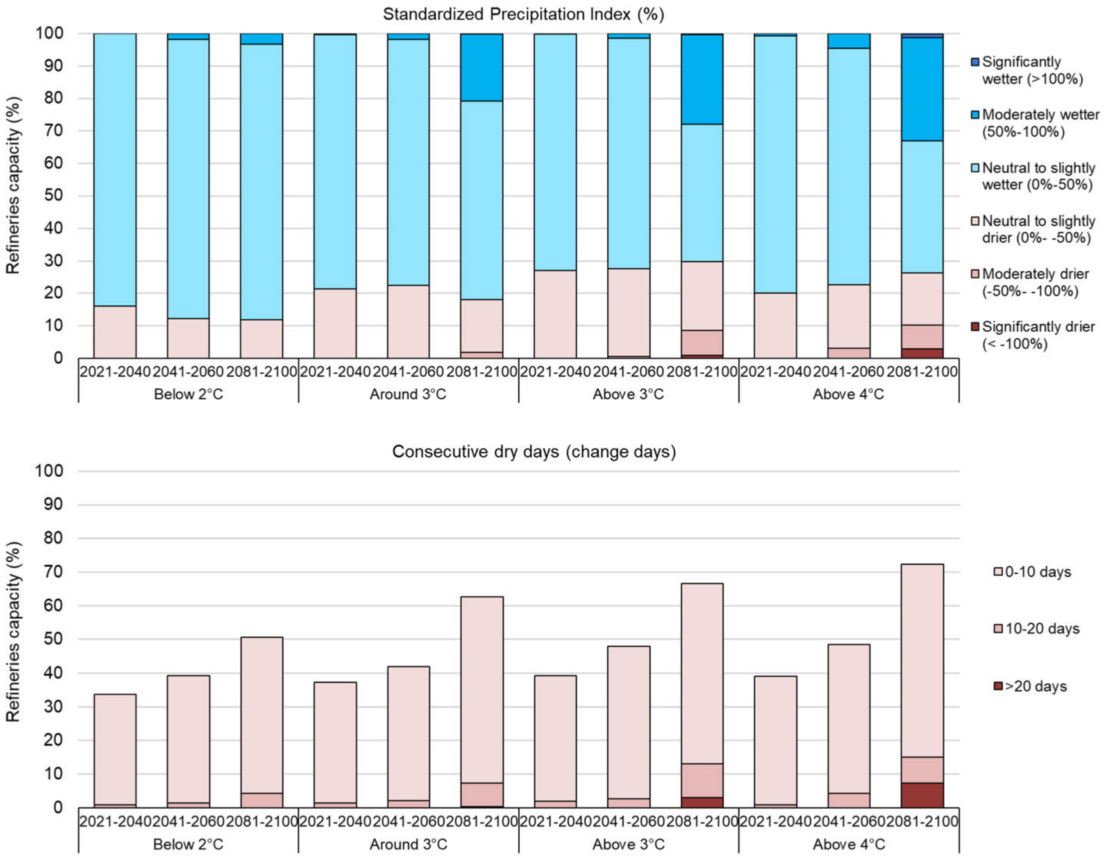
More than half of the world's refineries are currently exposed to more than 50 fire weather days per year. One-quarter of refineries are experiencing meteorological conditions favourable to wildfires for over 200 days per year. More than 10% of refineries are under the risk of wildfires during the entire year.

Climate change is likely to lengthen and intensify fire weather seasons in Australia, the United States, Canada, Russia and some parts of China. Wildfires near oil fields can reduce oil production by forcing a pre-emptive shutdown and result in a loss of stored resources. Fires at oil production sites can continue for weeks, severely disrupting oil production while releasing GHG emissions (increasing the effects of global warming, worsening droughts and thus wildfires in a self-reinforcing mechanism) and causing air pollution.

Increasing aridity and droughts in some regions could challenge shale production and refinery operations

Increasing aridity in some major production areas is another major climate-related concern. Climate projections indicate rising aridity and drought frequency in the southwestern and western United States, southern and eastern Australia and some parts of China, particularly in a high-emissions scenario. Although a majority of refineries will see no or slight changes in precipitation, 14% of refineries are projected to see a notable increase in consecutive dry days in 2080-2100 (more than ten days, compared to 1850-1900) in a high-emissions scenario (SSP5-8.5). Refineries may experience additional maintenance and operational and capital expenses to manage increased water temperatures and water availability, which could be quite high for individual facilities, especially in cases of significant and sustained drought.

Refineries exposed to increasing aridity by climate scenario

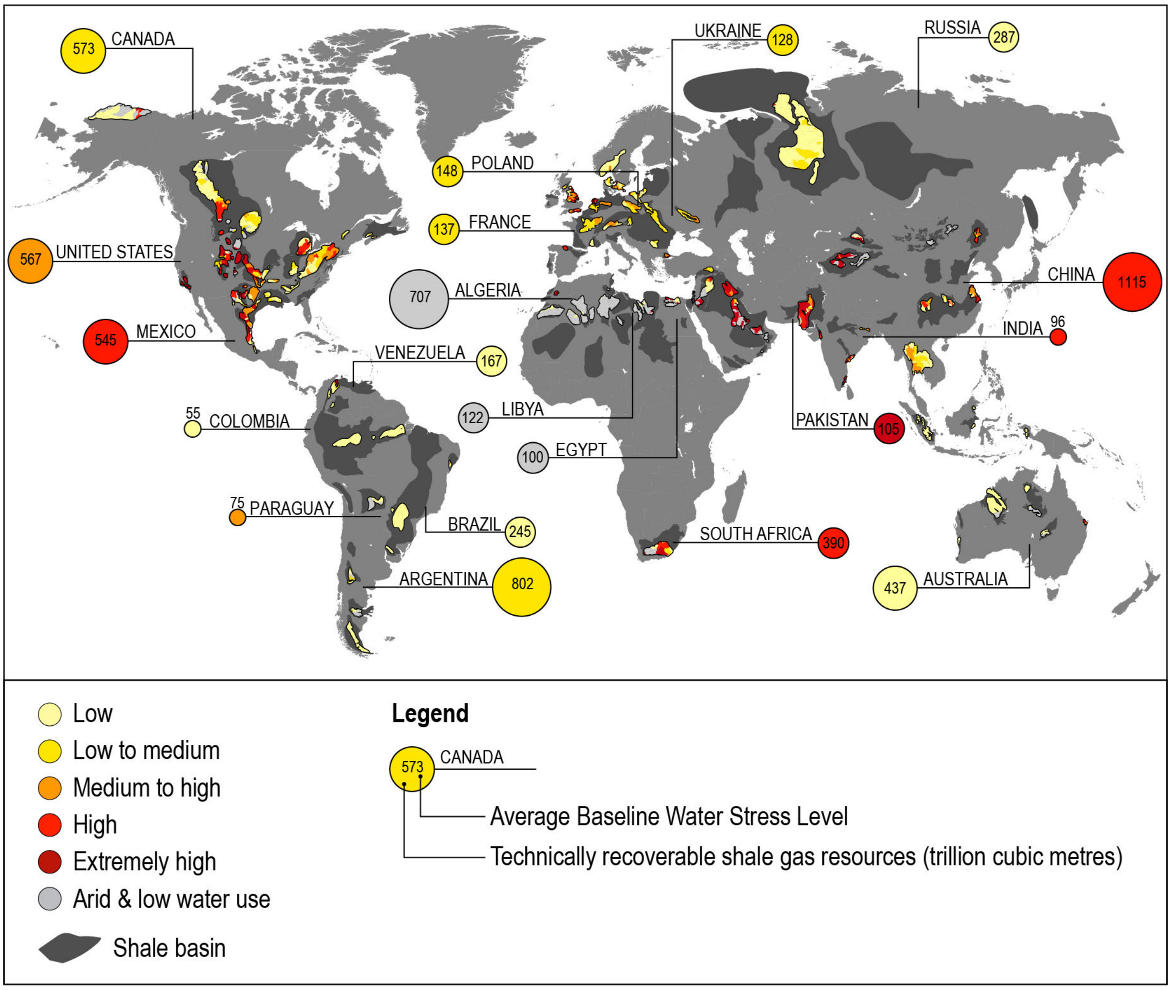


IEA. CC BY 4.0.

Note: The graphs show the share of refineries capacities for each level of standardised precipitation using the Standardized Precipitation Index and consecutive dry days, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

A potential increase in aridity and droughts in major shale reserves can negatively affect shale oil and gas production. Extracting gas or oil held within shale resources requires large amounts of water for drilling and hydraulic fracturing. Thus, limited availability of freshwater can be a major barrier for extraction and development of shale resources, depending on the particular location of the shale resources and the specific type of water resources available. The projected increase in aridity or droughts in some countries with the largest technically recoverable shale oil and gas resources (e.g. Algeria, South Africa, Mexico, China, southern Australia and the western part of the United States) may hinder shale oil and gas production. The World Resources Institute estimates that 38% of the world's shale resources are in areas that are either arid or under high to extremely high levels of water stress. If these areas face increasing competition over water withdrawals due to urbanisation, population growth or economic development, oil and gas production using hydraulic fracturing could become more expensive or subject to greater regulatory restrictions.

Location of world's shale plays, volume of technically recoverable shale gas in the 20 countries with the largest resources, and the level of baseline water stress



Notes: Twenty labelled countries have the world's largest technically recoverable shale gas resources. Circle colour indicates average water stress level across a country's shale plays. Circle size indicates overall volume of recoverable shale resources.
Source: WRI (2014).

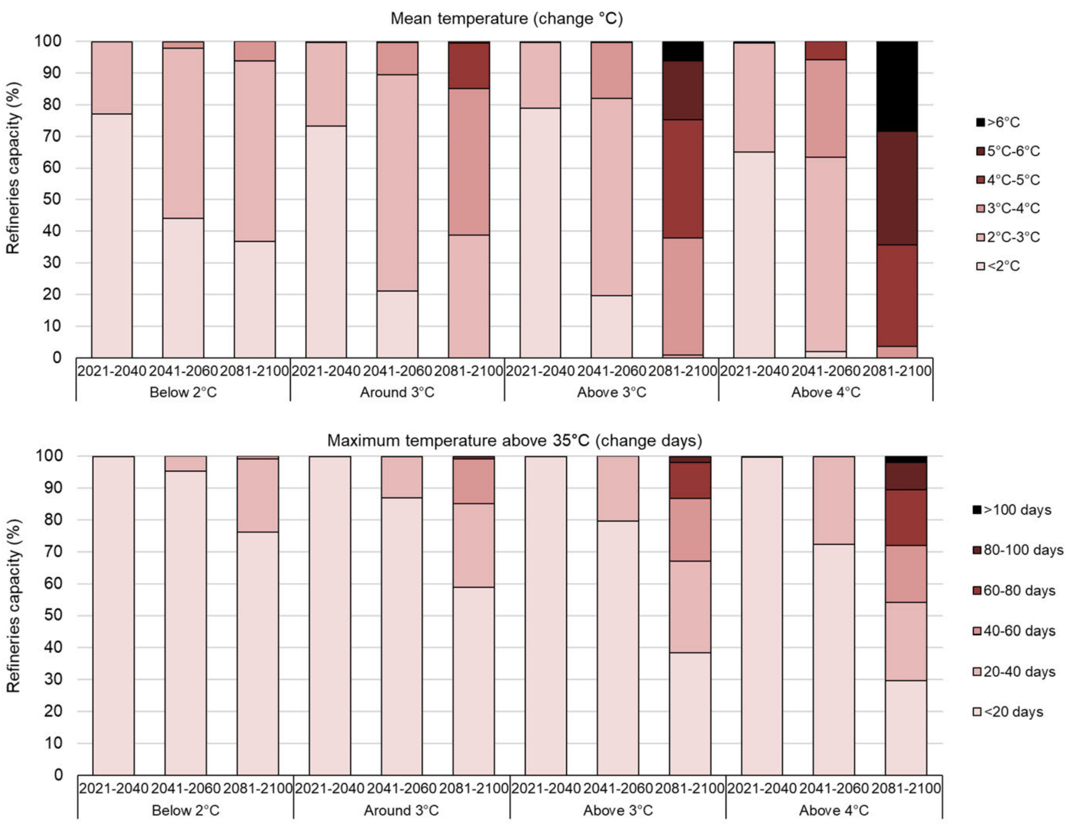
Oil and gas transport infrastructure is negatively affected by increasing temperatures

Temperature rise may influence the integrity and reliability of existing oil and gas pipelines that operate in diverse climatic conditions. Higher heat can lead to expansion in pipelines and increased risk of rupture. Increasing temperatures leading to ice and permafrost melt might threaten fossil fuel transport and storage in the Arctic region, which is heating twice as fast as the global average. Degrading permafrost may challenge oil and gas extraction and transport and have negative impacts on consumers, such as Europe. In Alaska, permafrost thaw and the subsequent ground instability is estimated to lead to USD 33 million in damages to fuel pipelines in a high-emissions scenario (Representative Concentration

Pathways [RCP] 8.5) until the end of the century. To address the issue, the Alaska Department of Natural Resources has approved the use of about 100 thermosyphons to keep the permafrost directly below the pipeline frozen and prevent further damage to the pipeline's support structure. A rupture of the pipeline would result in an oil spill in a delicate landscape, where it would be extremely difficult to clean up.

Over 60% of refineries are projected to see a temperature rise above 2°C even in a low-emissions scenario. Almost the total refineries capacity would experience a notable increase in mean temperature (above 4°C) if GHG emissions are not mitigated; 30% of refineries could see a temperature rise above 6°C, compared to the pre-industrial period, in a high-emissions scenario. Days of extreme heat will also become more frequent. Over 20% and 70% of refineries are projected to experience an increase of more than 20 days of maximum temperature above 35°C in a low-emissions and high-emissions scenario, respectively.

Refineries exposed to temperature rise and extreme heat by climate scenario



IEA. CC BY 4.0.

Note: The graphs show the share of refineries capacities for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

Coal

In 2021, coal accounted for 26% of total energy supply and was the single largest source of global carbon emissions. Over 40% of electricity and heat was generated from unabated coal. A few countries are currently leading coal production: around half of coal is produced in China, and 35% comes from India, Indonesia, Australia, the United States and Russia.

While the share of unabated coal in total energy supply declines in the STEPS to 22% in 2030 and 15% in 2050, it will remain an important energy source for several major economies over the next decades. In the NZE, the share of coal use drops significantly to 15% in 2030 and zero in 2050, while the share of coal with carbon capture, utilisation and storage (CCUS) reaches 1% in 2030 and 3% in 2050. Up to 2050, it is expected that coal production could be affected by climate change in some regions, although coal's importance should decline in the longer term.

A wetter climate might ease water stress in some coal production areas but will raise "wet coal" issues

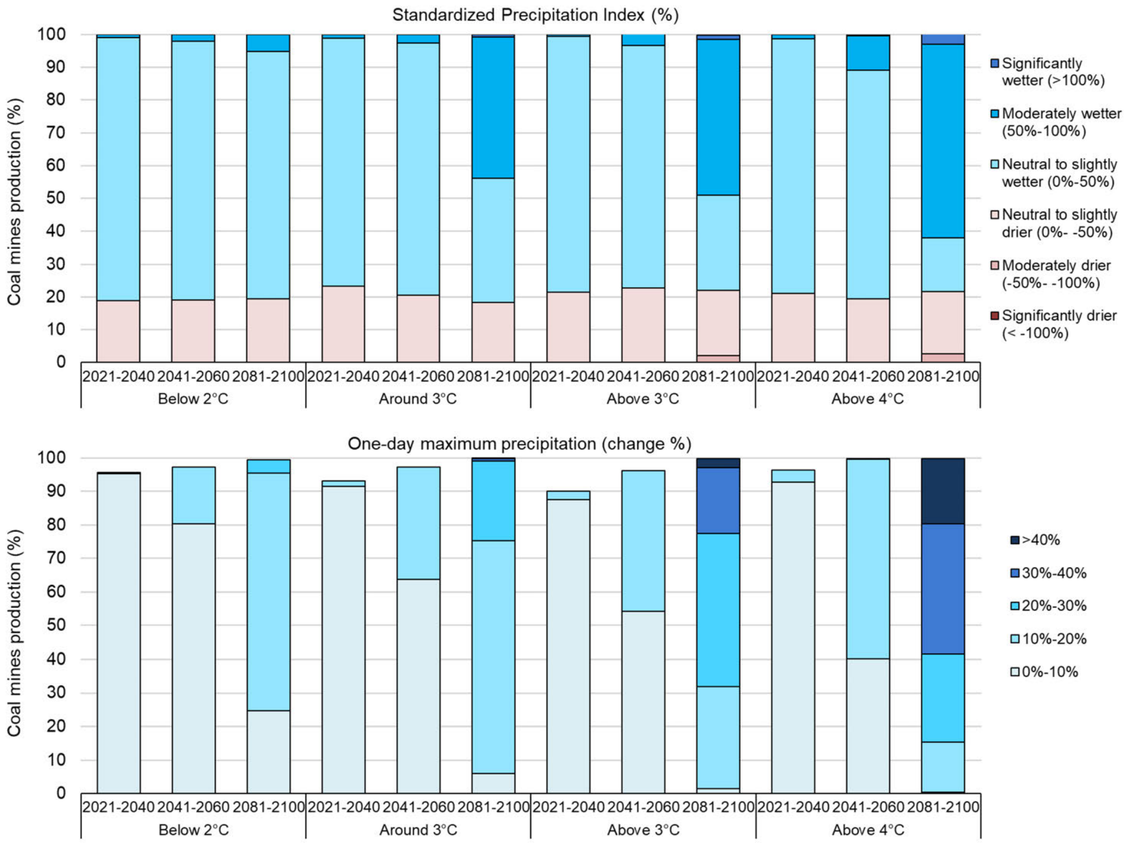
Coal mining and production is sensitive to water availability because it requires a significant volume of water. Generally, water is used for coal washing, extraction, dust control and evaporation. Underground coal mines tend to require more water than open-cut mines because they need water to reduce the hazard of fires or explosion by cooling the cutting surfaces of mining equipment and preventing coal dust from catching fire. In Australia, for instance, approximately 653 L of water on average are used per tonne of coal, mainly for coal handling and preparation plants[8] (47%) and dust suppression (42%). Such a high water requirement has sometimes led to competition for water between coal production and other uses, as seen in South Africa and India.

In the future, climate conditions in major coal production areas are projected to become wetter. In some places, water stress might ease, although excessive water may bring another issue. The high water requirement of coal production does not mean "the wetter, the better". If coal is soaked at mines or stock yards by excessive precipitation or floods, its quality declines, and consumers (e.g. coal power plants) need to evaporate the moisture before pulverising the coal into a fine powder. Heavy rainfall and floods can also suspend production and force operation at reduced capacity, as seen in the floods in eastern Australia in early 2021.

[8] A coal handling and preparation plant is a facility that washes coal of soil and rock. It crushes coal into graded, sized chunks, stockpiling grades while preparing it for transport to market. The more of the waste material that can be removed from coal, the lower its total ash content, the greater its market value and the lower its transport costs.

Coal production areas still operating after 2050 are likely to experience increased water-related disruptions, given the projected increase in heavy precipitation and pluvial floods in most of the major coal production areas. Over 60% of coal production sites are projected to be in a moderately or significantly wetter condition in 2080-2100 in a high-emissions scenario (SSP5-8.5). Even in a low-emissions scenario (SSP1-2.6), 80% of coal mines are projected to experience a neutral or slightly wetter climate. Most coal production areas will see an increase in one-day maximum precipitation in 2080-2100, compared to 1850-1900. In a high-emissions scenario, 99% of coal mines will see an over 10% increase in one-day maximum precipitation, and over the half of them will see an over 30% increase. Even in a low-emissions scenario, around three-quarters of coal mines are projected to see an over 10% increase in one-day maximum precipitation.

Coal mines exposed to a wetter climate by climate scenario



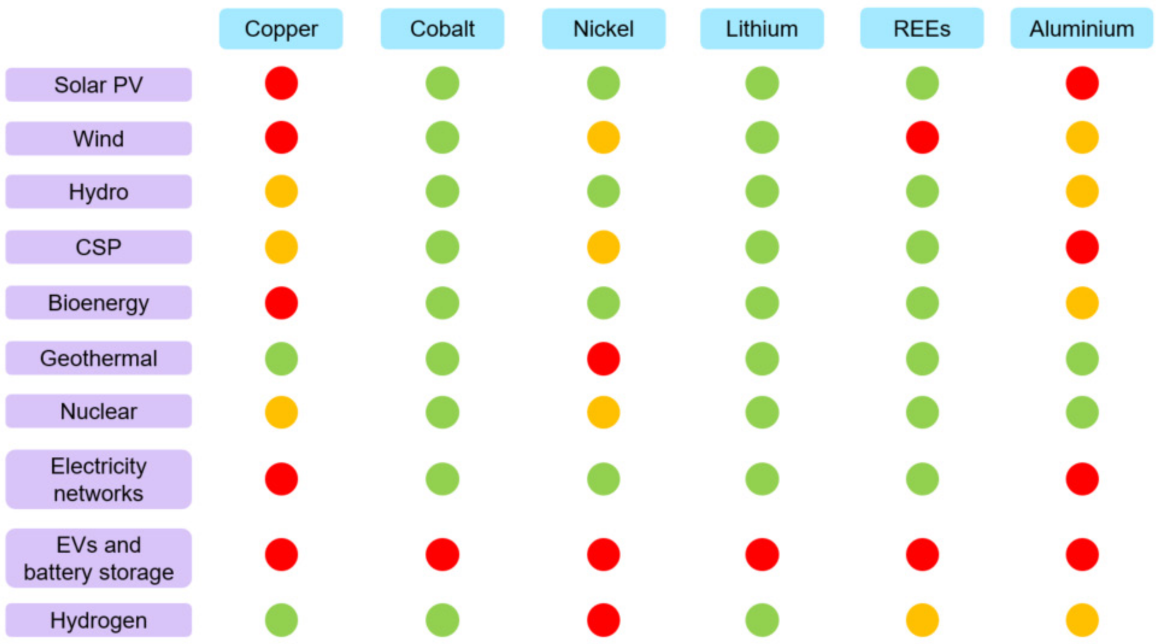
Note: The graphs show the share of coal mine production capacities for each level of standardised precipitation using the Standardized Precipitation Index and one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on Global Energy Monitor (2022a) and IPCC (2021b).

More frequent floods due to a wetter climate may have indirect impacts on coal production by impeding coal transport. Floods in eastern Australia in 2021 affected the coal supply chain through interruptions to rail transport and port operations. The same happened in 2022, when Australia's main rail lines for coal transport were closed for two days due to heavy rain, affecting the supply to the world's largest coal export port.

Critical minerals

Various minerals are currently essential for the deployment of clean energy technologies. Lithium, nickel, cobalt, manganese and graphite are crucial to battery performance, longevity and energy density. Rare earth elements are essential for permanent magnets that are vital for wind turbines and EV motors. Electricity networks need a huge amount of copper and aluminium, with copper being a cornerstone for all electricity-related technologies.

Critical minerals needs for clean energy technologies



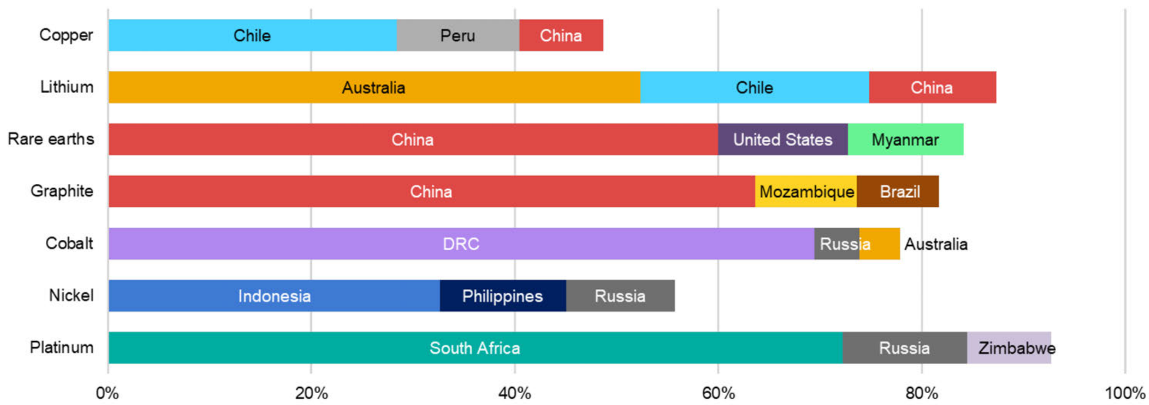
Note: Colours indicate the relative importance of minerals for a particular clean energy technology (red = high; orange = moderate; green = low). Overall mineral demand for each of the clean energy technologies has been estimated using four main variables: clean energy deployment trends in the STEPS and the Sustainable Development Scenario; sub-technology shares within each technology area; mineral intensity of each sub-technology; and mineral intensity improvements. See Annex of *The Role of Critical Minerals in Clean Energy Transitions* report for methodologies and data sources. CSP = concentrating solar power. REEs = rare earth elements.
Source: IEA (2021b).

Clean energy technologies generally require considerably more minerals than their fossil fuel counterparts. A typical electric car requires six times the mineral inputs of a conventional car, and an onshore wind plant requires nine times more mineral resources than a gas-fired power plant. Therefore, overall mineral requirements are projected to increase with the further deployment of clean energy technologies, almost double between today and 2050 in the STEPS and triple in the NZE.

How demand for critical minerals will evolve is difficult to forecast. It is subject to various factors, including technology development pathways, climate policies, geopolitical situation and commodity prices. For example, cobalt demand could be anything from 6 to 30 times higher than today's levels, depending on assumptions about the evolution of battery chemistry and climate policies. Lithium demand in 2040 may be 13 times or 51 times higher than today's levels. Likewise, rare earth elements may see three to seven times higher demand in 2040 than today, depending on the type of wind turbines[9] developed and the strength of policy support. Tense geopolitical situations and rising commodity prices make it more difficult to project demand trajectories, producing bottlenecks in the critical minerals supply growth. Prices of many minerals and metals (e.g. lithium, nickel, cobalt and aluminium) soared in 2021 due to a combination of rising demand, disrupted supply chains and concerns around tightening supply.

Production of many critical minerals is more concentrated than that of oil or natural gas. For platinum, lithium, rare earths, graphite and cobalt, the world's top three producing nations control well over three-quarters of global output. The Democratic Republic of the Congo (DRC) is responsible for around 70% of the global production of cobalt, while China accounts for around 60% of rare earth elements and graphite production. South Africa covers over 70% of platinum, while Australia and Chile provide three-quarters of lithium. In terms of processing operations, China takes 50-70% for lithium and cobalt, and nearly 90% for rare earth elements.

Share of top three producing countries in total production of selected minerals, 2019



Sources: IEA (2021b); USGS (2021).

[9] For example, turbines based on permanent-magnet synchronous generators, which dominate the offshore market due to their lighter and more efficient attributes, as well as lower maintenance costs, require rare earth elements.

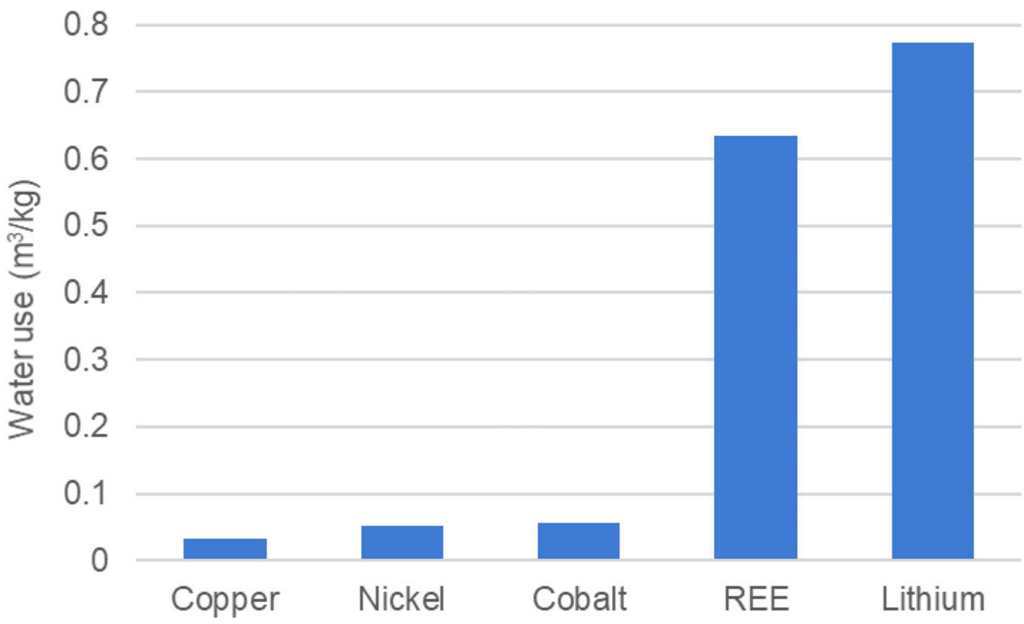
Increasing water-related hazards due to climate change could disrupt the supply of critical minerals

Climate change impacts in top producer countries could affect supply chains and global energy security. Climate-driven impacts can disrupt mineral supplies and lead to price spikes. For instance, floods in 2020 in southwestern China stopped rare earth elements processing and led to tens of millions of dollars of losses.

A 2012 paper published by the West Australian Government and Bureau of Meteorology indicated that the extraction of minerals is highly affected by the flooding of mines.

Climate change is likely to increase pressure on critical minerals extraction in regions where water availability is projected to decrease. For critical minerals extraction, water is essential for both open pit mining (to suppress dust and to wash equipment) and underground mining (to transport ore to the surface). If increasing aridity and reduced rainfall cause water shortages in the mining areas, critical minerals production could drop considerably.

Water requirement for mineral mining



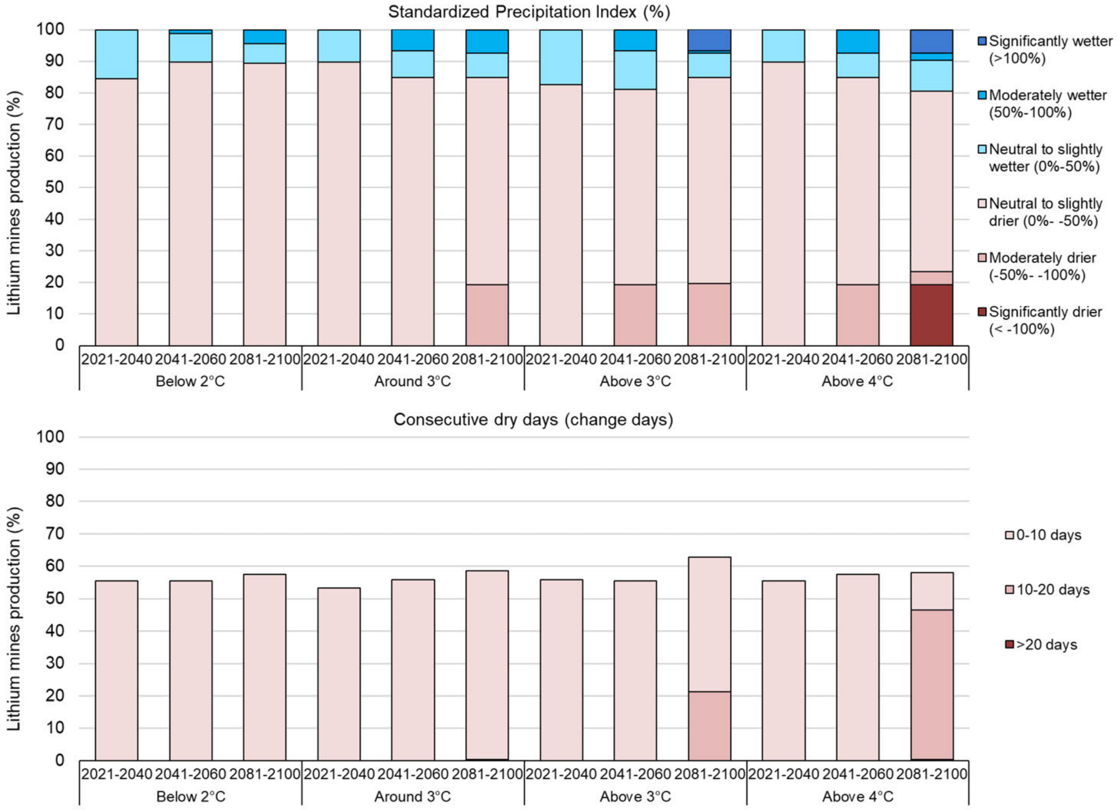
Note: REE refers to neodymium iron boron magnet.
Sources: IEA (2021b); IEA analysis based on Farjana, Huda and Mahmud (2019) (cobalt, copper, nickel); Jiang et al. (2020) (lithium); Marx et al. (2018) (REE).

Climate change is likely to make the main lithium production areas drier

Lithium mining is particularly exposed to climate change impacts that could make major production areas drier. Although the level of water use for lithium mining is higher than for other minerals, over 50% of lithium production is currently concentrated in areas with high water stress levels, creating conflicts about water use. For instance, Chilean regulators have looked to sue or fine some mining firms for excess water use in the Atacama desert, a major source of lithium.

Climate change is projected to make lithium mining areas drier in the future. In a high-emissions scenario (SSP5-8.5), more than 20% of lithium mines are projected to experience a moderately or significantly drier climate in 2080-2100. Even in a low-emissions scenario (SSP1-2.6), almost 90% of mines are projected to face a neutral or slightly drier climate. The number of consecutive dry days in these regions is likely to increase in the high-emissions scenario, with 46% of lithium mines seeing an increase of more than ten days.

Standardised precipitation and consecutive dry days of lithium mines by climate scenario, compared to 1850-1900



Note: The graphs show the share of lithium mine production capacities for each level of standardised precipitation using the Standardized Precipitation Index and the number of consecutive dry days, compared to the level of the pre-industrial period (1850-1900).

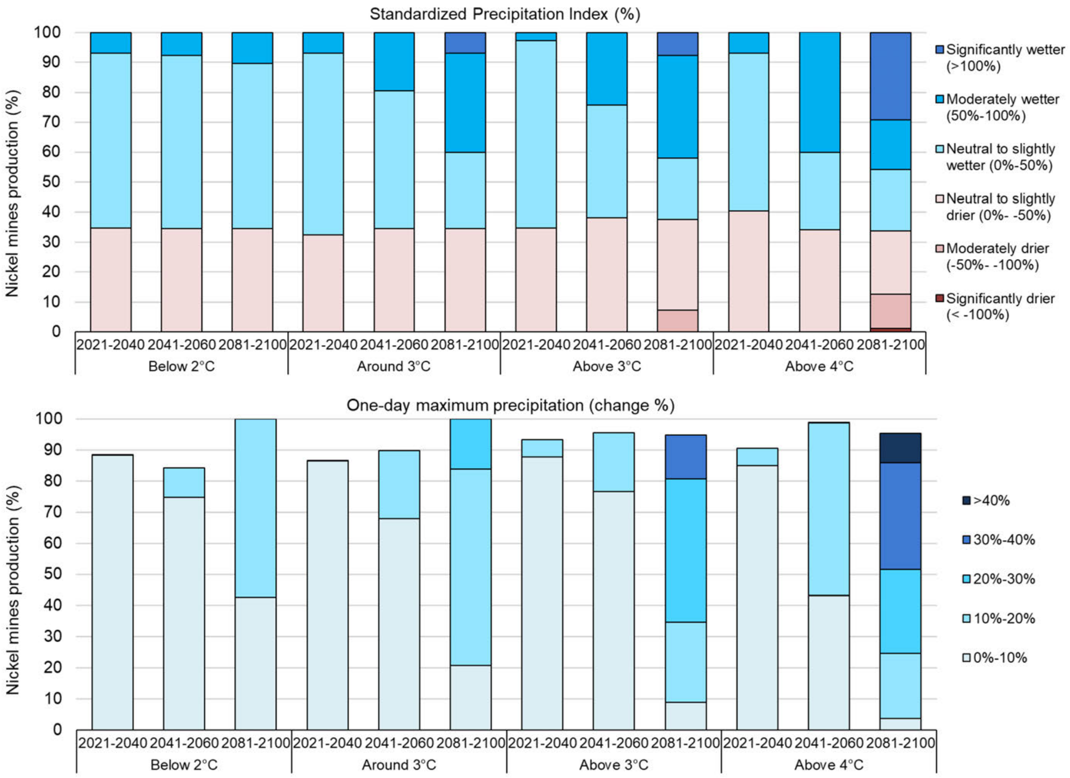
Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

Increasing heavy precipitation and floods could disrupt nickel and cobalt production

In other regions, climate change could lead to a wetter climate, increasing the possibility of mineral production disruptions due to heavy rainfall and flooding. Severe flooding can halt mining operations by damaging mining facilities and indirectly affect mining operations causing power outages. In 2019, South Africa, one of the world's foremost producers of platinum, stopped production in two of the biggest platinum mines after it was left functioning at 20-30% of normal power because of load shedding triggered by heavy rains. Flooding can also lead to spills of hazardous waste from mine sites or waste storage, and tailings dam failure, with extensive environmental damage.

Nickel production areas are likely to experience a wetter climate in the rest of the 21st century, possibly with heavy rainfalls and floods. Indonesia, the biggest nickel producer in the world, has already gone through climate-driven disruptions in nickel supply due to heavy rainfall and floods. For instance, flooding in June 2019 forced a number of mines to stop operating for several weeks and reduced the quality of nickel due to high water content. In August 2020, the Weda Bay smelter complex, one of the main nickel-processing hubs in Indonesia, was hit by flooding caused by heavy rain. More than 40% of nickel production areas are projected to face a moderately or significantly wetter climate in a high-emissions scenario (SSP5-8.5) and 10% in a low-emissions scenario (SSP1-2.6). In most production sites, one-day maximum precipitation is projected to increase. Over half of nickel production areas will see an over 10% increase in one-day maximum precipitation in any climate scenario.

Standardised precipitation and one-day maximum precipitation of nickel mines by climate scenario, compared to 1850-1900

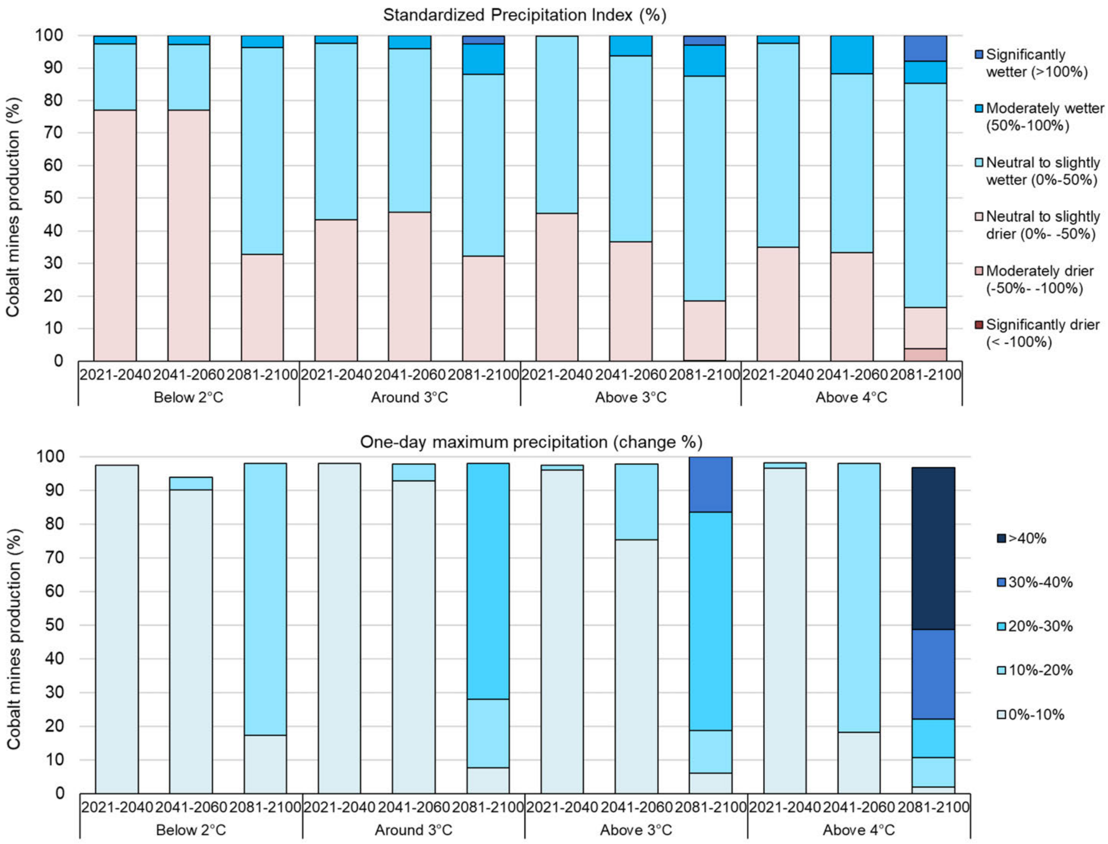


Note: The graphs show the share of nickel mine production capacities for each level of standardised precipitation using the Standardized Precipitation Index and one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

Some cobalt mines are also likely to see a wetter climate by 2100, with an increase in heavy rainfalls and floods. Around 15% of cobalt mines are projected to see a moderately or significantly wetter climate in a high-emissions scenario, while the share drops under a low-emissions scenario. Around 80% of cobalt mine production is projected to see an increase in one-day maximum precipitation by over 10% in 2080-2100 compared to 1850-1900 in a low-emissions scenario. In a high-emissions scenario, almost half of cobalt mines are projected to see a more than 40% increase. Such increases could interrupt global cobalt supply, as seen in South Africa in April 2022. Severe flooding at Durban port, the main port for cobalt deliveries from the Democratic Republic of the Congo, the dominant producer of cobalt, suspended cobalt export for weeks.

Standardised precipitation and one-day maximum precipitation of cobalt mines by climate scenario, compared to 1850-1900



Note: The graphs show the share of cobalt mine production capacities for each level of standardised precipitation using the Standardized Precipitation Index and one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

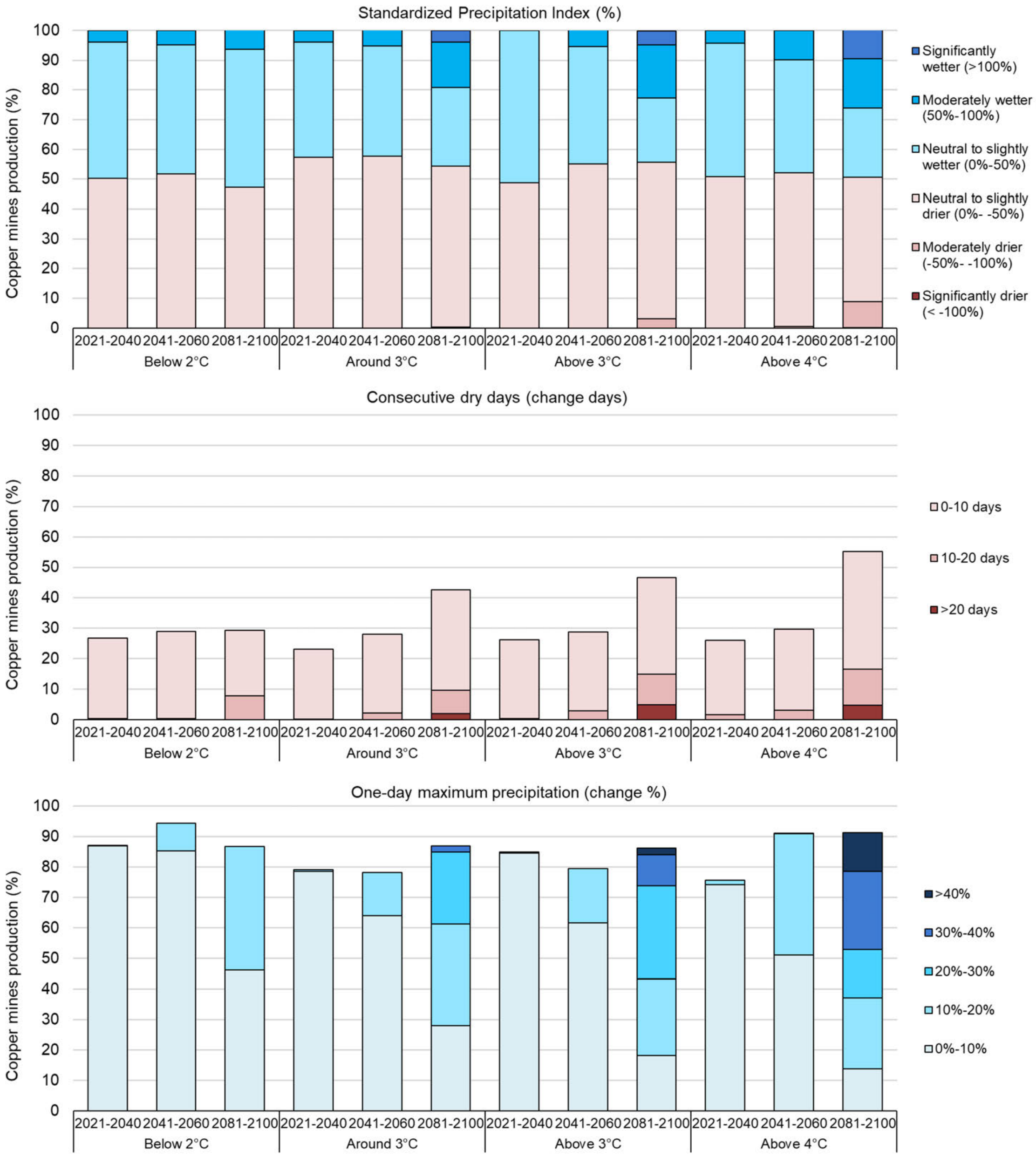
Copper production is projected to see mixed impacts from climate change, depending on production sites

Climate change could bring mixed impacts for major producers of some minerals, such as copper. Leading copper producers are likely to see two types of climate impacts. Copper mines in places like Chile and Australia could face a drier climate, while those in places like Peru and China could face a wetter climate. In a high-emissions scenario (SSP5-8.5), 9% of copper mines are projected to experience a moderately or significantly drier climate, while 26% would see a wetter climate. In a low-emissions scenario (SSP1-2.6), more than 90% of copper mines would remain relatively stable,[10] while the rest would experience wetter conditions. The number of consecutive dry days is likely to increase in some regions, with 8-27% of copper mines seeing an increase of more than ten days, depending on climate

[10] Neutral to slightly drier and neutral to slightly wetter.

scenarios, compared to 1850-1900. At the same time, around 40-80% of copper mines are projected to see an over 10% increase in one-day maximum precipitation.

Standardised precipitation, consecutive dry days and one-day maximum precipitation of copper mines by climate scenario, compared to 1850-1900



Note: The graphs show the share of copper mine production capacities for each level of standardised precipitation using the Standardized Precipitation Index, consecutive dry days and one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on IPCC (2021b) and S&P Global (2021a).

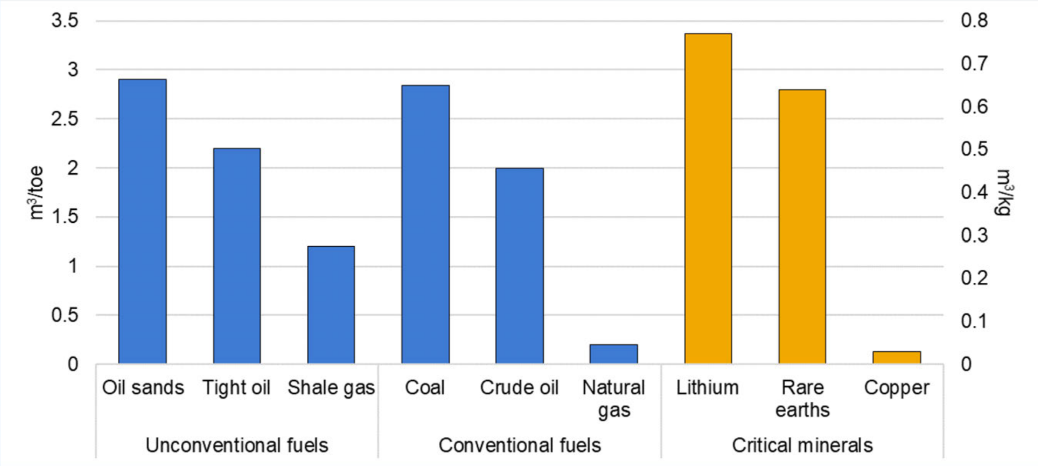
The projected increase in dryness could increase stress on the water supply for copper mining in some countries. In Chile, the world's top copper-producing country, some 80% of copper output is produced in mines located in high water stress and arid areas. A record-breaking 13-year drought in Chile is severely affecting copper production. Antofagasta Minerals saw a 24% drop in production at its Los Pelambres mine in the first quarter of 2022 due to extreme drought and lack of rain. Anglo American's Los Bronces mine also saw production fall 17% year-on-year in the first quarter of 2022. Climate change is projected to reduce precipitation, making the situation in Chile worse. This has triggered companies to invest in desalination capacity and other alternative water sources, and to improve water efficiency.

In contrast, the projected increase in precipitation in other copper mines raises concern about flooding. According to the IPCC's latest report, Peru and China are projected to become wetter, with an increase in mean precipitation. Although a wetter climate may ease concerns about water requirements in some sites, flooding could bring another challenge to copper production. Indeed, some copper mines in China experienced disruptions due to floods in central China in July 2021. These interrupted copper supply and contributed to the rise in global copper price, which hit the highest level in two years. A large part of China is projected to have more frequent heavy precipitation and floods over the rest of the century, which could be an issue for copper production.

Fuel and resources water needs: Competition with other water users

Water is required for nearly all production and conversion processes in the energy sector, including fuel production and processing, and minerals extraction. Unconventional oil and gas operations use particularly large amounts of water. Hydraulic fracturing involves injecting high pressure water mixed with chemicals to extract tight oil or shale gas resources. Studies have shown that unconventional wells often require over 15 ML of water per year and that this water footprint has been intensifying over the years. Likewise, oil sands surface mining requires three to four barrels of water per barrel of heavy oil, most of which comes from groundwater resources. Coal mining has a high water requirement, including water use for coal washing and cooling of drilling equipment. According to the US Department of Energy, total water used for coal mining in the United States ranges from 260 ML to 980 ML per day. Extraction of critical minerals, especially lithium and rare earth elements, also requires large amounts of water, as shown in the figure below.

Freshwater use for the production of selected minerals and fuels



IEA. CC BY 4.0.

Notes: These are representative values based on literature review and expert consultations. Water use can vary significantly by facility and region, depending on the technologies employed and water availability. Water use generally reflects withdrawals (the volume of water removed from a source), which are always greater than or equal to water consumption (the volume withdrawn from a source that is not returned and thus is no longer available for other users). The columns in blue refer to m^3/toe. The columns in orange refer to m^3/kg.

Sources: IEA (2022c); IEA analysis based on Jiang et al. (2020) (lithium); Marx et al. (2018) (rare earths); Farjada, Huda and Mahmud (2019) (copper); Schornagel et al. (2012) (conventional fuels); Kondash, Lauer and Vengosh (2019) (unconventional oil and gas); Government of Canada (2016) (oil sands).

Besides increased exposure to water stress levels with climate change, competition with other water users are becoming a growing concern to the energy sector in some countries. For instance, water use for shale production may create competition with irrigated agriculture. Indeed, irrigated agriculture is the largest water user in 40% of the shale plays. Coal mining also causes serious groundwater losses, while continuous expansion of lithium extraction activites may negatively affect the level of soil moisture.

The conflict is not only about how water reserves are used but also the quality of the water discharged from mining activities, which can create environmental damage and indirectly harm other economic sectors. Drilling and excavation often directly encounter aquifers, posing contamination risks to groundwater resources. Dewatering (when groundwater inflows are pumped out to maintain access to mines) can cause a decrease in the surrounding water table or contaminate nearby aquifers. Water that comes out of oil and gas wells can have high salinity and contain chemical products and residual hydrocarbons, potentially affecting soil and groundwater quality.

To avoid competiton over water resources, fuel and mining industries can explore options to reduce their water needs or switch to alternative water sources. Water use can be cut by controlling losses (e.g. minimising wet areas or filtrating tailings) or using dry processing technologies. Mining operations can also use water of lower quality, such as water from mine dewatering and surface runoff, as well as recycled process water, produced water, treated wastewater or desalinated seawater. In coastal areas, using seawater could be an alternative. Meanwhile, innovative technologies, such as direct lithium extraction technologies, could reduce the need for water in the initial steps of production.

Bioenergy

Bioenergy represents the energy obtained from solid, liquid and gaseous products derived from biomass feedstock and biogas.[11] It includes solid bioenergy, liquid biofuels and biogases. Solid bioenergy includes charcoal, forest biomass, dung, agricultural residues, wood waste and other solid wastes. Liquid biofuels are derived from biomass or waste feedstock and include ethanol, biodiesel and biojet fuels. Biogases include both biogas and biomethane.

Bioenergy accounted for roughly one-tenth of world total primary energy supply in 2021. Almost 90% of total bioenergy consumed today comes from solid biofuels, accounting for around 55 EJ. Almost half (25 EJ) is used in traditional methods for cooking and charcoal production. Modern solid bioenergy, which accounts for the remainder, is used to produce liquid biofuels, biogases, electricity and heat, or is consumed directly in end-use sectors.

Bioenergy is a versatile energy source that can be used in all sectors. In the NZE, solid bioenergy demand would see a fourfold increase in the electricity sector and in liquid biofuels production (mainly for shipping and aviation) and a sixfold increase in biogases production (used in the industry, buildings and transport sectors) by 2050. Solid bioenergy demand in the NZE also doubles in the industry sector to meet high temperature needs. In the electricity sector, bioenergy accounts for more than 4% of total generation in 2050.

Bioenergy feedstock can be classified as conventional and advanced. The conventional bioenergy crops come from food crops, such as corn, rapeseed and sugarcane. To avoid conflicts between food production and affordability, there is a general shift towards advanced bioenergy produced from dedicated crops that do not compete with food crops, including organic by-products and residues from agriculture, forestry, municipal solid waste and wastewater. Today, conventional biofuels represent around 93% of total biofuels production and are more vulnerable to climate change impacts.

[11] A mixture of methane, CO_2 and small quantities of other gases produced by anaerobic digestion of organic matter in an oxygen-free environment.

Bioenergy can be negatively affected by increasing droughts, despite the potential benefits of a warmer climate and CO_2 fertilisation

Global bioenergy production, particularly of conventional bioenergy, is affected by the level of CO_2 in the atmosphere and by ambient temperature. Some studies show that higher levels of CO_2 may have a positive effect on photosynthesis and water retention, increasing crop yields. However, the positive impacts of increased CO_2 fertilisation and higher temperatures on crop yields would be concentrated in regions where bioenergy production is currently constrained by low temperatures (e.g., the northern high latitudes and in mountainous regions). In many regions, especially tropical croplands, higher temperatures may put more stress on plants, as higher temperatures can constrain photosynthesis efficiency.

Changes in precipitation patterns and water availability directly affect bioenergy. Drought conditions will affect bioenergy crops in the same way they do other agriculture production, threatening consistent and high crop yields, reducing photosynthesis and changing the chemical composition of crops. Droughts can change the chemical composition of crops in ways that negatively affect yields of bioenergy products derived from the biomass (e.g. significant accumulation of soluble sugars with decreases in structural sugars, changing lignin component distribution).

A projected increase in agricultural and ecological droughts in major biomass producers in the Americas could be a concern. Currently, around two-thirds of global biofuel production comes from North America and Latin America, and the largest producers are the United States and Brazil. However, some areas of Brazil and the United States are projected to see an increase in droughts that could significantly affect crop yields. Recently, Brazil's 2021/22 sugar production decreased from 38.5 Mt to 32 Mt due to historic drought and frosts.

Hydrogen

Global hydrogen demand reached more than 94 Mt in 2021, mainly from the chemical and refining sectors. The demand was met almost entirely (99%) by fossil fuel-based hydrogen, with natural gas being the main fuel for hydrogen production (59%). Coal accounted for 19% of hydrogen production, mainly in China, which represents the largest producer of hydrogen today. By-product hydrogen produced in facilities designed primarily for other products accounted for 21%. Water electrolysis covers only 0.05% of hydrogen production so far, although the share in 2021 almost doubled compared to 2020 and could triple in 2022.

In the STEPS, there would be small increases in the use of low-carbon hydrogen and hydrogen-based fuels to 2030. In the NZE, around half of low-carbon hydrogen production in 2030 is from electrolysis and half is from coal and from natural gas equipped with CCUS (although this ratio varies considerably among countries). If all the announced projects for hydrogen from water electrolysis or fossil fuels with CCUS currently under development are realised, the annual production of low-emissions hydrogen could reach 22 Mt by 2030.

Climate impacts on fossil fuel supply would be applicable to hydrogen production facilities, particularly given that 59% and 19% of hydrogen are currently produced using natural gas and coal, respectively. Hydrogen production from water electrolysis requires water and electricity, meaning that the impacts related to the energy needs are similar to those affecting electricity generation plants and grid infrastructure, as discussed in the power sector section.

Climate impacts on the hydrogen supply in particular are not yet fully analysed, since some technologies needed for hydrogen supply are still at earlier stages of development, and there is currently no dedicated long-distance hydrogen transport infrastructure. Hydrogen today is mostly produced close to where it is used, mainly industrial facilities and refineries, or transported through limited natural gas pipelines. Although there are 2 million km of natural gas transmission pipelines worldwide, only approximately 2 600 km of pipelines in the United States and around 2 000 km in Europe are being used for hydrogen.

Future studies on the climate resilience of hydrogen need to take into account the unique features of hydrogen, considering technical differences between hydrogen and natural gas and covering the entire hydrogen infrastructure. Although there are similarities between hydrogen and natural gas infrastructure, some technical differences may prevent the retrofit and repurpose of gas infrastructure for hydrogen uses. Indeed, practical experience on repurposing natural gas pipelines to hydrogen is very limited, and there is only a 12 km repurposed pipeline in the Netherlands. Such technical differences may need to be considered not only in pipelines but also in other parts of hydrogen infrastructure, including compressors, trucks, ships, liquefaction and conversion plants, storage tanks and underground storage facilities.

Hydrogen could be vulnerable to heatwaves and water shortage, although the climate impacts on hydrogen production are still unknown

Hydrogen could be more vulnerable than natural gas to the impact of heatwaves, since its liquefaction requires much lower temperatures than LNG. Gaseous hydrogen is liquefied by cooling it to below -253°C compared to -162°C for natural gas, so handling and transporting it requires advanced technologies and careful handling to minimise hydrogen loss and hazardous risks. Storage of liquefied hydrogen would also require tank insulation with ten times higher thermal resistance than for LNG, due to its lower density and boiling temperature. During heatwaves, the impact of higher ambient temperatures on cooling energy needs could be more severe for hydrogen than for LNG.

Water is essential to all the main hydrogen production options. Gas reforming processes and coal gasification are the main technologies for hydrogen production using fossil fuels. These technologies require large amounts of water for steam in the reformation process, with or without carbon capture. Hydrogen production from natural gas with CCUS pushes water use to 13 kg to 18 kg of water per kg of hydrogen (H_2O/kg H_2), and it can jump to 40 kg to 85 kg H_2O/kg H_2 from coal gasification, depending on water consumption for coal mining. Producing hydrogen by electrolysis from low-emissions electricity has the smallest water footprint at about 9 kg H_2O/kg H_2. To anticipate production challenges linked to water availability, research and development is underway for hydrogen production using salt water, with the major technical challenge being electrode corrosion from the high salinity.

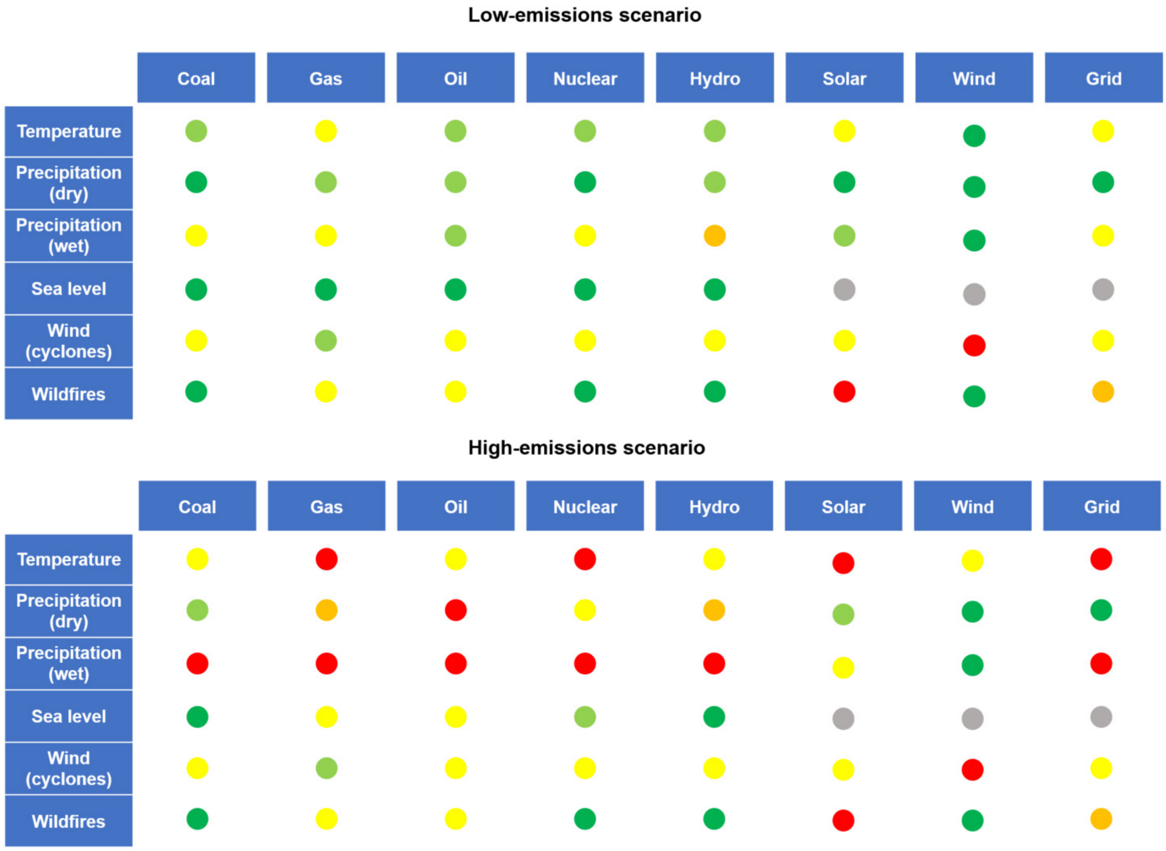
Power sector

Electricity is the fastest-growing source of final energy demand. Electricity accounted for 17% of world total final energy consumption in 2010 and 20% in 2020. The share is expected to increase in the next decades with global efforts to reduce GHG emissions through the rapid electrification of transport and industry. In the NZE, electricity accounts for 52% of world final energy consumption in 2050.

At the same time, electricity systems are witnessing increasing pressure from climate change impacts, which already pose significant challenges to the resilience of electricity systems. These impacts can shift generation potential and output, pose physical risks to electricity grids and increase the likelihood of climate-driven disruptions. Although the size of impacts varies across electricity technologies, most of the technologies, including traditional thermal power and renewables, are exposed to a certain level of climate change risks.

The size of climate change impacts on power plants and grids is largely determined by climate pathways. In a low-emissions scenario, power systems are projected to face a comparatively low level of climate risks, associated with temperature and sea-level rise, although some power plants and grids would struggle with heavy rainfall, tropical cyclones and wildfires. In addition to these, in a high-emissions scenario, gas and oil power plants are projected to see considerable impacts related to sea-level rise, while major low-carbon power generation assets, such as nuclear, wind and solar, would also be challenged by a warmer climate.

Comparison of climate change risks to power systems in the low-emissions and high-emissions scenarios, 2080-2100



Notes: These tables show climate change risks to power plants and electricity grids at a global scale. SSP1-2.6 and SSP5-8.5 are used for the low-emissions and high-emissions scenarios, respectively. The levels of climate risks are divided into five categories, from dark green for low risks to red for high risks. Grey cells indicate no information. The levels are determined based on the combination of hazard, exposure and vulnerability. Hazard and exposure are calculated through GIS analysis, while vulnerability is determined through qualitative research. For temperature, the level of exposure of power plants and grids to the increase in mean temperature and the number of days with maximum temperature above 35°C data is used. For precipitation (dry), the level of exposure of power plants and grids to a drier climate based on the Standard Precipitation Index and the number of consecutive dry days is used. For precipitation (wet), the level of exposure of power plants and grids to a wetter climate based on the Standard Precipitation Index and one-day maximum precipitation is used. For sea level, the level of exposure of power plants and grids to the projected rise of sea level is used. For wind, the level of exposure of power plants and grids to tropical cyclones based on the analysis of historical trends of tropical cyclones and major tropical cyclones (above Category 3) is used. For wildfires, the level of exposure of power plants and grids to wildfires based on the analysis of historical trends of fire weather is used.

Fossil-fuelled thermal power

Fossil-fuelled thermal power plants account for the largest share of total electricity generation: 62% as of 2021. Coal power plants generate 10 201 TWh, 36% of total electricity generation, larger than the total generation from all renewables (28%). Natural gas power plants produce 6 552 TWh, equivalent to 23%, while oil power plants generate 682 TWh, covering 2% of total electricity generation.

The share of conventional thermal power plants using fossil fuels is projected to decrease significantly. If current policies and trends are maintained (STEPS), the share of fossil-fuelled thermal power plants could decline to around half of the current level (26%). If further efforts are made to meet net zero emissions by 2050 (NZE), no electricity will come from unabated fossil fuels in 2050, while some thermal power plants equipped with CCUS technology could produce 2% of total electricity.

Some fossil-fuelled thermal power plants already face a significant level of climate risks. Some 28% of coal power plant installed capacity and 29% of oil power plants are exposed to tropical cyclones, and over half of them could experience major tropical cyclones above Category 3. Over 30% of oil and gas power plants are also exposed to wildfire risks, with more than 200 days of fire weather per year. In some regions, fossil-fuelled thermal power plants are experiencing a high level of water stress, while others are expected to face an increasing frequency and intensity of heavy rainfall and associated floods. These impacts are sensitive to overall levels of warming; the more fossil-fuelled thermal power generation remains in the latter half of this century, the stronger the climate change impacts on thermal power plants.

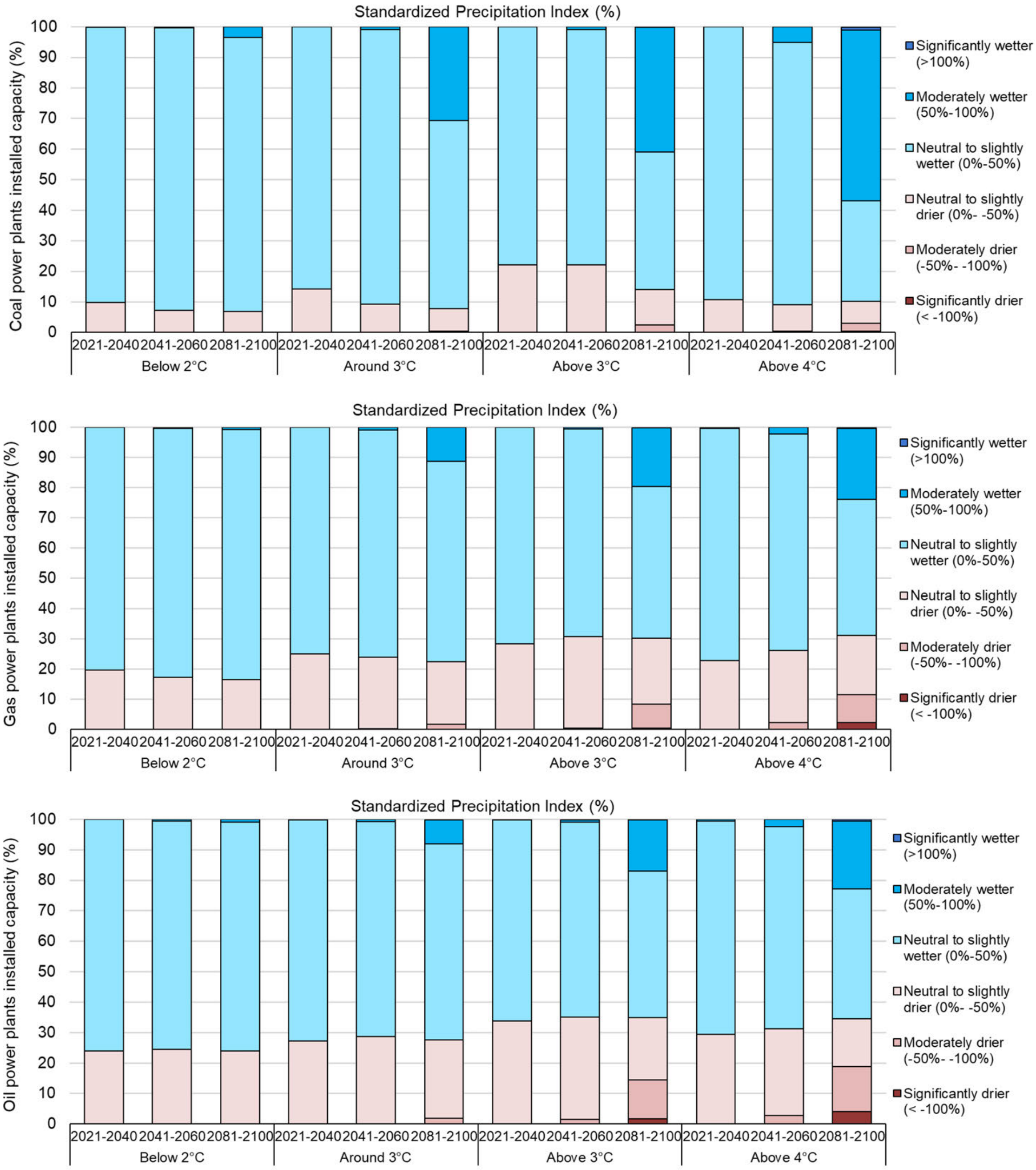
More frequent heavy rainfalls and floods could disrupt fossil-fuelled thermal power plants

Excessive water flow and heavy rainfall are also a concern for fossil-fuelled power plants. Although thermal power plants are generally equipped with flood protection structures that work in most cases, severe floods could prompt disruptions, including pre-emptive shutdown. For example, over five gas-fired power stations in Sylhet, Bangladesh, were shut down pre-emptively when flood water engulfed the stations in June 2022, although the power plants were not ultimately flooded due to preventive measures and their higher locations. Excessive water flow caused by heavy rainfall can also transport waste into thermal power plants' cooling water sources. For instance, increased river flow in the aftermath of record rainfall from Hurricane Florence caused a shutdown of the L.V. Sutton natural gas power plant in the United States by bringing waste into the plant's cooling lake.

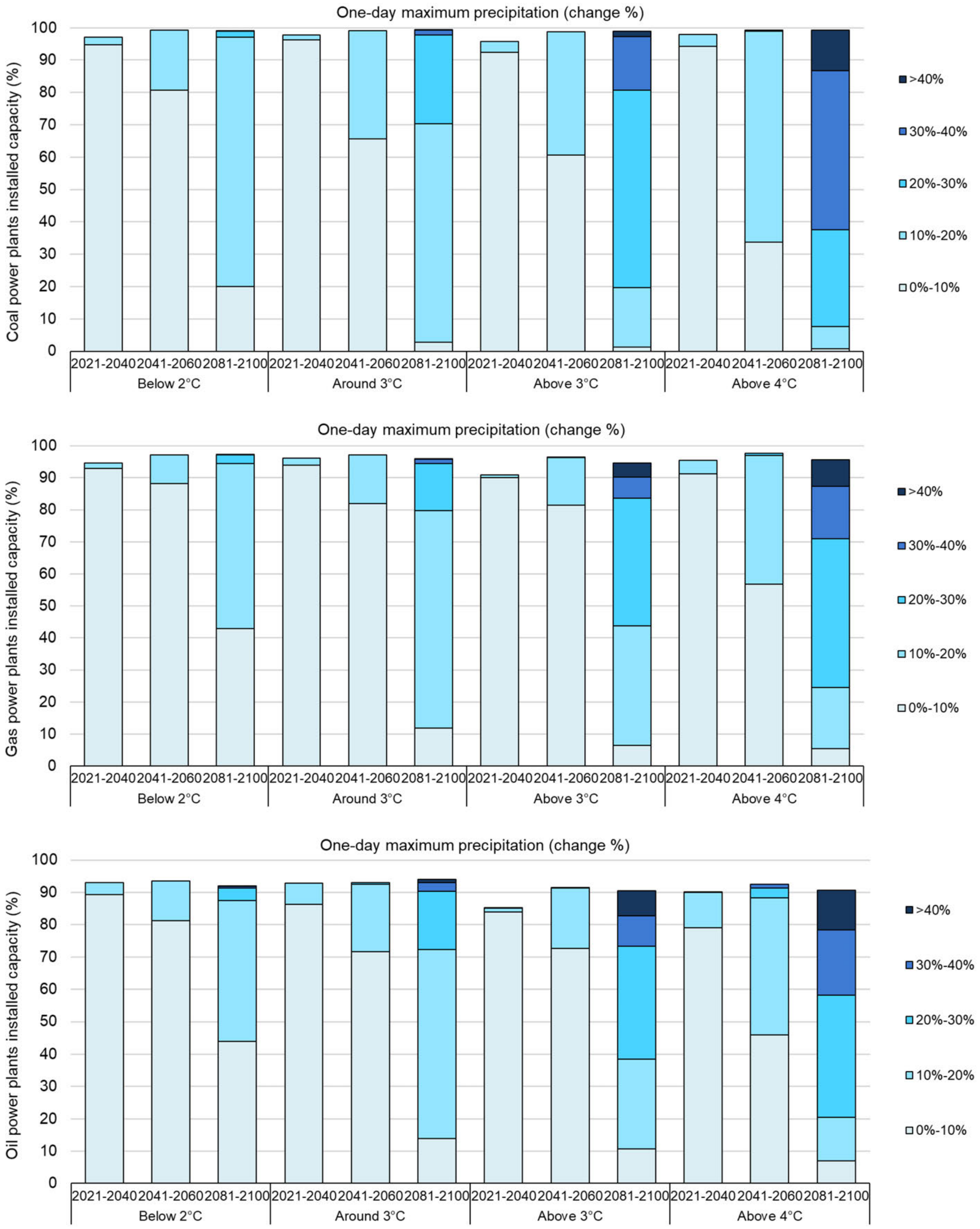
Floods and heavy rainfall can also cause disruptions to coal power generation through impacts on coal production. When a severe flood hit the Rhenish lignite mining area in Germany in 2021, its connected 2 GW Weisweiler power station was suspended for several days and ran at reduced capacity. Similarly, three out of four units of the Yallourn coal power plants of Australia were shut down for a few days when its brown coal mine stopped supplying coal due to floods in 2021.

Given that heavy precipitation and floods are likely to increase in large parts of Asia, Europe, Africa, North America and eastern South America, disruptions related to flooding may become more frequent. Climate projections show that almost 80% of coal power plants and around 50% of gas and oil power plants installed capacity will see an over 10% increase in one-day maximum precipitation in 2080-2100 in a low-emissions scenario. If emissions are not mitigated, the number will increase to over 90% for coal and gas power plants, and around 60% of coal power plants could see an over 30% increase in one-day maximum precipitation.

Fossil-fuelled power plants exposed to a wetter climate by climate scenario



Fossil-fuelled power plants exposed to a wetter climate by climate scenario (continued)



Note: The graphs show the share of fossil-fuelled power plants installed capacities exposed to a wetter climate using the Standardized Precipitation Index and one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

Water shortage could become a growing concern for fossil-fuelled thermal power plants that rely on wet cooling systems

Growing concerns related to water shortages could pose a challenge to fossil-fuelled thermal power plants because a majority of them rely on water to cool the steam used to drive turbines and generate power. In the United States, 96% of coal power plants, 87% of gas power plants and 100% of oil power plants used water for cooling in 2020. This heavy reliance on water means that water could threaten plant operation. A dramatic decrease in water level due to lack of rain and heatwaves in Poland led to energy consumption limits for large energy consumers in 2015, as coal power plants could not run.

Globally, around one-third of existing thermal power plants using freshwater cooling are located in high water stress areas, and this share is set to increase as the changing climate turns today's low-risk sites into high-risk ones. For instance, about 37.1 GW of coal power plants in Texas, Indiana, Illinois, Wyoming and Michigan are projected to face water stress due to climate change in 2030. Some gas power plants are also exposed to water shortages, as seen in the Central Valley plants in California.

In some areas where the water stress level is growing, more and more thermal power plants are adopting less water-intensive cooling systems. Once-through cooling systems are becoming unfavourable due to the large amount of water withdrawal and environmental impacts on aquatic life, even though most of the withdrawn water may return to the source. Instead, thermal power plants are increasingly equipped with closed-cycle cooling systems (e.g. recirculating cooling systems or cooling ponds) that require relatively low water withdrawal, although these systems tend to record relatively high water consumption[12] due to higher evaporation loss. Most new power plants in the United States adopt closed-cycle cooling. As of 2020, 69% of coal power plants capacity and 63% of natural gas plants capacity use recirculating cooling systems and cooling ponds, while 27% of coal power plants and 24% of natural gas plants use once-through cooling systems.[13]

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[12] Refers to the portion of the withdrawn water not returned to the source.

[13] The share of once-through cooling systems is still high for oil plants. Only one-quarter of oil power plants use closed-cycle cooling, while the rest use once-through cooling.

Water withdrawal and consumption for power plant cooling in the United States

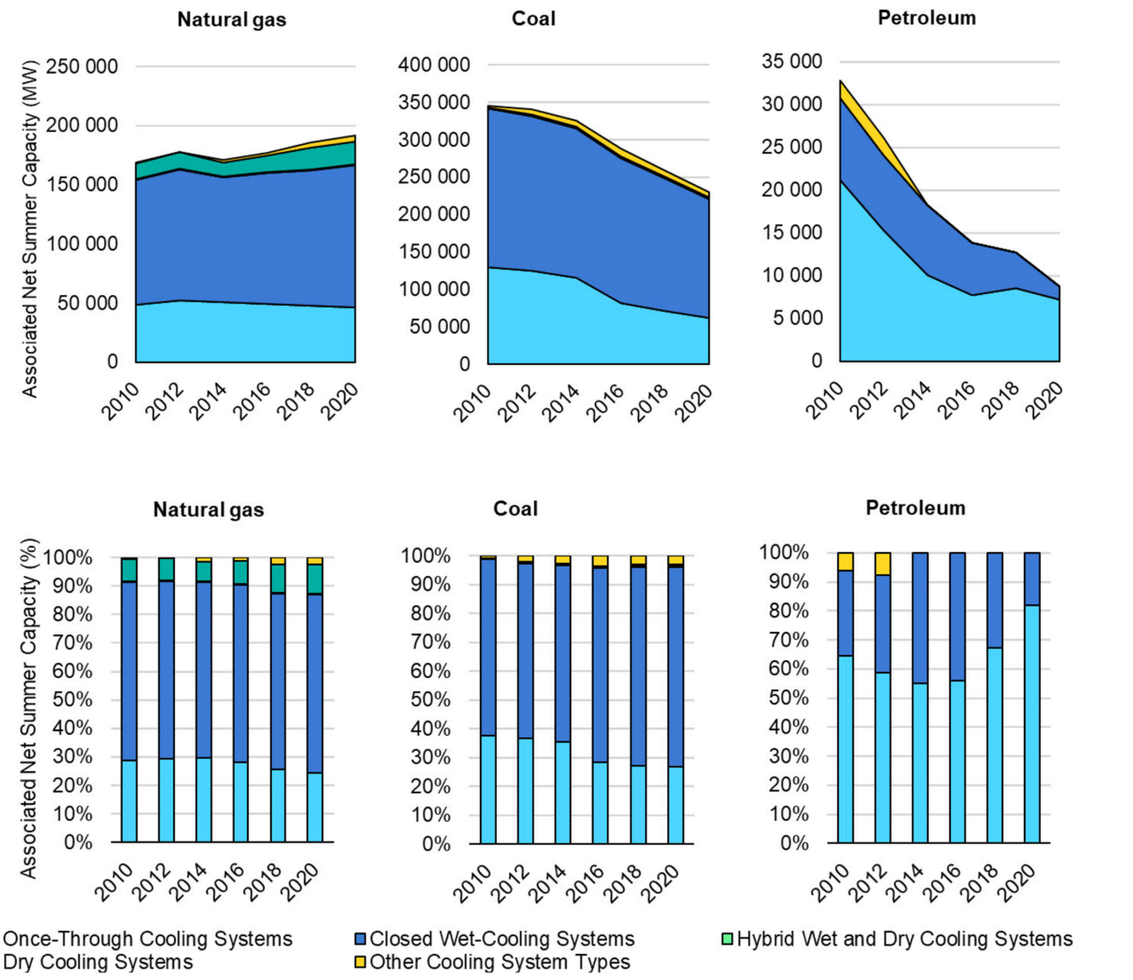
	Once-through		Recirculating		Dry cooling	
	Withdrawal	Consumption	Withdrawal	Consumption	Withdrawal	Consumption
Coal (conventional)	20 000-50 000	100-317	500-1 2000	480-1 100	n/a	n/a
Natural gas (combined-cycle)	7 500-20 000	20-100	150-283	130-300	0-4	0-4
Nuclear	25 000-60 000	100-400	800-2 600	600-800	n/a	n/a
Solar thermal (trough)	n/a	n/a	725-1 109	725-1 109	43-79	43-79

Note: Water withdrawn and consumed for power plant cooling in gallons of water required per MWh of electricity produced.
Source: Macknick et al. (2012).

Some places with a high level of water stress are switching to dry or hybrid (wet and dry) cooling systems, despite capital costs and energy requirements being higher than for wet cooling systems. Due to the capital costs and energy requirements, a majority of applications of dry cooling systems are with natural gas combined-cycle technology, which requires less cooling per MWh than others. For instance, in the United States, more than 20 000 MW of net summer capacity of natural gas plants (equivalent to 10%) is currently equipped with dry or hybrid cooling systems, while only 1% of coal power plants and no oil power plants are using them. In some countries with increasing aridity and droughts, such as South Africa, dry and hybrid cooling is increasingly adopted, even for coal power plants. Most coal power plants new and planned since 1991[14] are equipped with dry or hybrid cooling systems.

[14] Except for the Lethabo coal power plant, which uses closed-cycle cooling.

Changes in cooling systems for thermal power plants in the United States, 2010-2020



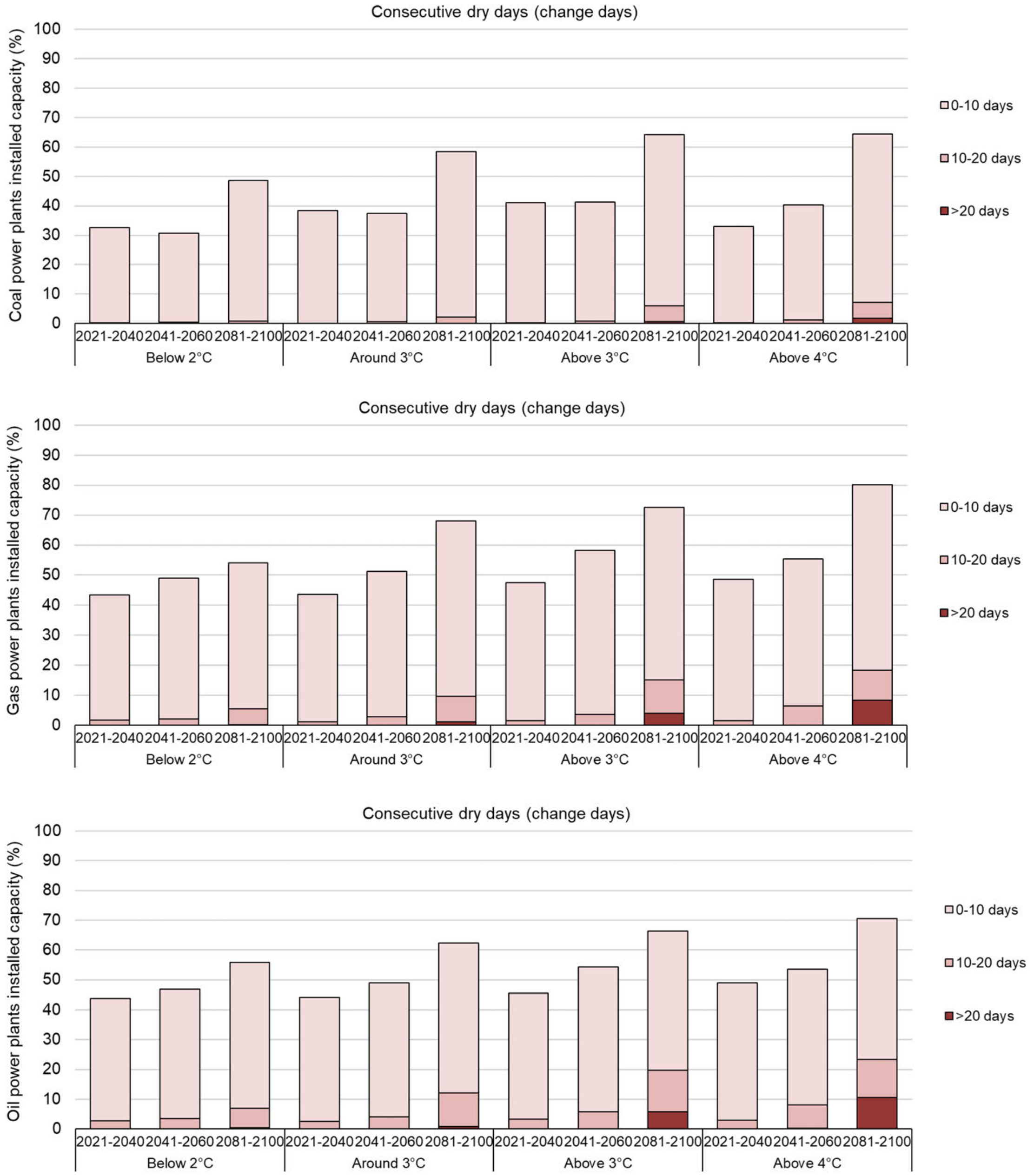
Notes: Associated net summer capacity is defined as the net summer capacity of the generators that are associated with the operation of this environmental equipment.

Sources: EIA EIA-767, Steam-Electric Plant Operation and Design Report and EIA-860, Annual Electric Generator Report (2021).

Increasing water stress could be a challenge to further deployment of CCUS technology. In order to meet net zero emissions in 2050, all remaining thermal power plants need to be equipped with CCUS. Until 2021, over 40 power plants announced plans to be equipped with CCUS. In general, a carbon capture system requires additional water for cooling and make up, although the levels of additional water required may vary among capture technologies (from around 56% per MWh for an oxy-combustion retrofit to around 87% for supercritical pulverised coal). The additional water requirements may limit the operation of power plants equipped with CCUS in areas of increasing water stress due to climate change.

Climate models show that the level of water stress will be critically affected by the level of GHG emissions. Although there could be more water shortages in some countries even in a low-emissions scenario, the level of impacts at a global scale would be much smaller than that in a high-emissions scenario. In a high-emissions scenario, a significant number of gas and oil power plants are projected to see a considerable increase in dryness. For instance, 23% of oil power plants and 18% of gas power plants will see an increase of over ten days in the number of consecutive dry days.

Fossil-fuelled power plants exposed to a drier climate by climate scenario



Note: The graphs show the share of fossil-fuelled power plants installed capacity exposed to a drier climate using the change in consecutive dry days, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

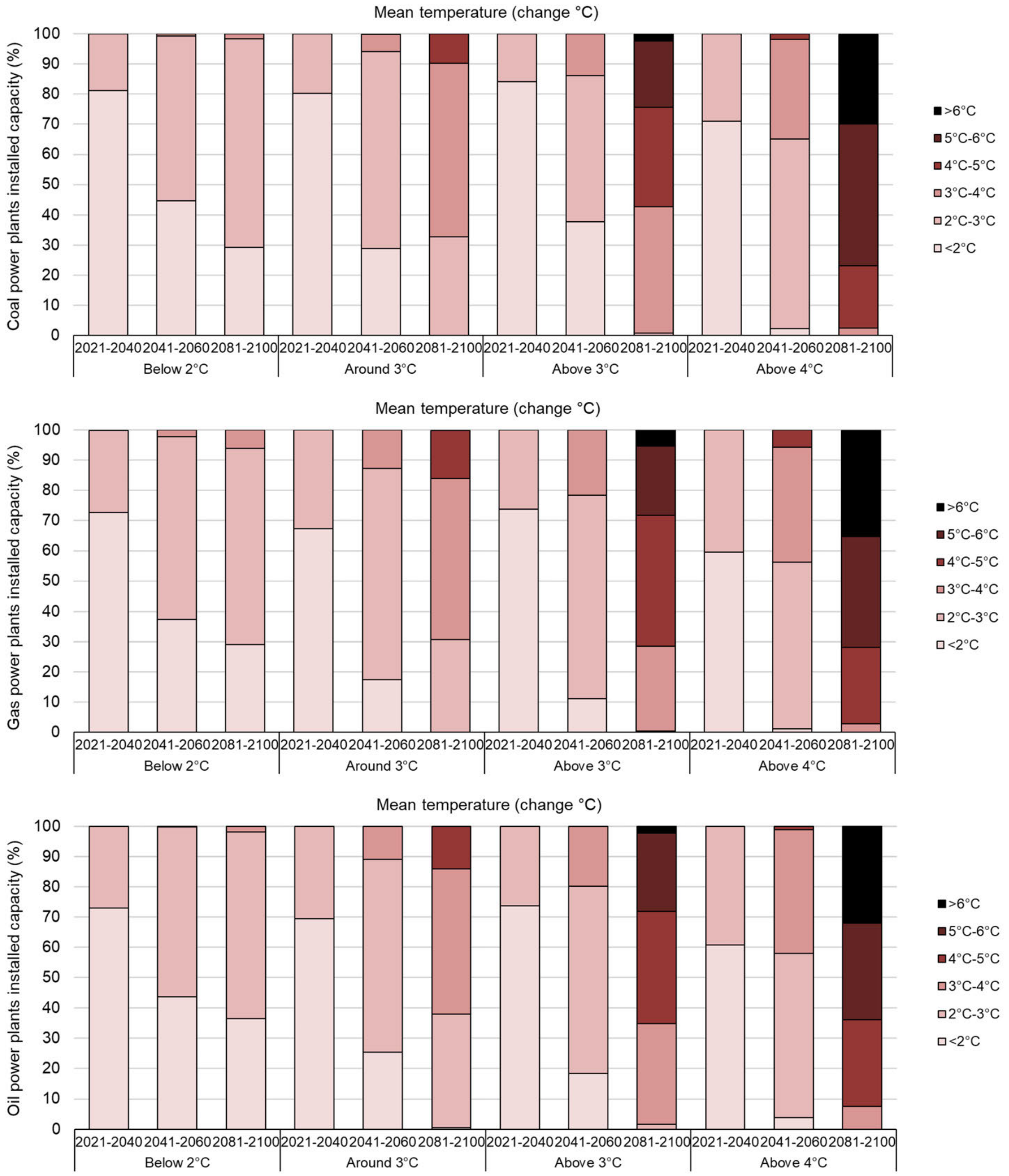
Higher temperatures can curtail the generation of fossil-fuelled thermal power plants

Rising global temperatures could also decrease electricity generation from fossil fuel power plants. When comparing two leading types of thermal power generation, natural gas combined-cycle power plants are generally more sensitive and more exposed to changes in ambient temperatures than coal power plants. The performance of natural gas combined-cycle power plants strongly depends on the air mass flow entering the gas turbine compressor. The air mass flow is determined by the density of the air, which decreases when ambient temperature increases. Multiple studies show that the decreased air mass flow will lead to a decrease in generation capacity and efficiency, although the level of decrease may vary among power plants. For instance, a study on the HABAŞ natural gas combined-cycle power plant in Turkey showed that an increase in ambient temperature from 8°C to 23°C decreases electricity generation capacity from 227.7 MW to 197.3 MW and leads to a slight fall in efficiency, from 43.3% to 42.7%. Another study on a natural gas combined-cycle power plant with CO_2 capture in Mexico estimates a generation capacity drop from 676.3 MW to 530 MW and efficiency reduction from 50.95% to 48.01% when temperature increases from 15°C to 45°C.

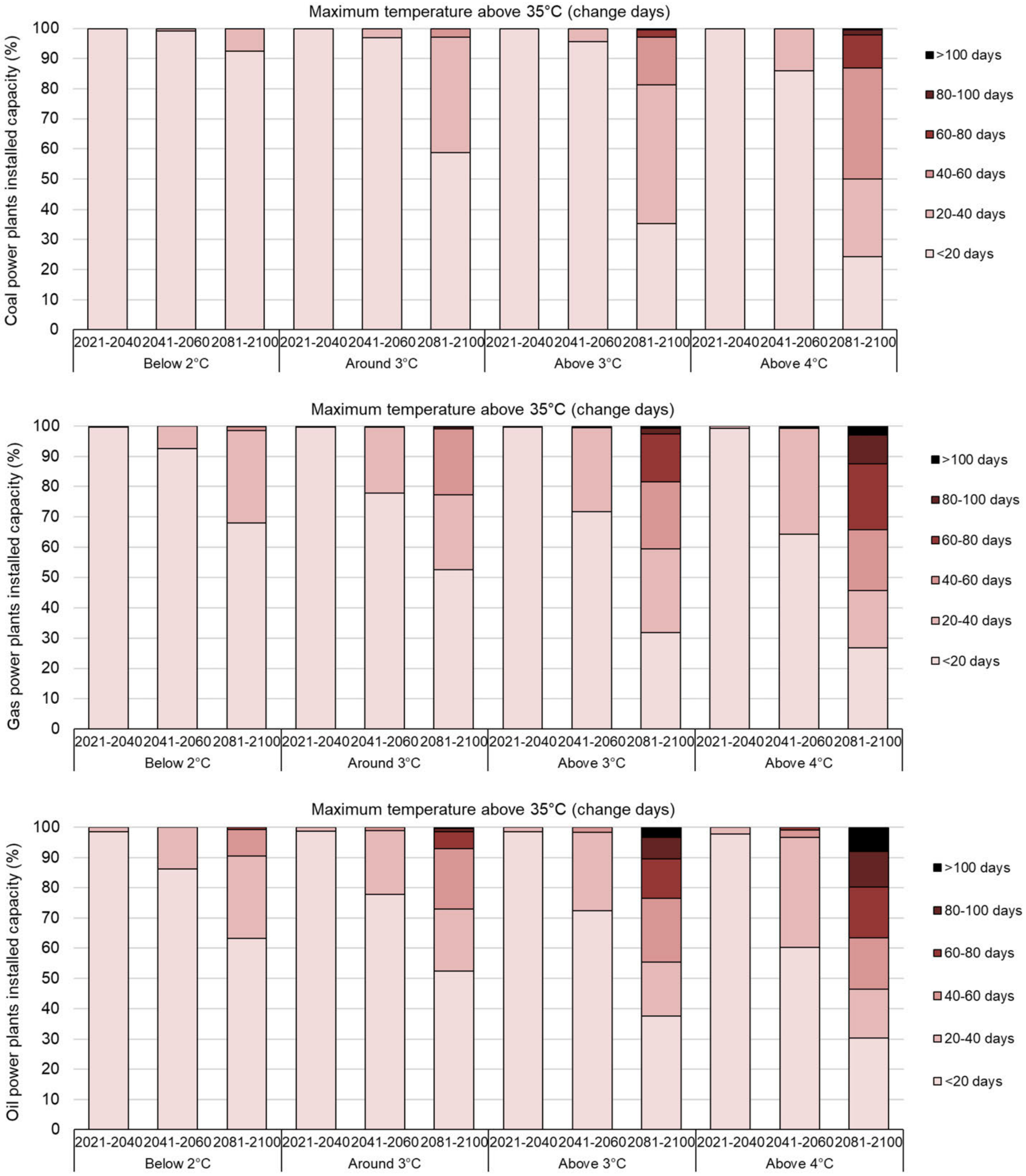
Meanwhile, global warming that could lead to warmer intake water temperatures or discharge water temperatures can curtail generation output from coal power plants. Coal power plants tend to be more sensitive to water temperature changes than natural gas combined-cycle power plants because they generally require a larger quantity of cooling water. Intake water temperature that is too high can reduce plant operating efficiency and maximum generation capacity. Excessive water temperatures discharged from power plants after cooling can curtail power or cause shutdown if there are regulations on discharge water temperatures. In the United States, 13 out of 18 incidents of power curtailment involving coal power plants from 2000 to 2015 were related to high discharge water temperatures or warm intake water temperatures. Similarly, a hard coal power plant in Karlsruhe, Germany, had to shut down because the cooling water source temperature increased to above 28°C, the threshold for cooling water discharge.

Additional measures can prevent and compensate for the loss of output caused by a temperature rise. For instance, some natural gas power plants in hot regions use inlet air cooling technologies to reduce ambient air temperature before air enters. Coal power plants experiencing warmer cooling water issues build extra cooling towers to stay in the permitted limits of discharge water temperature.

Fossil-fuelled power plants exposed to a temperature rise and extreme heat by climate scenario



Fossil-fuelled power plants exposed to a temperature rise and extreme heat by climate scenario (continued)



Note: The graphs show the share of fossil-fuelled power plants installed capacity for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

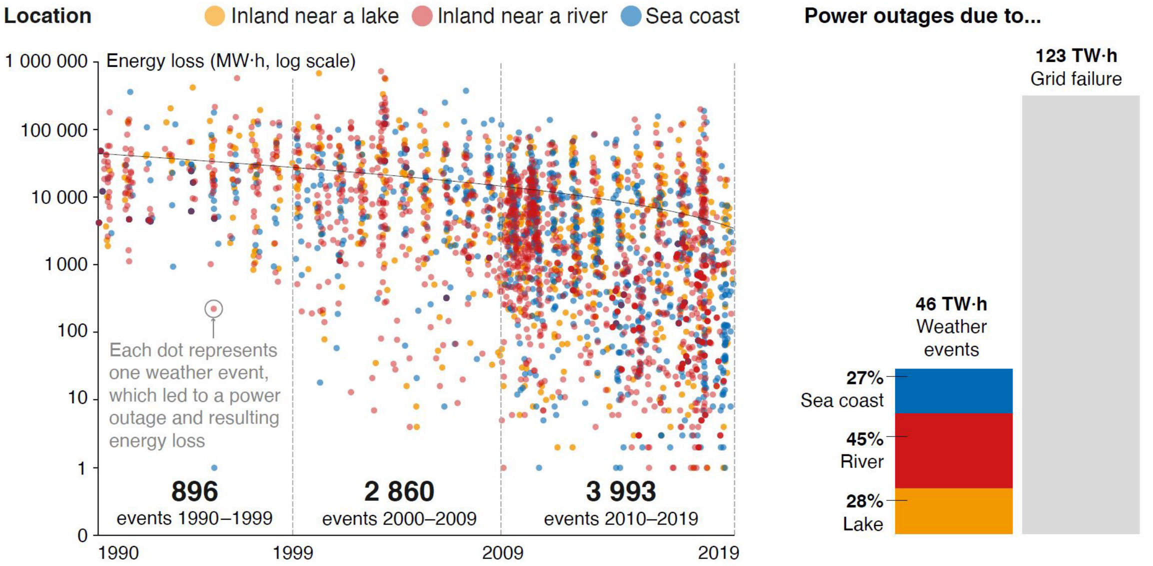
Nuclear power

Nuclear power is the second-largest source of low-carbon electricity today, providing 10% of electricity generation. In 2021, the global capacity of nuclear power was 413 GW, declining by almost 3 GW globally as newly completed reactors were not able to compensate for over 8 GW of retirements. If existing policies and trends are maintained (STEPS), nuclear capacity in 2050 could reach 590 GW. To achieve net zero emissions by 2050, nuclear capacity needs to grow towards 871GW, which requires annual capacity additions to be nearly four times their recent historical average.

Nuclear power is extensively used as a baseload source of electricity in many countries. It generally runs at close to a maximum capacity factor continuously and is comparatively resilient to extreme weather events thanks to high safety measures. In the United States, nuclear power plants produce maximum power more than 93% of the time during the year, demonstrating their resilience against extreme weather conditions. For instance, when Hurricane Harvey devastated Texas in 2017, two nearby nuclear reactors of 2.7 GW operated at full capacity, while there were wild fluctuations in electricity generation from other sources. According to the OECD-NEA, in 2004-2013, weather-related outages represent a loss of only 0.17% of total electricity production.

Although nuclear power plants are generally resilient and function as key assets even under extreme weather conditions, they are also exposed to the growing risks of climate change. The International Atomic Energy Agency (IAEA) shows that weather-related disruptions increased five times in three decades between 1990 and 2019, with a notable acceleration since 2009, although the resulting impacts in terms of production losses diminished thanks to improved operation practices and evolving regulatory obligations. According to recent analysis, the average frequency of climate-induced outages (full and partial) has dramatically increased, from 0.2 outages per reactor-year in the 1990s to 1.5 in the 2010s, while non-climate-driven outages have only increased by 50% over the same period. If the growth pattern of past climate-induced outages continues into the future without adaptation measures undertaken, the average annual energy loss could be around 0.6% in the long term (2081-2100) in a low-emissions scenario (RCP 2.6) and 1.4-2.4% in a high-emissions scenario (RCP 8.5).

Nuclear power plant outages due to weather events, 1990-2019



Sources: IAEA (2022b) based on IAEA Power Reactor Information System (PRIS) Database.

Changes in cooling water temperature and availability are a major concern for nuclear power plants

Climate impacts on cooling water temperature and availability are one of the major causes of the climate-driven disruptions and reduced output of nuclear power plants. Since most nuclear power plants rely on cooling water[15] from rivers, lakes or the sea, changes in cooling water temperature and availability can affect the operation and safety of nuclear power plants.

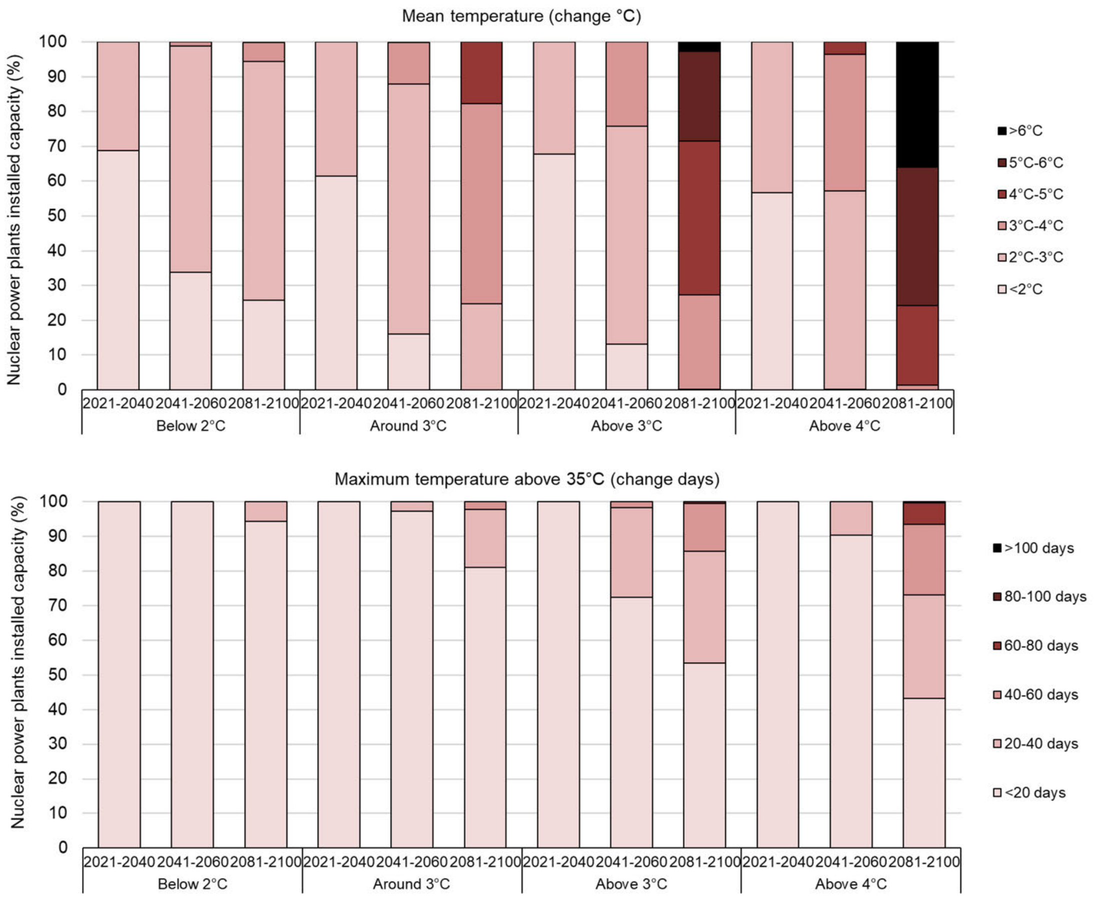
Warmer cooling water can gradually lower the generation efficiency and eventually reduce generation output. When water temperature increases, the cooling capacity of the reactor is reduced, and the efficiency of components (e.g. turbines) drops. If the cooling capacity falls below a certain limit, nuclear power plants need to shut down for safety and cut their generation output. For instance, in July 2012, nuclear power plants in Ohio and Vermont curtailed output to their lowest seasonal power generation levels in nine years due to the cooling water stress caused by extreme heat and droughts.

Rising water temperature can also curtail or temporarily shut down nuclear power generation if there are environmental regulatory thresholds for thermal release. Some countries, including the United States and France, regulate the release of used cooling water to protect the plants and ecosystems of rivers and lakes. In France, the heatwaves in June and July 2019 forced the power utility Électricité

[15] As of 2021, only one nuclear power plant (Bilibino nuclear power plant in the northeastern region of Russia) is using dry cooling.

de France [to curb or entirely stop the output of some nuclear reactors](#) based on the [French regulations](#) that power generation must be cut when water temperatures go above 28°C.[16] Some countries have lifted the thresholds for thermal release from nuclear power plants in light of increasing water temperatures due to climate change. For instance, the U.S. Nuclear Regulatory Commission allowed the [Millstone plant in Connecticut](#) to use Long Island Sound seawater up to 26.7°C in 2014, lifting the previous 24°C limit. In the same year, it approved [an increase in the intake temperature limit](#) for the Turkey Point plant in Florida to 40°C from 37.8°C. [According to the OECD-NEA](#), the warm cooling water issue is the biggest weather-related risk, which accounted for nearly 70% of weather-related outages in 2004-2013.

Nuclear power plants exposed to a temperature rise and extreme heat by climate scenario



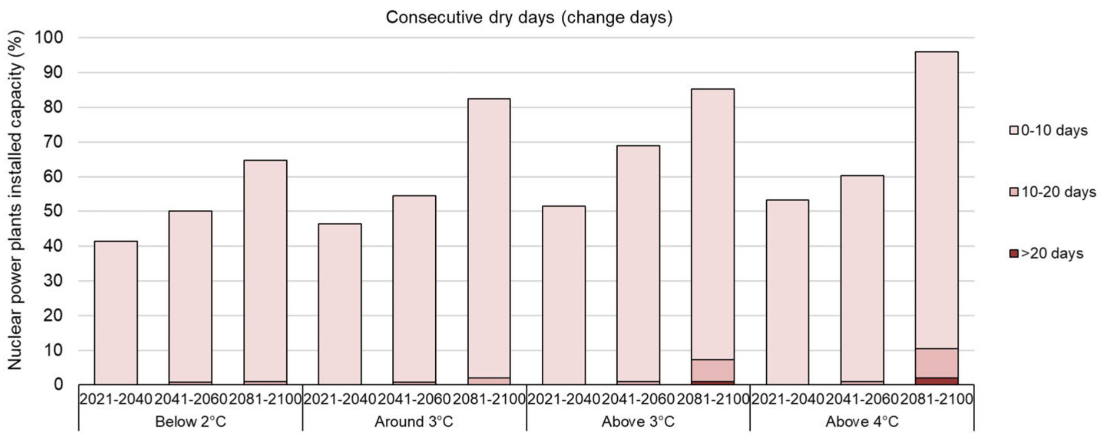
Note: The graphs show the share of nuclear power plants installed capacity for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on [S&P Global](#) (2021a) and [IPCC](#) (2021b).

[16] With [exceptions during periods of peak demand](#), as long as the company reduces output at other times of day.

Given that the mean surface temperature is projected to rise, water temperature could rise too, becoming a major concern for some nuclear power plants. Climate projections show that around three-quarters of nuclear power plants are likely to be exposed to over 3°C of warming in a low-emissions scenario and over 5°C in a high-emissions scenario in 2080-2100, compared to the pre-industrial period. If GHG emissions are not mitigated, over 50% of nuclear power plants could experience at least 40 more days maximum temperature above 35°.

Severe droughts that limit cooling water availability can force nuclear power plants to curtail output or temporarily shut down. Lack of cooling water is particularly critical to nuclear plants because they have greater cooling needs than other thermal power plants. According to the National Energy Technology Laboratory in the United States, nuclear power plants need 2 725 L of water per MWh for cooling, while coal or natural gas plants need only 1 890 L and 719 L, respectively. If the water level drops below a certain point, the operation of nuclear power plants can be instantly stopped. For example, when severe drought hit France in 2020, the Chooz nuclear power plant was closed from late August to the beginning of October to comply with an agreement between France and Belgium to protect the minimum flow rate of the Meuse River. Although the low water level issue has rarely prompted outages in the past decades, climate change is likely to increase the problems related to low water levels in some locations.

Nuclear power plants exposed to a drier climate by climate scenario



Note: The graph shows the increase in consecutive dry days, compared to the pre-industrial period (1850-1900).
Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

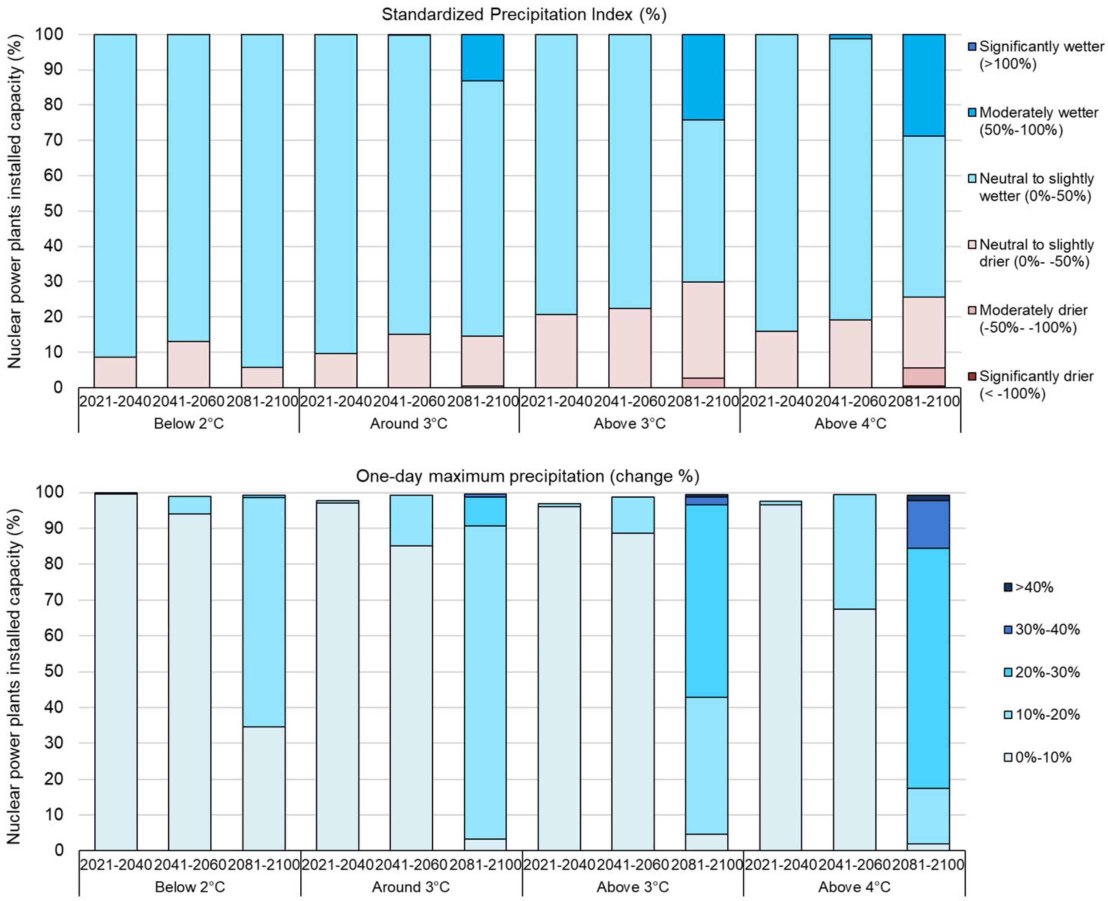
In some places, climate change could bring some unintended benefits to nuclear power generation by reducing the probability of interruptions caused by frazil ice formation in cooling water. Air temperature drops with strong winds, and a decrease in seawater salinity can create frazil ice and block cooling water intake, leading to the temporary shutdown of nuclear power plants. The Olkiluoto nuclear power plants in Finland had to shut down in 1988, 1995 and 2008 due to frazil ice formation incidents. According to the OECD-NEA, this cold cooling water issue accounted for over one-fourth of weather-related outages in 2004-2013, the second-largest share of outages after warm cooling water problems. Disruptions related to frazil ice formation may decrease, given that climate change is projected to suppress the creation of frazil ice with rising air temperatures and reduced mean wind speed in some regions, such as northern Europe and Russia.

More frequent floods, combined with heavy rainfall, could disrupt nuclear power generation

Nuclear power facilities are also exposed to floods. Floods can damage multiple parts of nuclear power plants; reactor auxiliary systems, pumps and electrical components are generally the most affected. To date, floods have rarely caused outages of nuclear power plants but can affect plant operation even when damage is limited. For instance, flooding along the Missouri River due to record snowmelt runoff combined with heavy spring rains surrounded the Fort Calhoun nuclear power station in Nebraska in June 2011 and resulted in some water leakage into the turbine building. Although critical parts of the plant were protected from the flooding, the power station was shut down for nearly three years.

Given that climate projections show that heavy precipitation, pluvial floods and river floods increase in western and central Europe, East Asia and North America, where a majority of global nuclear capacity is located, floods could be a potential risk to nuclear power operation and safety. Indeed, nuclear power plant sites of 65% of installed capacity are projected to see an over 10% increase in one-day maximum precipitation in a low-emissions scenario, and the share of exposed nuclear power plants could go up to 97% in a high-emissions scenario. Nuclear power plants sites accounting for 15% of total installed capacity in the world could experience an over 30% increase in one-day maximum precipitation if GHG emissions are not mitigated. The projected increase in floods and heavy rainfall, and lessons learned from previous disruptions, are driving enhancement of protection measures.

Nuclear power plants exposed to a wetter climate by climate scenario



IEA. CC BY 4.0.

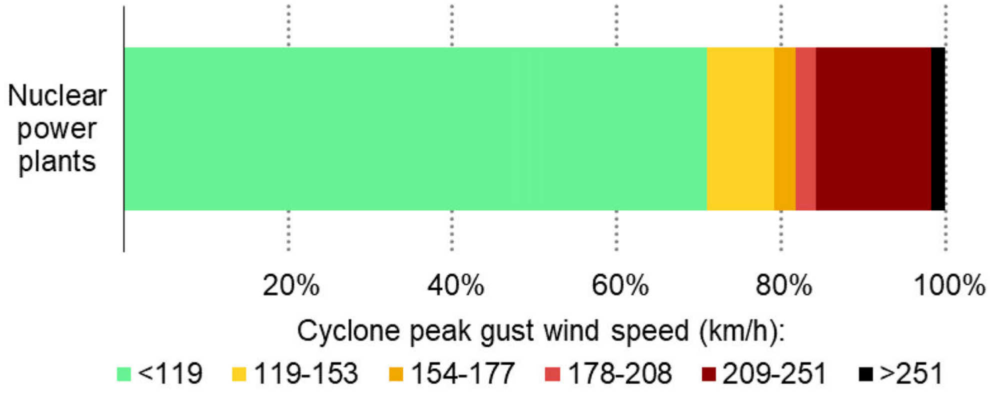
Note: The graphs show the share of nuclear power plants installed capacity for each level of standardised precipitation using the Standardized Precipitation Index and changes in one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

More intensified tropical cyclones could lead to longer disruptions and more energy loss of nuclear power generation

Tropical cyclones are another potential cause of climate-induced disruptions to nuclear power generation. Almost 30% of existing nuclear power sites in terms of capacity are exposed to tropical cyclones, and around 60% of them could face intense tropical cyclones above Category 3. Although tropical cyclones were not a major cause of climate-induced disruptions to nuclear power generation in the past three decades, a recent analysis shows that they were the major causes of climate-driven full outages in North America, East Asia and South Asia during the last decade. Although many cases were related to pre-emptive shutdowns[17] in anticipation of coming tropical cyclones, there were still some cases of unplanned shutdown due to physical damages to the equipment and grid. For instance, Typhoons Maysak and Haishen, which hit Korea in early September 2020, prompted a shutdown of eight reactors due to flashovers (a high-voltage electrical short circuit caused by high wind). The flashovers happened because of strong winds that brought a large amount of salinity to the power supply equipment in six reactors and moved cables close to tower structures.

Nuclear power plants exposed to tropical cyclones



Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.
Sources: IEA analysis based on S&P Global (2021a) and UNDRR Global Assessment Report (2015).

Given that climate projections show that the proportion of intense tropical cyclones will increase at the global scale, the number of unplanned outages of nuclear power plants could increase if no improvement in design and operation is undertaken. Furthermore, the duration of outages and energy loss can increase in the future with the growing number of unplanned shutdowns, although in the past, the average duration of outages caused by tropical cyclones was relatively short (65 hours per outage) and resulted in a comparatively small energy loss compared with other climate-driven outages[18] thanks to a high share of pre-emptive shutdowns.

[17] For instance, under the federal law of the United States, nuclear plants are required to shut down at least two hours before the impact of hurricane-force wind of 72 miles per hour or greater. Inspection and approval from the Federal Emergency Management Agency and the Nuclear Regulatory Commission are required to restart plants. Once a plant receives the approval, it can take 72 to 120 hours to reach full power.
[18] Such as cooling water issues (110 hours per outage).

Hydropower

Hydropower is the backbone of low-carbon electricity, generating more electricity than all other renewables combined. Over the last 20 years, hydropower's total capacity rose by 70% globally, reaching 1 358 GW, and supplied 15% of electricity generation in 2021. Hydropower plays a major role in providing flexibility and maintaining the security of electricity systems. Hydropower plants can ramp up and down their generation much faster than other power plants, such as nuclear, coal and natural gas. Hydropower is therefore being used to adjust electricity supply, reflecting changes in demand and fluctuations in variable renewable energy supply. Today, hydropower plants account for almost 30% of the world's capacity for flexible electricity supply.

Hydropower has potential to grow. Globally, around half of hydropower's economically viable potential is untapped. If existing policies and trends are maintained (STEPS), hydropower capacity in 2050 could reach 2 027 GW. If efforts are made to meet net zero emissions by 2050, hydropower capacity could grow to 2 685 GW, or twice the current level. To meet this level, approximately 3% average annual generation growth rate would be needed.

Further development of hydropower capacity will be subject to future climate conditions. Changes in precipitation and temperature due to climate change could shift hydropower generation potential and output. They can change water availability (e.g. with changes in annual mean precipitation), shift seasonal flows (e.g. with early snow melt), increase the variability in streamflow (e.g. with more frequent heavy rainfalls and droughts), add risks of physical damages to assets (e.g. with more debris and sediment due to intense tropical cyclones and their associated events, such as landslides and floods) and increase evaporation losses from reservoirs (e.g. with extended droughts).

At a global scale, the effect of climate change on hydropower generation remains uncertain. Some experts say that global hydropower production could go either direction in the range of -5% to +5% by the 2080s in a high-emissions scenario, while others project a small increase, highlighting the expected increase in gross hydropower potential (2.4-6.3%) by 2080s, compared to a baseline period of 1971-2000.[19] Another study suggests that climate change impacts on global hydropower generation remains uncertain, although the technical potential for hydropower technology could increase due to climate change.

[19] In IPCC RCP 4.5 and RCP 8.5.

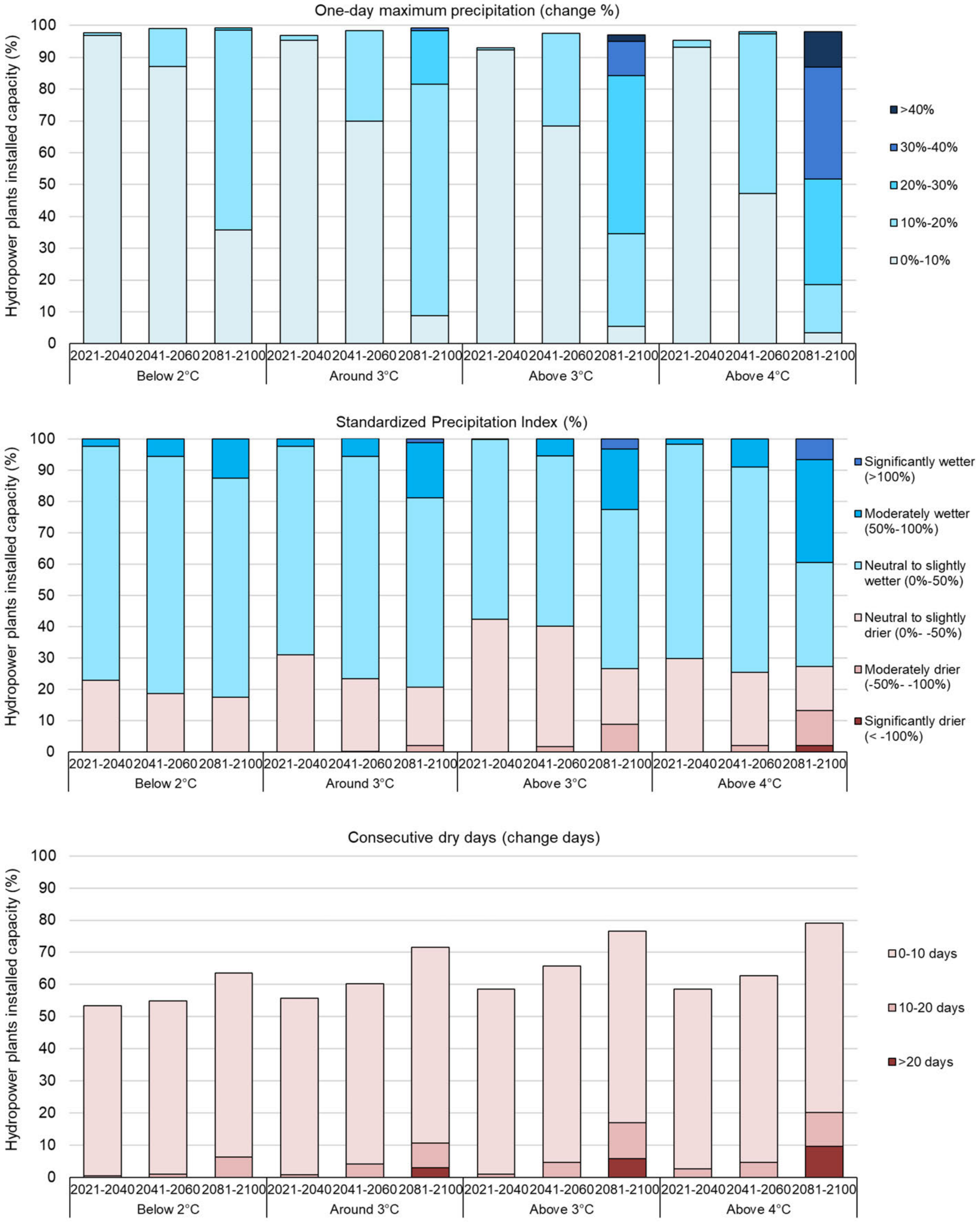
Climate change will increase geographical and temporal variabilities in hydropower generation, creating winners and losers

Despite uncertainty regarding climate impacts on global hydropower generation, growing evidence suggests that climate change creates significant regional gaps in future hydropower generation, making winners and losers in hydropower production. According to an analysis of climate impacts on existing hydropower dams around the world, the Mediterranean countries in southern Europe, northern Africa and the Middle East are likely to see the most prominent reduction in hydropower generation – by approximately 40% on average by the end of the century in a high-emissions scenario.[20] In contrast, some countries in Scandinavia are projected to experience a significant increase of around 15%, on average.

Similarly, climate projections indicate that 13% of hydropower plants would experience a drier climate in 2080-2100 in a high-emissions scenario, compared to the pre-industrial period (1850-1900), while 40% could see a wetter climate. Some 20% of hydropower plants are also projected to see an over ten-day increase in consecutive dry days, while 46% could see a notable increase in one-day maximum precipitation by more than 30%. In a low-emissions scenario, 64% of hydropower plants are projected to see an increase in one-day maximum precipitation by more than 10%, while 6% of hydropower plants experience an over ten-day increase in consecutive dry days.

[20] In the SRES A2.

Hydropower power plants exposed to a wetter or drier climate by climate scenario

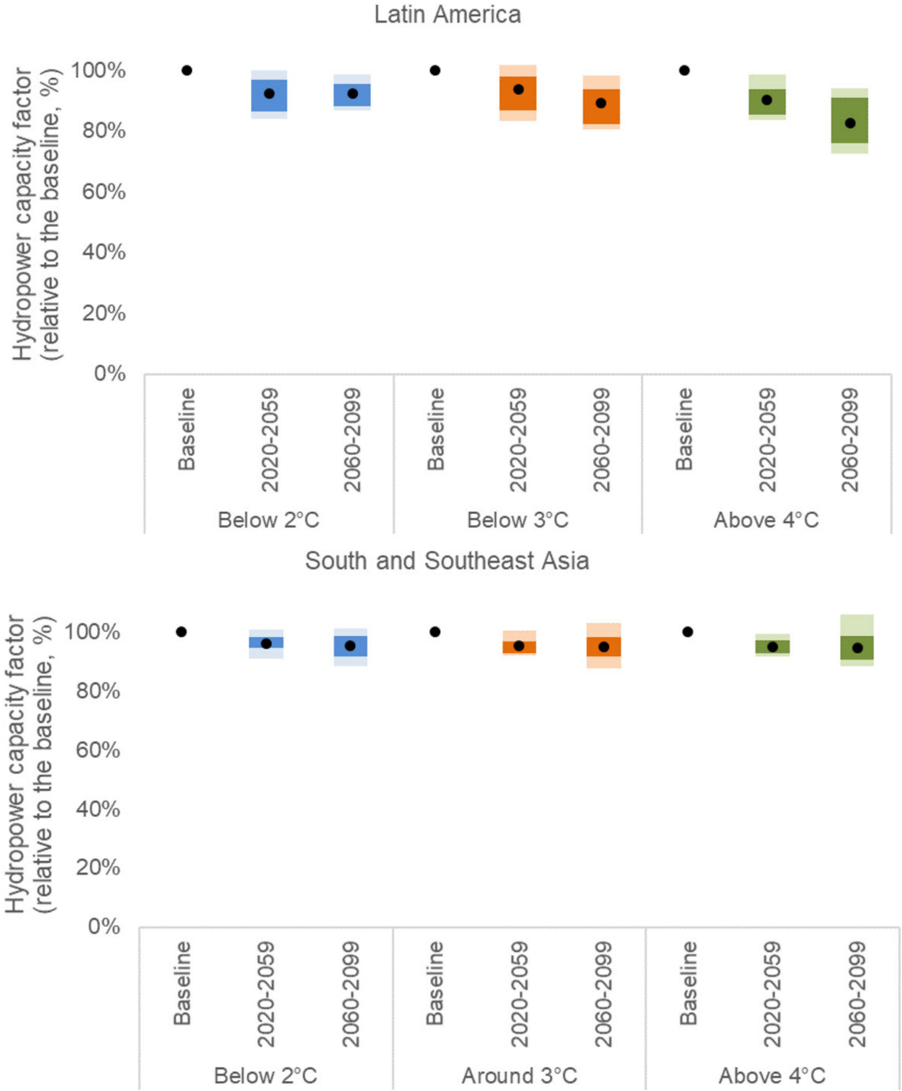


Note: The graphs show the share of hydropower plants installed capacity for each level of standardised precipitation using the Standardized Precipitation Index, consecutive dry days and changes in one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).

Sources: IEA analysis based on S&P Global (2021a) and IPCC (2021b).

The IEA also conducted climate impact assessments for existing hydropower plants in Africa, Latin America and South and Southeast Asia comparing various climate change scenarios. The assessment shows that a majority of existing hydropower plants in these regions are projected to experience an overall decline in hydropower generation while showing significant geographical variabilities. For instance, the regional mean hydropower capacity factor of Latin America is projected to be lower in 2060-2099 than in 1970-2000 by over 11% on average,[21] while that of South and Southeast Asia will decline only around 5%.[22]

Latin America and South and Southeast Asia mean hydropower capacity factor by scenario, 2020-2099 relative to the baseline 1970-2000



Notes: The black dots indicate the average hydropower capacity factor of the selected hydropower plants based on results from 20 combinations of General Circulation Models (GCMs) and Global Hydrological Models (GHMs) per scenario. The coloured bars indicate the range of the results; the darker colours in the bars show the range of 80% and 60% of the results for Latin America and South and Southeast Asia, respectively.

Sources: IEA (2021h) and IEA (2021g).

[21] From 7.5% in RCP 2.6 to 17.4% in RCP 8.5.
[22] From 4.7% in RCP 2.6 to 5.4% in RCP 8.5.

Even within a continent, spatial variability is notable, and higher GHG emissions are likely to widen the geographical gap. In Latin America, a large part of Central and South America are projected to see a consistent decrease in hydropower generation by 2100 in both low-emissions and high-emissions scenarios. Among other countries, Chile, Guatemala and Mexico are likely to see the largest drop in hydropower capacity factors, followed by Costa Rica, Brazil and Paraguay. The decrease of hydropower capacity factors in Chile, Guatemala and Mexico (in 2060-2099, compared to 1970-2000) will be more significant, with higher GHG emissions: 33-38%,[23] compared to 6-10% in a low-emissions scenario.[24] In contrast, some Andean countries along the northwest coast of South America (Colombia, Ecuador and Peru) are projected to see a slight increase or remain at the same level.

Similarly, climate change will lead to a larger geographical gap in hydropower capacity factors in South and Southeast Asia. Some countries (Thailand, Lao People's Democratic Republic and Pakistan) are likely to see a decline in hydropower capacity factors, while others (Bhutan, Nepal, Malaysia and the Philippines) could experience a slight increase or no significant change (in 2060-2099, compared to 1970-2000). In a high-emissions scenario, Thailand, Lao People's Democratic Republic and Pakistan are projected to see a decline of over 10% in 2060-2099, while Malaysia and the Philippines experience a slight increase of 6% and 3%, respectively.

The regional gap is also projected to increase in terms of hydropower generation potential, which could affect future hydropower development. According to an analysis, gross hydropower potential is likely to increase more than 20% in regions like central Africa, India, Central Asia and northern high-latitude areas, while southern Europe, northern Africa, southern United States and parts of South America, southern Africa and southern Australia would experience over 20% decreases.

Climate change is also likely to increase temporal variability, resulting in larger annual or seasonal variations in hydropower generation. For instance, rising temperatures and the associated decrease in glacier volumes increases the temporal variability of hydropower generation, affecting flow rates, quantities and seasonality. In the Hindu Kush Himalayan region, melting glacier and snowpack have a dramatic impact on hydropower, increasing seasonal variability by provoking glacier lake outburst floods in spring and adding annual variability in generation output with a short-term increase in generation (with more water from the melting glaciers and snowpack) and a long-term decrease in river flows (due to the glacier recession). The latest IPCC report projects that change in snow and

[23] Guatemala (38%), Chile (34%) and Mexico (33%) in RCP 8.5.
[24] Chile (10%), Mexico (10%) and Guatemala (6%) in RCP 2.6.

glacier melt runoff will lead to a decline in hydropower production in mountain basins in India, Switzerland and the United States.

More frequent and intense droughts in some regions can also increase the temporal variability of hydropower generation. Globally, for the period 1981-2010, the utilisation rate of hydropower was reduced by 5.2% during drought years, compared to long-term average values. Climate change is likely to bring more frequent hydrological droughts in some regions, such as the Mediterranean and southern Africa, with negative impacts on hydropower generation. Indeed, some hydropower plants in these regions are already experiencing disruptions due to droughts. For instance, the power supply in Zambia, where more than 80% of electricity comes from hydro, has been significantly affected by declining water availability due to more frequent droughts and a shorter rainy season. In February 2016, the water level of the Kariba Dam, one of the biggest electricity sources for Zambia and Zimbabwe, dropped to near record lows (12%), prompting blackouts and power rationing. The disruption occurred again in August 2019, and the Kariba station needed to cut output and impose daily blackouts. Climate change is projected to cause a further decrease in hydropower generation in Zambia and Zimbabwe of over 9% in 2060-2099, compared to 2000-2010.[25]

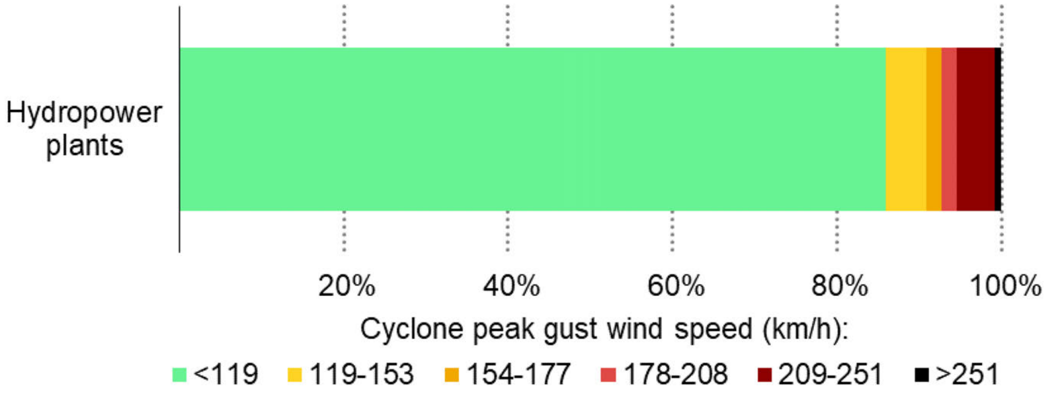
Tropical cyclones are another challenge to hydropower plants

Tropical cyclones and associated heavy rainfall, floods and landslides can also challenge hydropower generation. Tropical cyclones and associated events can increase sediment, floating debris and torrential streamflow, which can impair hydropower equipment, threaten dam security and cut generation output. For instance, Tropical Cyclone Idai made two major hydropower plants in Malawi go offline, causing flooding and excessive debris. Due to the halt, Malawi's hydropower capacity dropped by more than 80% and caused widespread disruption in electricity supply for several days.

The impacts of tropical cyclones on hydropower generation may increase in the future due to the projected increase in the proportion of intense tropical cyclones (Category 3-5). Currently, 14% of hydropower installed capacity is exposed to tropical cyclones, and 7% is estimated to be under threat of major tropical cyclones above Category 3.

[25] According to IPCC RCP 6.0.

Hydropower plants exposed to tropical cyclones



Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.

Sources: IEA analysis based on S&P Global (2021a) and UNDRR Global Assessment Report (2015).

Solar PV

Solar PV generation increased to 1 003 TWh in 2021, accounting for around 4% of electricity generation. Solar PV demonstrated the second-largest absolute generation growth of all renewable technologies in 2021, behind wind and ahead of hydropower. The unprecedented growth was largely due to large capacity additions in China (38% share of the total), the United States (17%) and European Union (10%), and to the fall in solar PV cost in most of the world.

However, average annual generation growth needs to increase much faster to meet net zero emissions by 2050. In the NZE, 4 160 GW of net solar PV capacity needs to be added between 2021 and 2030, until the installed capacity reaches 15 468 GW in 2050.

Solar PV relies on irradiance – the amount of solar radiation which can be turned into energy. Irradiance is determined by climate-related factors, such as season, weather, clouds, water vapour, fires, temperature and daylight hours, as well as non-climate factors, such as location, pollutants and volcanoes.

Potential changes in solar radiation due to climate change could have minor impacts on electricity generation from solar PV. If other variables remain unchanged, solar power generation will decrease in proportion to the reduction in solar irradiation. Climate models project that solar radiation increases in the northern part of South America, southern Africa, the Mediterranean and East Asia while decreasing in the higher latitudes, such as northern Europe and the Arctic regions. Some parts of West Africa and South Asia could see a decrease as well.

However, the decreasing irradiance in higher latitudes is expected to have comparatively small impacts in practice, as there is less solar PV potential and fewer installations.

Solar PV needs to manage the risks of more frequent heatwaves and wildfires

Heat is the climate impact most likely to affect solar power generation. Higher temperatures lead to a lower voltage and less electricity generation, as solar PV works best in cool, sunny weather. Moreover, solar power generation efficiency degrades as the temperature increases, generally from -0.3% to -0.5% per degree above 25°C. Extreme temperature can also increase the electrical resistance of the circuits and damage the cell and other materials.

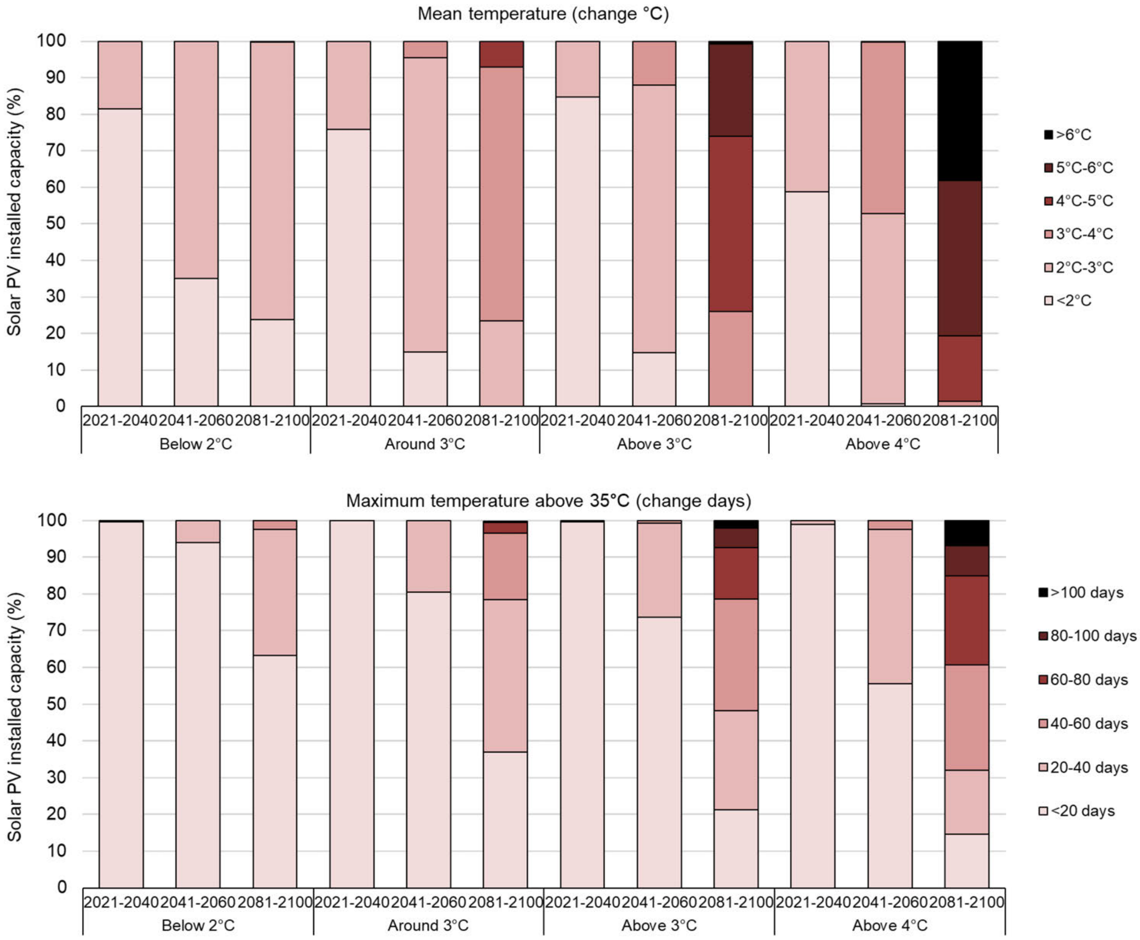
Climate models show continued temperature increases on average at the global scale and show a majority of places experiencing an increase in extreme heat events, even in a 2°C warming scenario. The number of days with maximum temperature above 35°C will be higher by 17 days per year, compared to the pre-industrial period (1850-1900). If GHG emissions are not mitigated, this could reach 54 days per year.

The significant decrease in solar PV efficiency during extreme heat events could add challenges to meeting soaring electricity demand for cooling in summer. For instance, if surface temperature goes above 35°C and raises solar panel temperature to 70°C,[26] solar PV efficiency can drop by 13.5-22.5%, leading to a notable reduction in generation output if no adaptation measures and technological enhancements are undertaken. The decrease in electricity generation from solar PV could add stress to electricity systems often already strained to meet cooling demand in hot weather. Given that the northern part of South America, large parts of Africa (the Sahara, West Africa and southern Africa), northern and central parts of Australia, the Arabian Peninsula and the west coast of India are all projected to experience a notable increase (over 24 days) in number of days with maximum temperature above 35°C,[27] backup measures to compensate for reduced solar power generation may be needed.

[26] Solar PV's efficiency standard is based on the solar panels' temperature, which is generally significantly higher than the surface temperature – potentially twice as high.

[27] These regions are projected to show an increase of more than 24 days in 2081-2100 in SSP1-2.6, compared to 1850-1900.

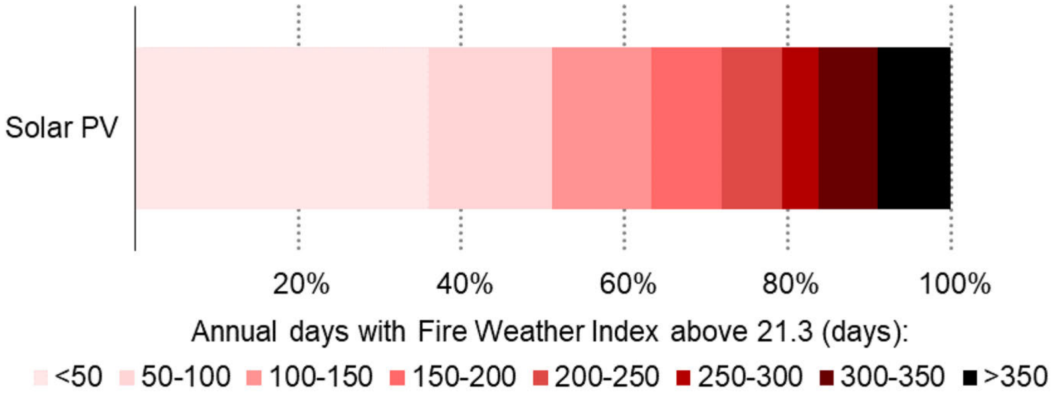
Solar PV exposed to a hotter climate by climate scenario



Note: The graphs show the share of solar PV installed capacity for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C.
Sources: IEA analysis based on Global Energy Monitor (2022b) and IPCC (2021b).

Rising temperature, coupled with increasing aridity and wind, can lead to a higher risk of wildfires for solar power plants. Over 60% of today's solar PV plants are located in regions with more than 50 days of fire weather per year, and around one-quarter are exposed to 200 days. Wildfires that emit a large amount of smoke particulates into the atmosphere can significantly reduce solar power generation, absorbing and scattering incoming solar radiation. The wildfires in September 2020 in the United States are considered responsible for 10-30% of solar power generation decrease in California during peak hours. In addition, wildfires cause physical damage to solar PV plants. In the United States, roughly 50% of all claims for solar asset damage due to extreme weather were caused by wildfire, and it has cost the solar industry tens of millions of dollars in losses over the last decade. If climate change is not mitigated, wildfire is likely to become a massive threat to solar power plants, with higher frequency, longer duration and spread rate.

Solar PV exposed to wildfires



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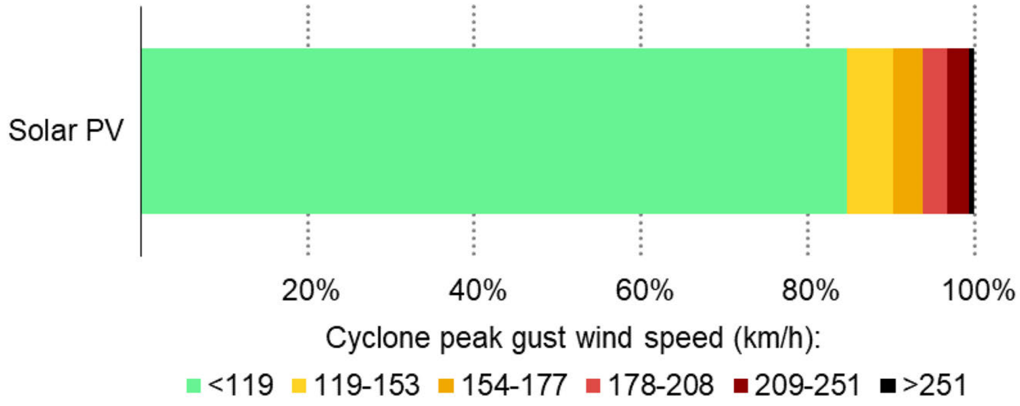
Note: The FWI is a meteorologically based index used worldwide to estimate fire danger. The higher the FWI, the more favourable the meteorological conditions to trigger a wildfire. The FWI can be categorised into six classes of danger: Very low danger (FWI less than 5.2), Low danger (FWI between 5.2 and 11.2), Moderate danger (FWI between 11.2 and 21.3), High danger (FWI between 21.3 and 38.0), Very high danger (FWI between 38.0 and 50) and Extreme danger (FWI greater than 50).

Sources: IEA analysis based on Global Energy Monitor (2022b) and Copernicus Emergency Management Service (2022).

Solar PV needs to address the destructive impacts of tropical cyclones

Solar PV systems can be also damaged by tropical cyclones. Solar panels that are not properly attached on rooftops or are located on the ground are at risk of wind damage. Solar PV panels can be also damaged by flying objects during tropical cyclones. In Japan, Tropical Cyclone Faxai destroyed the biggest floating solar plant (13.7 MW) in 2019 by tearing the modules off and causing fires. In Puerto Rico, Tropical Cyclone Maria destroyed the 100 MW solar PV system near Humacao in 2017. More resilient designs with better attachments and advanced sensors can not only minimise physical damage from tropical cyclones but also support building climate resilience by providing localised power to areas where power supply from the main grid is interrupted.

Solar PV exposed to tropical cyclones



Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.

Sources: IEA analysis based on Global Energy Monitor (2022b) and UNDRR Global Assessment Report (2015).

Wind power

In 2021, the total wind power capacity reached 832 GW and generated 1 870 TWh, which was around 7% of total global electricity generation. It showed a notable increase from the 2020 level thanks to the newly added capacity of 95 GW globally. About 22% of the capacity growth was delivered by offshore technology, the highest in history and three times the average of the previous five years. China was responsible for almost 70% of wind generation growth in 2021, followed by the United States at 14% and Brazil at 7%.

Wind power is expected to grow and play a significant role in clean energy transitions. According to the NZE, wind would become the largest source of electricity generation, accounting for 36% of total electricity generation. Total wind power capacity would reach 7 795 GW in 2050, which is more than 9 times the current level.

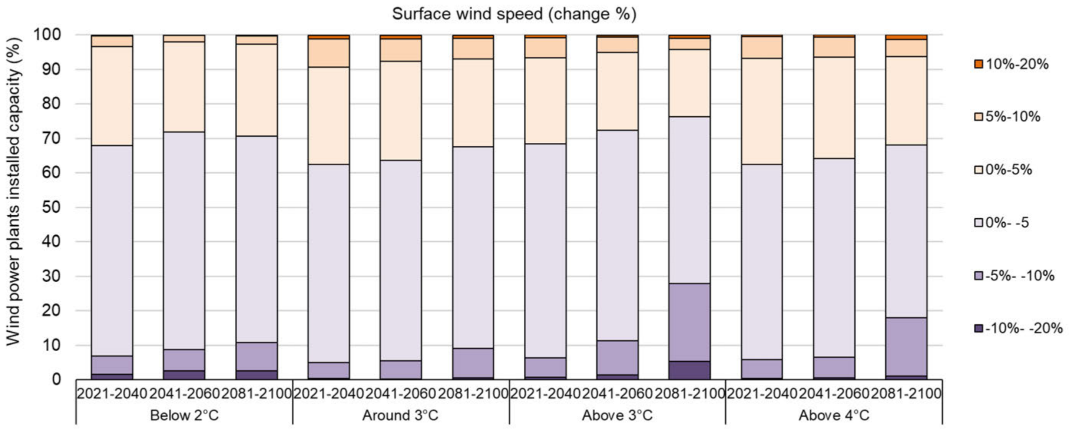
Major wind power regions could experience decreasing average wind speed

Wind power generation is subject to climate and weather conditions, since it uses the energy flow of the atmosphere generated from the uneven heating of the Earth's surface by the sun. In general, higher wind speeds make blades rotate faster, generating more power. The wind power generation is proportional to the cube of the wind speed, although excessively high wind speeds may lead to automatic shutdown or physical damages.

Climate change can reduce wind power generation in some regions by decreasing mean wind speed. In the past years, global mean wind speed decreased over most land areas where observational coverage is high. In particular, large parts of North America and Eurasia recorded declining trends in mean wind speed. The downward trend could continue, notably in the United States, the Mediterranean and other regions, such as northern Europe, Russia, China and Central and East Asia. However, confidence in the projected trend remains low because various factors contribute, including forest growth, urbanisation, local changes in wind measurement exposure and aerosols, and natural variability. Under the assessment of currently available data, 11% of wind power plants could see an over 5% decrease in mean wind speed in a low-emissions scenario. If GHG emissions are not reduced, wind power potential, particularly for onshore wind, could decrease further. The share of wind power plants that will see an over 5% decrease in mean wind speed could increase up to 18% in a high-emissions scenario.

Since major wind power generators are located in the northern hemisphere, where mean wind speed would decline, climate change could have negative impacts on global wind power generation. China and the United States, the top two wind power generators in 2020, accounting for over 50% of total world wind power generation, are projected to see a mean wind speed decrease. New wind power development in some parts of the southern hemisphere, where mean wind speeds are expected to rise (e.g. the Amazonian region and southern Africa), may offset the decrease in the northern hemispheres.

Wind power exposed to changes in mean wind speed by climate scenario



Note: The graph shows the share of wind power plants installed capacity for each level of change in surface wind speed, compared to the pre-industrial period (1850-1900).
Sources: IEA analysis based on Global Energy Monitor (2022c) and IPCC (20221b).

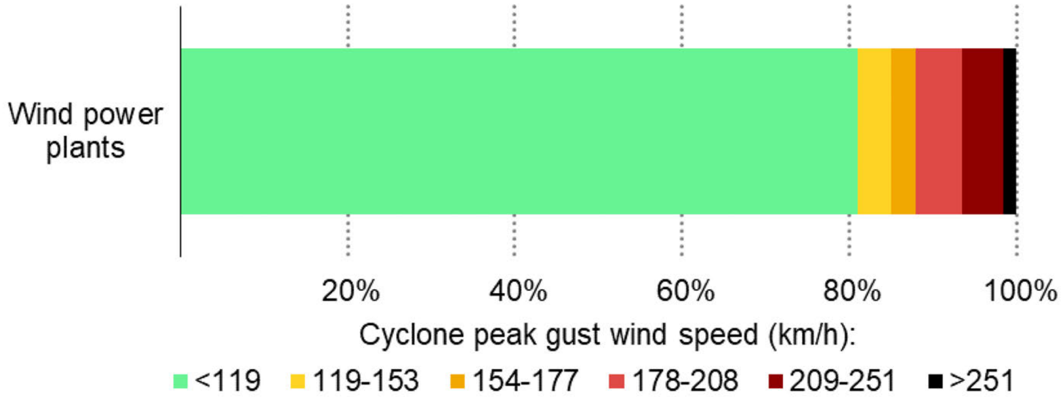
More intense tropical cyclones and severe storms could lead to automatic shutdown and physical damage

Although a higher wind speed leads to a higher generation output, an excessive increase could limit power generation. Wind power plants are set to shut down automatically beyond a certain wind speed limit (around 20 m/s to 25 m/s) to avoid physical damages. High-speed wind events, such as tropical cyclones and severe storms, can therefore result in a sharp cut in wind power generation, as well as physical destruction, if no adaptation measures are undertaken.

An increasing share of intense tropical cyclones adds challenges to wind power generation. Over the past four decades, the global proportion of major tropical cyclone intensities (Category 3-5) has increased and is likely to continue to rise – by 10% with 1.5°C warming, 13% with 2°C and 20% with 4°C. The average peak tropical cyclone wind speeds will also increase at a global scale. In East Asia, one of the regions with the largest wind capacity, wind power plants are likely to face a double challenge: a decrease in surface wind speed and an increase in the number of intense tropical cyclones (also called typhoons or hurricanes). Climate models project a shift in their tracks to the northwest and north, increasing the size of affected areas in eastern China, Japan and Korea. Texas, the state with the largest wind power generation in 2021, is also likely to be more affected by the increase in intense tropical cyclones, with climate projections indicating a greater number of the most intense tropical cyclones around the state. With 64 tropical cyclones (30% of which were major hurricanes), Texas was one of the states most affected by intense tropical cyclones in 1851-2020.

The intensification of tropical cyclones can also negatively affect the development of offshore wind power plants. Today, a majority of offshore wind installations are located in less turbulent regions, such as the North Sea and the Baltic Sea. However, the offshore wind market could expand in regions with increasingly hostile meteorological conditions. According to the NZE, 80 GW of offshore wind capacity needs to be added annually by 2030, with huge growth in Asia and the United States, both areas exposed to tropical cyclones. Already, some offshore wind plants are exposed to physical risks from tropical cyclones, as seen in the Cangnan Wind Farm, where 20 out of 28 turbines fell due to Typhoon Sangmei in 2006. New turbine designs, together with improved operational practices, will become increasingly important to cope with cyclone-force winds.

Wind power plants exposed to tropical cyclones



IEA. CC BY 4.0.

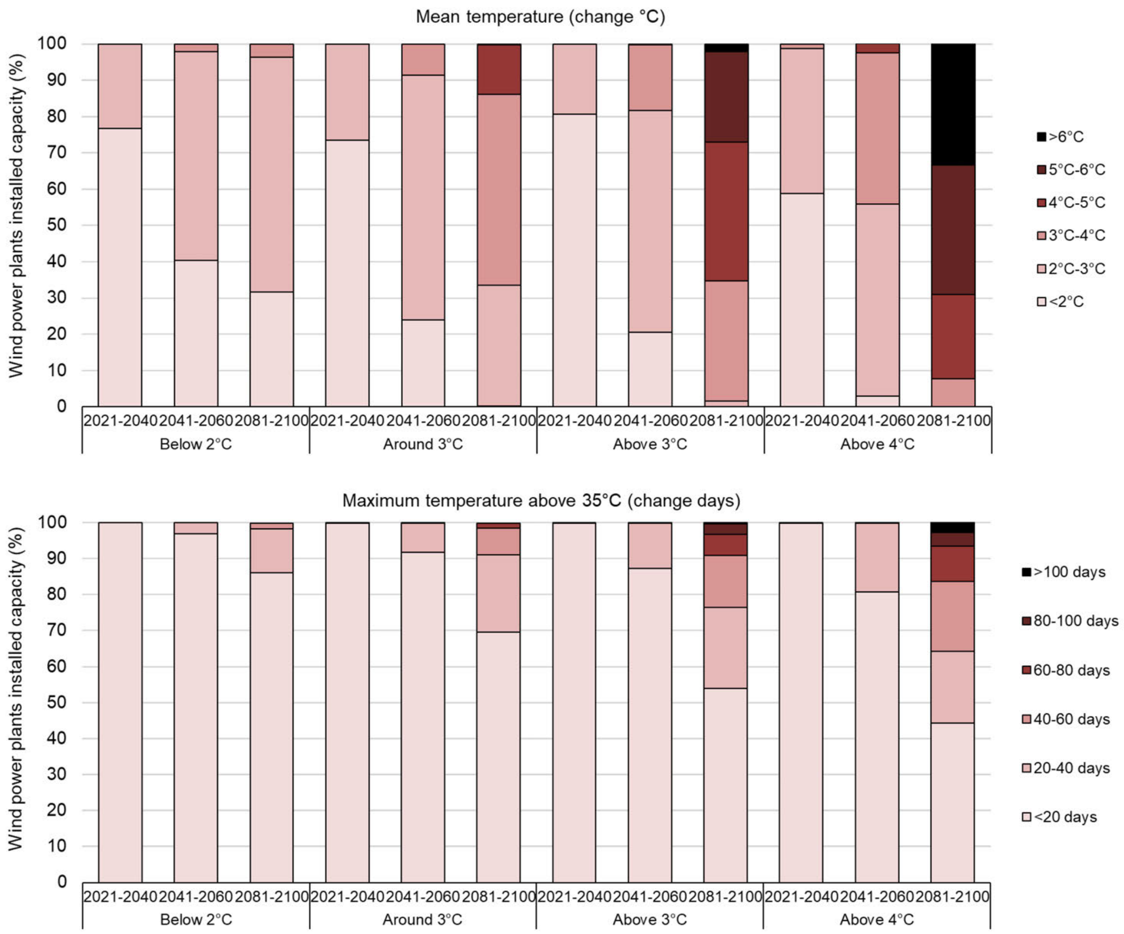
Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.

Sources: IEA analysis based on Global Energy Monitor (2022c) and UNDRR Global Assessment Report (2015).

Extreme heat can decrease wind power generation, with reduced life spans and automatic shutdown

The increasing extreme heat events can also add stress to wind power generation. Wind power plants are usually designed for a 25°C environment, and a standard wind turbine can work at full power up to an outside temperature of 35°C. Higher temperatures can reduce the life span of battery cells and other electronic components while making the lubrication oil for the turbine gearbox runny, which causes grinding in the gears. Under extreme heat, such as 45°C, a standard wind turbine may shut down completely. A new design is needed in countries with a high temperature environment. A new wind power plant design that can endure 45°C was adopted for the 50 MW Dhofar Wind Power Project in Oman.

Wind power plants exposed to a hotter climate by climate scenario



Note: The graphs show the share of wind power plants installed capacity for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C, compared to the level of the pre-industrial period (1850-1900).

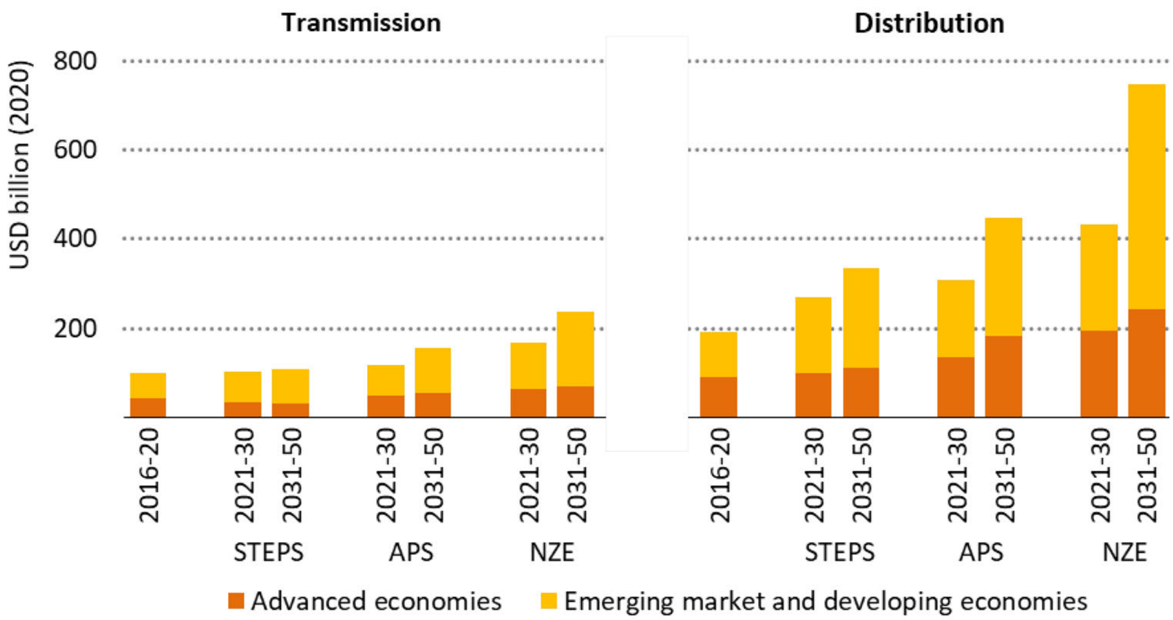
Sources: IEA analysis based on Global Energy Monitor (2022c) and IPCC (2021b).

Electricity networks

Electricity networks are the foundation of reliable and affordable electricity systems and play a key role in ensuring grid reliability, supporting clean energy transitions and achieving universal access to electricity. Electricity networks pool the potential of flexibility sources and bolster overall system flexibility. Large transmission lines assist the balancing of electricity demand and supply within and between regions. Strengthened distribution lines connect decentralised sources, including distributed solar PV, wind power and battery systems, enabling clean energy transitions and enhancing energy security with more localised electricity usage.

Currently, around 80 million km of electricity network is in place. Investment in the electricity network is expected to increase substantially due to electricity demand growth over the next decade. By 2030, electricity demand could rise by 24% if existing policies and trends are maintained (STEPS) and by almost 37% if efforts are made to meet net zero emissions (NZE). The increasing electricity demand will require a major increase in the annual investment in the electricity grid from current levels (less than USD 300 billion on average over the past five years). According to 2021 projections, annual investment to 2030 averages USD 370 billion in the STEPS, while it doubles from the current level, reaching USD 630 billion in the NZE.

Average annual electricity network investment by scenario, 2016-2050



Source: IEA (2021a).

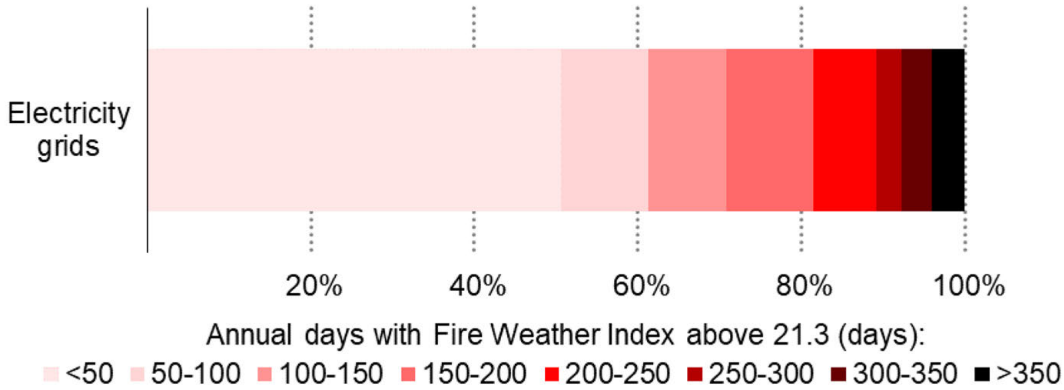
Climate change will add investment needs for power grid maintenance. Electricity networks are the leading cause of climate-driven outages in many countries and considered the most vulnerable to climate impacts in the electricity value chain. Future extension of transmission and distribution grids could increase exposure to climate change impacts, thereby increasing the possibility of climate-driven disruptions, and require greater investment in maintenance, upgrades and switching to more resilient options (e.g. underground lines).

Increasing fire weather seasons make wildfires a growing concern for electricity networks in some regions

Wildfires, which can cause multiple simultaneous faults in various parts of the electricity grid through fire and smoke, are a major concern. Wildfires can damage lines, poles and substation equipment, while causing the thermal derating of overhead lines. According to the IPCC's latest report, fire weather[28] seasons lengthened by 18.7% globally between 1979 and 2013 due to droughts and warmer temperatures. The fire weather will continue to extend in Australia, the Mediterranean, southern Africa, a large part of South America, the western part of North America and the northern part of Central America, adding more challenges to electricity network operation and maintenance.

Around a half of global electricity networks are currently exposed to fire weather for more than 50 days per year. Some 18% of global electricity networks have a higher risk of wildfires, with more than 200 fire weather days annually. Some countries are already experiencing major electricity outages due to wildfires. In Australia, wildfires in 2019-2020 caused unplanned power outages, mainly because flames damaged transmission and distribution lines. In New South Wales alone, the two main electricity suppliers reported the destruction of 4 000 power poles, leaving 158 000 people without electricity. Two First Nations communities in Manitoba, Canada, were left without power due to wildfires damaging transmission lines. It took about three months to restore power lines, affecting hundreds of people. In the United States, the southern Oregon wildfire in 2021 disrupted power transmission lines to California and the southwest (named California-Oregon AC intertie), reducing power supplies by as much as 5 500 MW for several days. To reduce the stress on the grid, California used backup generators and asked people to save electricity.

Electricity grids exposed to wildfires



Note: The FWI is a meteorologically based index used worldwide to estimate fire danger. The higher the FWI, the more favourable the meteorological conditions to trigger a wildfire. The FWI can be categorised into six classes of danger: Very low danger (FWI less than 5.2), Low danger (FWI between 5.2 and 11.2), Moderate danger (FWI between 11.2 and 21.3), High danger (FWI between 21.3 and 38.0), Very high danger (FWI between 38.0 and 50) and Extreme danger (FWI greater than 50).
Sources: IEA analysis based on OpenStreetMap and Copernicus Emergency Management Service (2022).

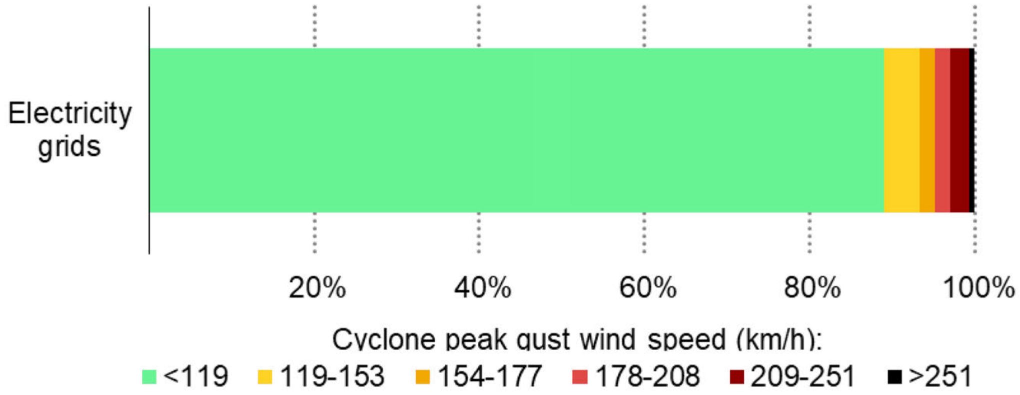
[28] Weather conditions conducive to triggering and sustaining wildfires, usually based on a set of indicators and combinations of indicators, including temperature, soil moisture, humidity and wind.

Tropical cyclones and storms have destructive impacts on electricity networks

Already, around one-quarter of global electricity networks are exposed to severe storms, and over 10% of the networks are exposed to tropical cyclones, notably in North America, Australia and East Asia. Severe winds can damage transmission and distribution lines, poles and transformers, mainly by toppling trees and branches. The projected increase in the global proportion of intense tropical cyclones and average peak wind speeds could bring more destructive impacts to electricity networks.

In the United States, the frequency and length of outages reached historical highs in 2020 due to damages to electricity network caused by an extremely disruptive Atlantic weather season. As a result, customers experienced more than eight hours of outages, double the 2013 level, when such record keeping began. The average number of outages also increased from 1.2 to 1.4. The destructive impacts of tropical cyclones and storms have been seen in Asian countries as well. Tropical cyclones have repeatedly caused blackouts in Japan, compromising electricity supply reliability. Typhoon Faxai damaged the electricity grid in the Tokyo area in September 2019, leaving some 900 000 households without power, and Typhoon Hagibis, which struck the same region one month later, caused power outages for 27 000 homes. In Korea, three successive tropical cyclones during two weeks in August and September 2020 caused 676 power outages, affecting more than 300 000 households for ten hours, on average. Of the three cyclones, Typhoon Maysak caused the greatest damage by breaking power poles and high-voltage lines, leaving 290 000 households without electricity. In the Philippines, Typhoon Odette (Rai) broke distribution and transmission lines and deprived more than 3 million families of electricity.

Electricity grids exposed to tropical cyclones



Note: The wind speed categories are divided according to the Saffir-Simpson Hurricane Wind Scale, a 1 to 5 rating based on a hurricane's maximum sustained wind speed. To be classified as a hurricane, a tropical cyclone must have a wind speed of at least 119 km/h, after which it falls into Category 1. Hurricanes rated Category 3 and higher (> 177 km/h) are known as major hurricanes.

Sources: IEA analysis based on OpenStreetMap and UNDRR Global Assessment Report (2015).

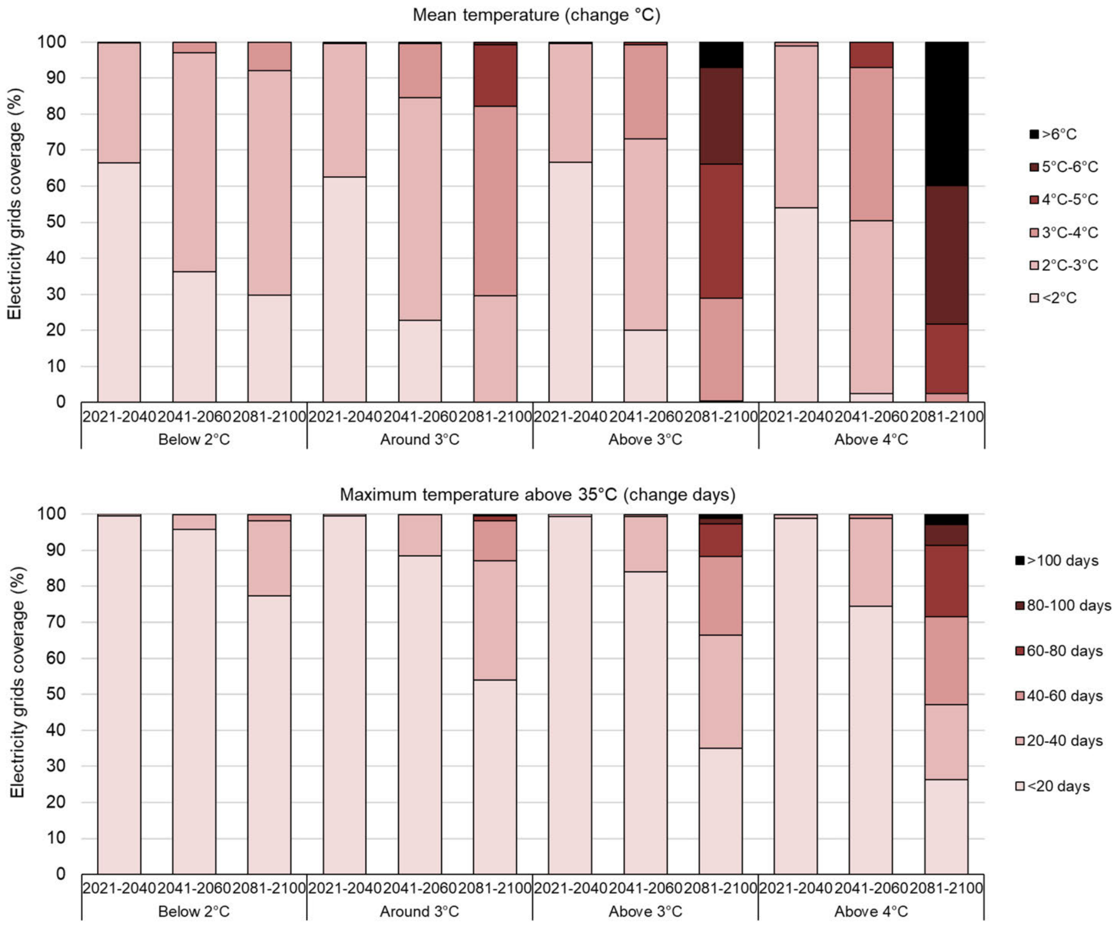
Climate projections also indicate a potential increase in the frequency and amplitude of severe windstorms in some parts of Europe, which can threaten the reliability of electricity networks. Although not affected by tropical cyclones, Europe has experienced outages due to storms. In Ireland, 194 000 people (around 4% of the country's 4.8 million inhabitants) experienced several hours of electricity outage when Storm Ellen hit its west coast in August 2020 and damaged the electricity network. In Estonia, storms caused trees to fall on electricity transmission lines, interrupting electricity supply to 34 000 households in July 2020 and over 11 500 in September 2020, with some waiting a day to recover power. In Italy, Storm Vaia brought down more than 300 000 trees in October 2018, some falling on electricity distribution lines and interrupting electricity supply for 200 000 households between the Veneto and Friuli-Venezia Giulia regions for several days.

Rising temperatures affect the operational limits of transmission and distribution equipment

Higher ambient temperatures generally reduce capacity and lead to higher losses. US studies 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 the 1990-2010 reference period. Overhead power lines can heat up, expand and sag. In some regions, lines can sag onto trees and branches, resulting in short circuits. Underground power cables are also vulnerable to heatwaves, particularly when combined with droughts. Heatwaves can overload and overheat underground power cables with the increasing demand for cooling, while droughts can exacerbate the situation by slowing the heat dissipation that is generally supported by moisture in the soil. The persistence of high temperatures can stress cable and joint insulating materials and result a short circuit. Indeed, in Italy, the number of faults in underground medium voltage cable joints has increased significantly in recent years during the summer. Similarly, in the Netherlands, electricity distribution network components overheated and failed due to high temperatures and dry soil, resulting in 18 power outages in 2020. The network operator needed to upgrade parts of the Frisian electricity grid to increase resilience to hot weather.

Climate projections show that electricity networks will face more heat-related stress in the long term. In a high-emissions scenario, electricity networks will see an additional 43 days of maximum temperature above 35°C on average, compared to 1850-1900. Around 28% of electricity networks could see an increase of over 60 days. Even in a low-emissions scenario, the number of days of maximum temperature above 35°C would be 13 days higher than the reference period, on average.

Electricity grids exposed to a hotter climate by climate scenario



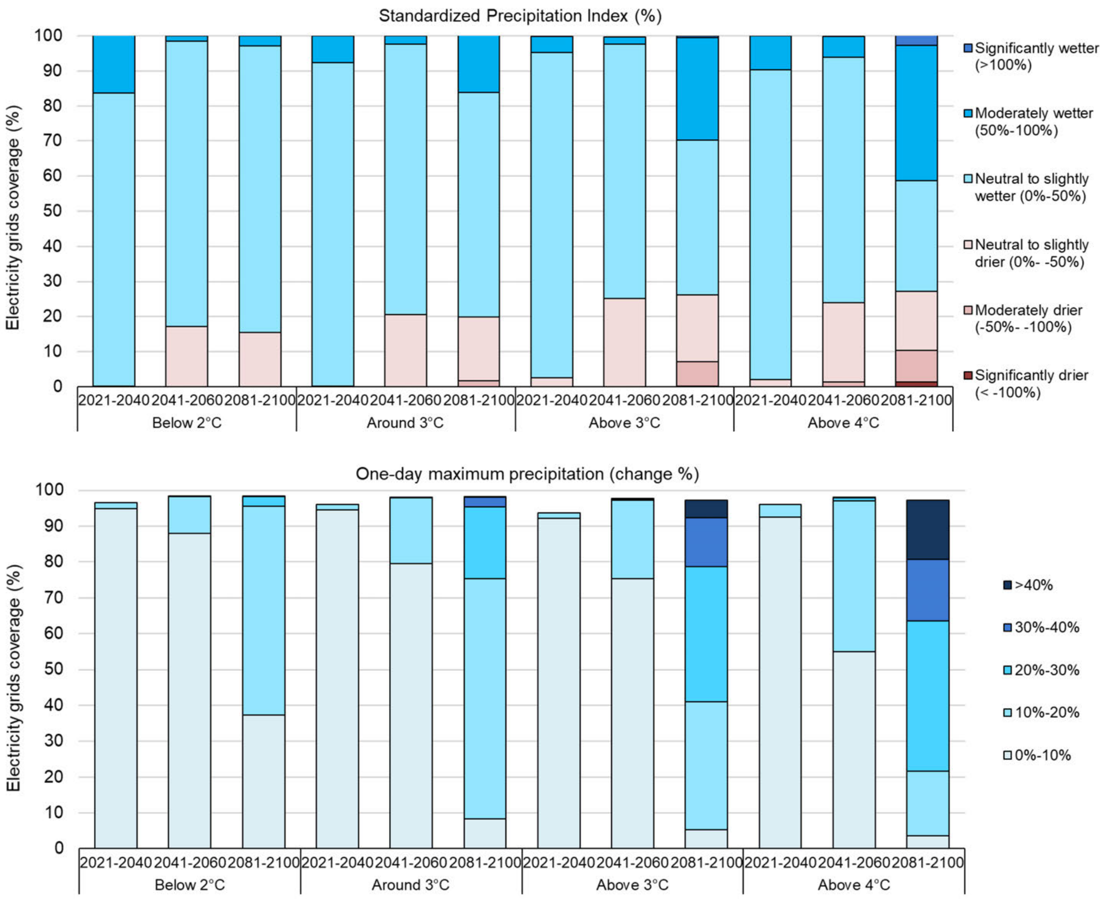
Note: The graphs show the share of electricity grids for each level of temperature rise and extreme heat using the mean temperature and the number of days with maximum temperature above 35°C, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on OpenStreetMap and IPCC (2021b).

Heavy precipitation and floods are a growing concern

Although the risk to grids of heavy precipitation and floods is relatively low in the near term (compared to the risks of wildfires and tropical cyclones), climate change is likely to increase the risk in the long term. In most regions in Europe, North America, Africa and Asia, climate change is projected to bring more intense and frequent heavy precipitation events and associated floods. In the low-emissions scenario, over 60% of the electricity grid could see an over 10% increase in one-day maximum precipitation. If GHG emissions are not mitigated, the share of the electricity grid exposed to increasing one-day maximum precipitation could reach 94%, with one-third seeing an over 30% increase.

The growing impacts of heavy precipitation and floods are becoming more visible in many regions. The floods that hit some European countries in 2021 prompted massive power outages in Belgium, Germany, Luxembourg and the Netherlands. In Germany, 200 000 households were deprived of electricity, and in some parts of western Germany, restoration took over two weeks, leaving 5 800 households without electricity.

Electricity networks exposed to a wetter climate by climate scenario



Note: The graphs show the share of electricity networks for each level of standardised precipitation using the Standardized Precipitation Index and changes in one-day maximum precipitation, compared to the level of the pre-industrial period (1850-1900).
Sources: IEA analysis based on OpenStreetMap and IPCC (2021b).

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Chapter 4. Climate change impacts on energy demand

Climate change impacts can shift energy demand in several ways. Some slow-onset events can increase energy demand, while others can reduce it. For instance, rising global temperatures can increase electricity usage during peak hours in summer months due to increased cooling needs in buildings, putting an extra strain on the electricity grid. At the same time, milder temperatures in winter can reduce energy demand for heating in buildings. The overall climate-induced effect is a global energy consumption increase by 7-17% to 2050, depending on overall temperature increase. The extent of this effect varies regionally, with the majority of climate-induced energy demand increase experienced by developing economies in the tropics.

Extreme weather events can also affect energy demand. Increased frequency or severity of extreme weather events, such as floods or cyclones, can lead to more damage to existing energy infrastructure and to more reconstruction than historically needed, increasing overall energy demand due to an increased volume of construction material. Prolonged droughts can also increase energy demand in some areas through increased use of energy-intensive desalination of seawater for drinking, agriculture, cooling of power plants and other purposes.

Climate change impacts on the energy system can also have broader socio-economic effects. An extreme weather event that disrupts the operation of a functioning power plant could activate the next available electricity dispatch source in the grid merit order, usually at higher costs. A disruption sustained over time could increase final electricity prices, potentially leading to social and economic impacts.

This chapter explores climate change impacts on energy demand, focusing on the three main end-use energy sectors: buildings, industries and transport. It analyses both slow-onset and extreme weather events, while presenting socio-economic effects where relevant and available, alongside real-world examples.

Buildings

The buildings sector, which includes residential, public and commercial properties, accounts directly and indirectly for 30% of final energy consumed globally, including almost 55% of global electricity consumption. Heating and cooling are the two main energy end uses in buildings operations. As of 2021, heating (mostly provided by fossil fuels) accounts for around 50% of final energy consumption.

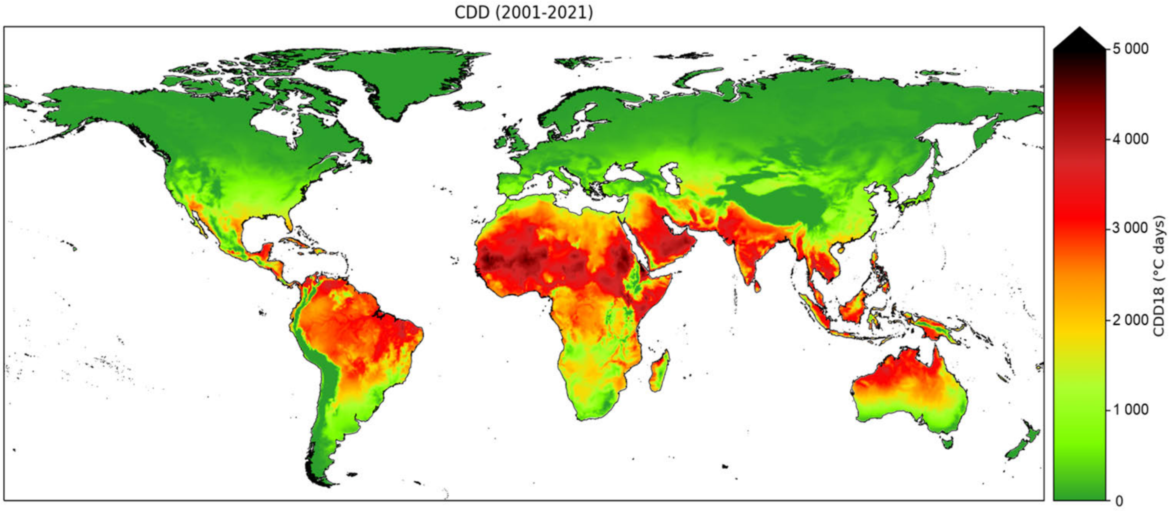
Cooling (predominantly provided by electricity) accounted for nearly 16% of the buildings sector final electricity consumption in 2020. In the past 30 years, global energy consumption for cooling has more than tripled, while energy consumption for heating has remained stable since 2010, with heating energy intensities (i.e. final energy use per m^2) decreasing by 2% per year since 2010.

Cooling

Rising temperatures increase electricity demand for cooling, placing major strains on electricity systems

Climate change, along with other factors, such as population and GDP growth, has direct impacts on energy demand in the buildings sector. Rising temperatures lead to an increase in cooling degree days (CDD) and a decrease in heating degree days (HDD).[29] In a high-emissions scenario (SSP5-8.5), CDD is projected to increase by 732 degree days in 2081-2100, compared to 1850-1900. Even in a low-emissions scenario (SSP1-2.6), it is estimated to increase by 268 degree days. The notable growth in cooling demand will lead to an overall increase in global energy demand, offsetting a decrease in heating demand.

Mean annual average of cooling degree days, 2001-2021

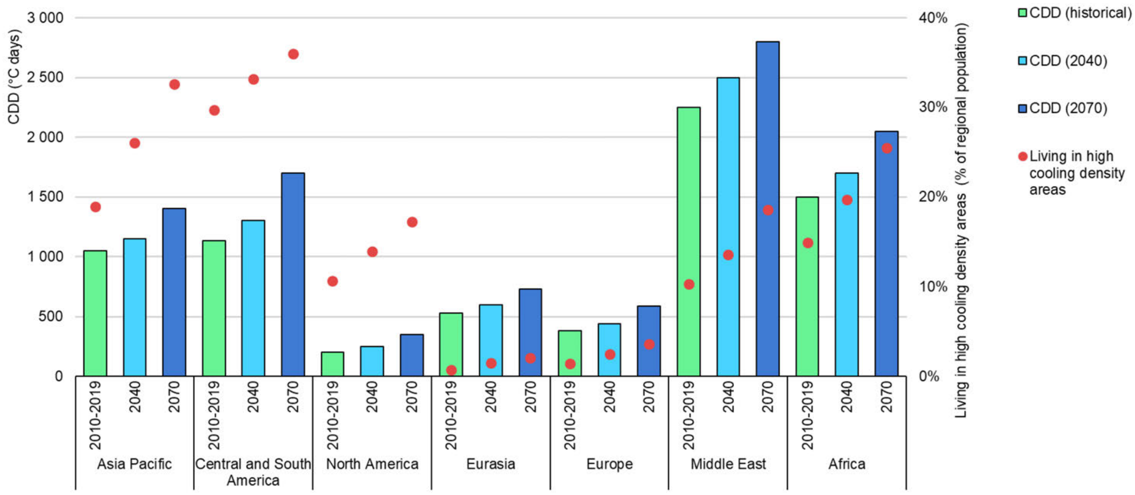


Source: IEA (2022).

[29] A degree day measures how cold or warm a given location is by comparing the mean of the high and low outdoor temperatures recorded each day to a standard temperature. CDD and HDD measure how much the mean temperature exceeds or is below the standard temperature each day over a given period (e.g. a week in the summer or the entire year), respectively. For a more detailed methodological explanation, please refer to Box 2.1 of the IEA The Future of Cooling report.

The increase in CDD is particularly marked in Africa, Central America, north-western South America, the Middle East, South and Southeast Asia and northern and central Australia, where a warmer climate is already boosting energy consumption for cooling. In many countries, including China, Brazil and Thailand, the future rise in average temperatures is expected to increase energy use, particularly electricity consumption from space cooling demand.

Evolution of cooling degree days and percentage of population living in high cooling density areas, 2010-2070



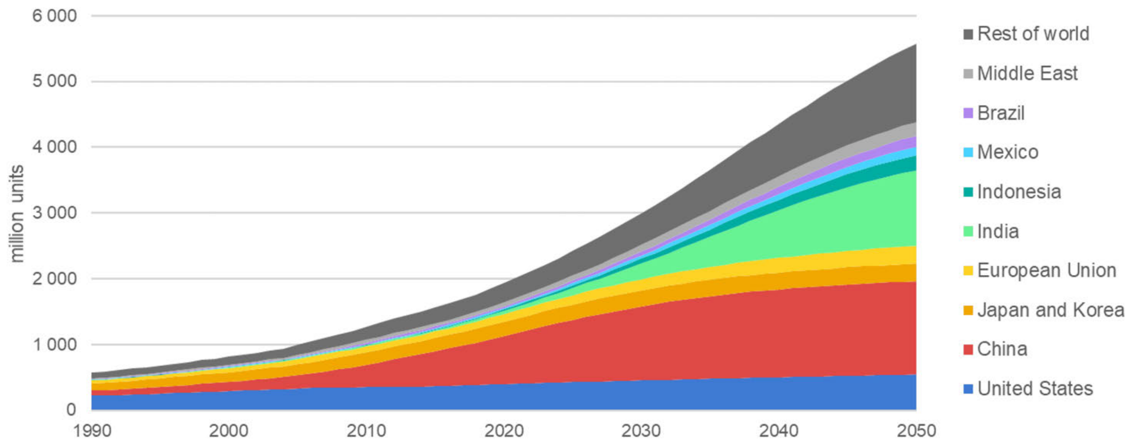
Note: CDD shown in the graph is calculated using daily average temperatures, base temperature (18°C), CDD (18°C). The scenario used for 2040 and 2070 projections for the percentage of population living in high cooling density areas is the STEPS, and the scenario used for 2040 and 2070 projections for CDDs is the IPCC SSP3-7.0.
Source: IEA analysis based on IPCC (2021).

In Brazil, CDD is expected to increase by 25% between 2022 and 2050, with 2040 space cooling energy use higher than today, increasing pressure on the electricity grid. Japan may see an increase in the summer peak electricity demand, with Tokyo's average temperature climbing twice as quickly as that of rural areas. Cooling energy demand is also expected to increase in southern Europe and the southern US states, with a simultaneous reduction in heating demand. For instance, Italy's average number of HDDs fell by around 19% in the past three decades, while energy demand for cooling increased significantly. The cooling demand in Italy is likely to continue rising, by as much as 50% by 2080. In Portugal, warming temperatures would move peak electricity demand from winter to summer.

The growth in cooling demand is likely to continue, with a marked increase particularly in emerging markets and developing economies (EMDEs). In 2022, of the 35% of the global population living in areas where it is hot every day, only around 15% owns an air conditioner (AC). Only 10% of households have ACs in India and Indonesia, while over 90% do in the United States and Australia.

As much as two-thirds of all households are projected to own an AC by 2050 as a result of rising average temperatures, expansion in building floor areas, improved living standards and policies to broaden access to essential energy services. Access to cooling in buildings is projected to expand to an additional 5 billion people by 2070. In some EMDEs, such as India, Indonesia and China, the increase in AC stock to 2050 is projected to be particularly high, accounting for half of the total global growth. In India alone, AC ownership could grow from less than 5% in 2020 to as high as 85% beyond 2050, comparable to current levels in Singapore, Malaysia, Japan and Korea. This will lead to a massive growth in electricity demand. The size of this demand increase will be affected by energy and urbanisation policies, including the efficiency of cooling technology, building codes and urban planning. Cooling energy demand can also increase due to extreme summer heatwaves in places where AC was not previously needed, such as the United Kingdom. Currently, only 1% of UK buildings have fixed cooling systems. In London, this is projected to increase to 20% by 2035 and 50% by 2075.

Global air conditioner stock, 1990-2050

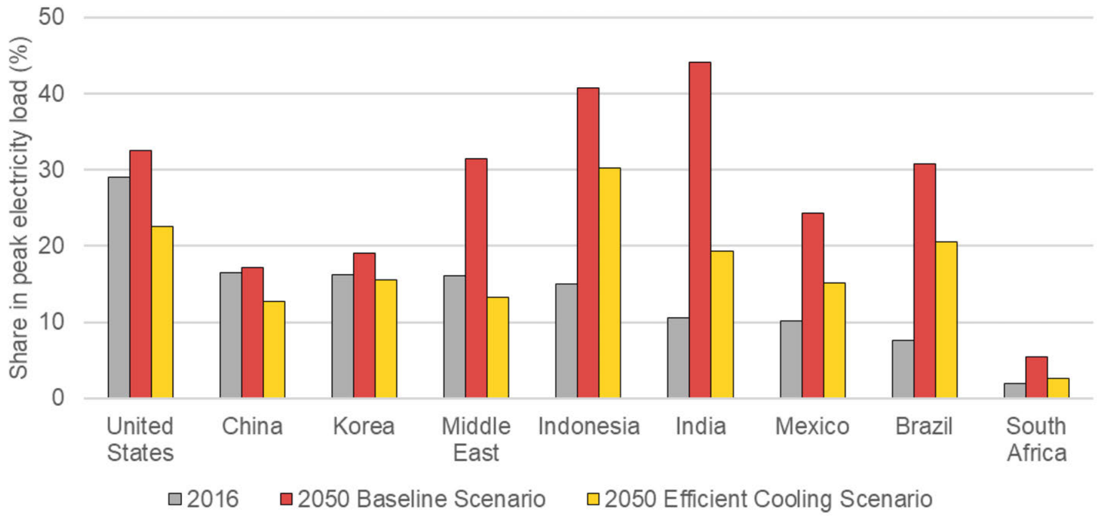


Note: The data refer to the Baseline Scenario used in the 2018 IEA The Future of Cooling report. It is driven by the assumption that those who require cooling for climatic reasons and become able to afford it will buy and use ACs, and that generation capacity to power them will have to be built. However, it also takes into account not only the policies and measures that governments have already put in place to curb the growth in energy use, limit energy-related emissions and improve energy efficiency but also the likely effects of announced policies, as expressed in official targets or plans.
Source: IEA (2018).

The projected growth in the peak electricity demand for cooling is expected to put stress on electricity systems. This is particularly relevant when people come home and turn on ACs in the evening simultaneously. Already, in major cooling markets like the United States, cooling demand in buildings accounts for as much as 30%

of peak electricity loads, on average (see Figure below). On extremely hot days, this number can be even higher. This impact on the grid is likely to be even stronger in hot places like India, where cooling could reach as much as 45% of the average national peak electricity demand. In some cases, the increased peak electricity demand could lead to power outages or brownouts, as seen in Cleveland, Ohio, during summer 2022. Power outages during a heatwave could expose the urban population to heat exhaustion or heat stroke.

Share of cooling in electricity system peak loads, 2016-2050



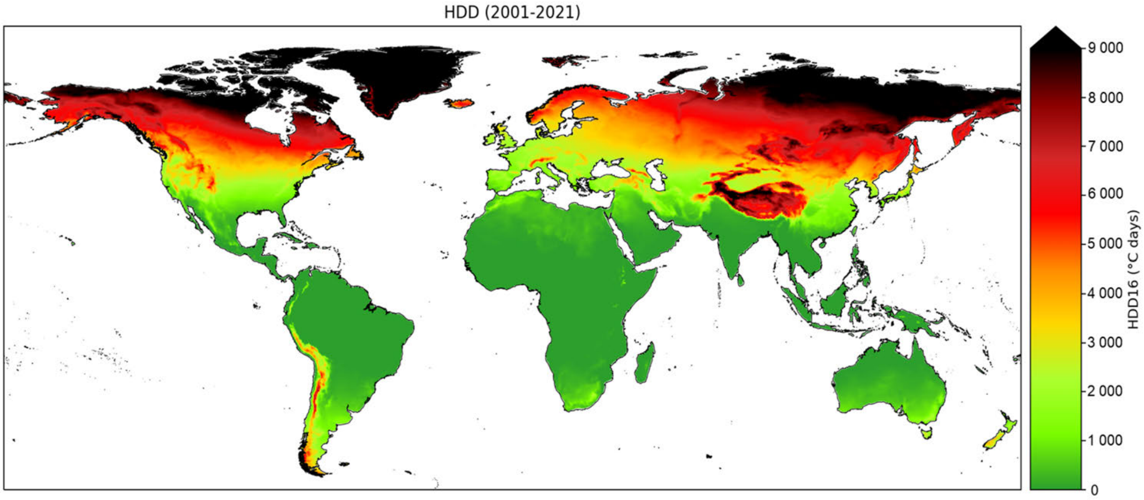
Note: The data refer to the Baseline and the Efficient Cooling Scenarios used in the 2018 IEA The Future of Cooling report. The Baseline Scenario is driven by the assumption that those who require cooling for climatic reasons and become able to afford it will buy and use ACs, and that generation capacity to power them will have to be built. However, it also takes into account not only the policies and measures that governments have already put in place to curb the growth in energy use, limit energy-related emissions and improve energy efficiency but also the likely effects of announced policies, as expressed in official targets or plans. The Efficient Cooling Scenario considers that minimum energy performance standards increased in all countries in an assertive and progressive manner, which drives up the average efficiency of installed equipment. The assumptions about CDD differ slightly between the two scenarios: on average, CDD increases globally by nearly 25% between 2016 and 2050 in the Baseline Scenario and by 20% in the Efficient Cooling Scenario.
Source: IEA (2018a).

Heating

Higher global temperatures will reduce heating demand

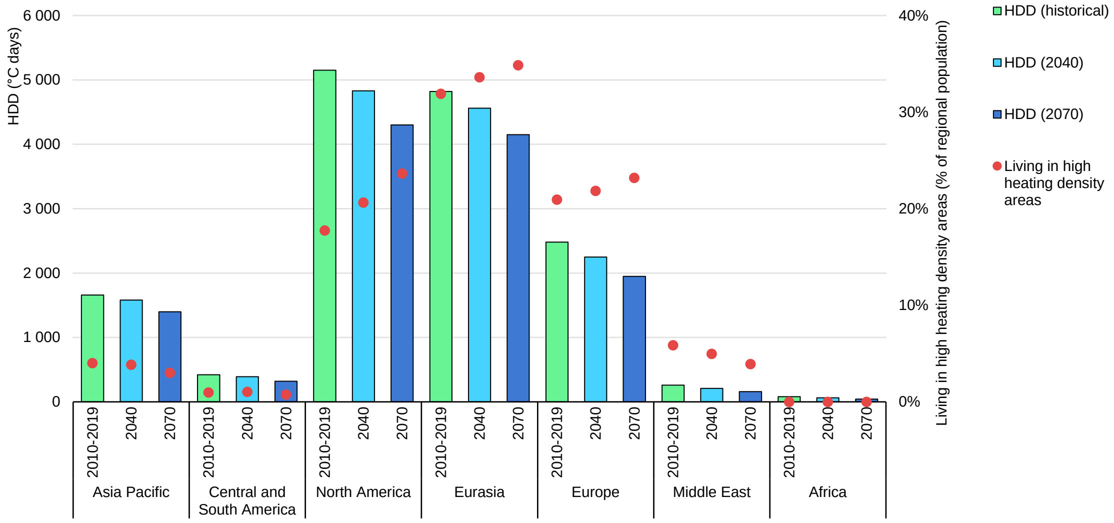
Energy demand for heating has decreased in the past decades due to global warming. According to the World Meteorological Organization (WMO), the historical average HDD in 1981-2010 (2 341 degree days) was lower than the 2 407 degree days of 1961-1990. Energy demand for heating is likely to continue declining due to the projected increase in global temperatures. IPCC climate models project that HDD would record an average drop of 776 degree days in a high-emissions scenario (SSP5-8.5) and 268 degree days in a low-emissions scenario (SSP1-2.6).

Mean annual heating degree days, 2001-2021



Source: IEA (2022).

Evolution of heating degree days and percentage of population percentage of population living in high heating density areas, 2010-2070



Note: HDD shown in the graph is calculated using daily average temperatures, base temperature (16°C), HDD (16°C). The scenario used for 2040 and 2070 projections for the percentage of population living in high heating density areas is the STEPS, and the scenario used for 2040 and 2070 projections for HDDs is the IPCC SSP3-7.0.
Source: IEA analysis based on IPCC (2021).

Although decreasing heating demand is likely to be offset by the increase in cooling demand at a global scale, some countries may experience an overall decrease in energy demand due to a rapid drop in heating demand that outpaces cooling demand growth. For example, northern US states are projected to see a decrease in total energy demand due to a decline in HDD by the end of this century, with an average decrease in peak electricity demand as well. Some studies show that the decrease in HDD will outbalance the increase in CDD until 2100 in most of Europe, leading to a decrease in energy demand. This is the case, for instance, in Austria, where the energy demand saved from reduced heating in warmer winters will outweigh the increased energy demand from cooling services in residential buildings, resulting in a net decrease of energy demand. In Germany, the increase in temperature is projected to reduce the demand for heat by up to 30% by the end of the century, and Sweden's heating demand could be as much as 37% lower in the 2080s than in 1961-1990. The greater number of CDDs are expected to boost electricity demand in the summer in Sweden, but peak demand would still occur in the winter.

Industry

Chemicals

The chemicals sector is the largest industrial energy consumer overall, accounting for approximately 11% and 8% of the global primary demand for oil and natural gas, respectively. Ammonia, a key ingredient for fertiliser production, is energy intensive, accounting for around 2% of total final energy consumption. The conventional production of ammonia, the basis of all synthetic nitrogen fertilisers, is especially highly energy intensive (46.2 EJ/t), more than both steel and cement. Around 70% of ammonia is currently used to make fertilisers for food production, particularly three cereals (wheat, rice and maize), which account for over 50% of the total global demand for nitrogen fertilisers, largely because they are three of the four largest-volume crops grown globally.

More frequent and severe precipitation events may increase demand in the chemicals industry due to increased fertiliser production needs

The demand for ammonia has been relatively flat at around 180 Mt per year in recent years. Demand for other synthetic fertilisers critical to modern agricultural systems (including those that deliver potassium and phosphates) has been increasing steadily, but these are less important from an energy standpoint. Ammonia production capacity is projected to expand globally in the coming years, with notable growth in Asia Pacific, which accounts for 35% of output growth to 2025.

Climate change that has negative impacts on soils could raise the demand for synthetic nitrogen fertilisers. Precipitation changes, especially heavy rains and floods, could overtake fields and strip nitrogen from land via the processes of leaching, denitrification and runoff. Such climate-related stresses may increase the demand for synthetic nitrogen fertilisers, which are currently used in approximately half of the world's food production and are projected to increase by nearly 40% by 2050 in the STEPS, mainly driven by the need to increase food production due to economic and population growth. Fertiliser needs in Indian agriculture are expected to rise considerably to counteract the adverse impacts of climate change on the yield and nutritional qualities of food. For instance, climate change is projected to reduce the wheat yield in India in the range of 6-23% by 2050 and 15-25% by 2080. An increased use of nitrogen fertilisers in Indonesia is already occurring to try to counterbalance the climate-induced decline in rice production (mostly due to large variations in rainfall patterns), combined with the rising demand for food.

Cement, iron and steel

Industry energy consumption represents almost 40% of current global total final consumption and is still dominated by fossil fuels, particularly coal. The process of concrete production is associated with high levels of energy intensity (3.4-3.5 GJ/t clinker) and CO_2 emissions. Steel production is highly energy and emissions intensive (19 GJ/t and 1.4 tCO_2/t of crude steel in 2019), accounting for around 8% of global energy demand and 7% (2.6 Gt CO_2) of total emissions from fuel combustion. Demand for industrial products has risen considerably in the past two decades, along with energy consumption and CO_2 emissions, mainly driven by population growth and socio-economic development. Cement production increased particularly strongly (2%) in 2020, despite the economic downturn caused by the coronavirus (Covid-19) crisis.

Climate-related extreme weather events could lead to higher demand for iron, steel and cement for physical hardening and post-disaster reconstruction

There is limited assessment of how climate impacts could affect industrial energy demand. One potential factor could be an increased demand stemming from the projected increase in destructive climate hazards (e.g. floods, sea-level rise and tropical cyclones). More frequent and intense extreme weather events could damage infrastructure more frequently. If preventative measures are not taken (see Chapter 5), this could translate into greater cement, iron and steel production for post-disaster reconstruction, with impacts on overall energy demand. Recent examples of damages to infrastructure include Hurricane Katrina, which hit the south-eastern United States in 2005, killing 1 500 people and costing around USD 300 billion in infrastructure damages; the flash floods in Germany in 2021, which caused EUR 40 billion in damages; and the floods in eastern Australia between February and March 2022, which were the costliest floods in the country's history, with a record AUS 3.35 billion in insured losses.

Adapting to climate impacts may also involve greater use of building materials for preventive physical hardening and for protecting existing assets, with impacts on industrial energy demand. Today's buildings and energy-related infrastructure are likely insufficiently prepared to cope with the growing concern of extreme weather events. For instance**,** one-third of the housing stock in the United States (around 35 million houses) is at high risk from natural disasters related to climate change. Use of energy-intensive construction materials is currently the primary means to improve the resilience of the built environment against extreme weather events. The most frequently used flood prevention measures are "grey infrastructure" projects, i.e. built structures or human-engineered solutions, including flood control dams and reservoirs, channel modifications, floodwalls and levees. A 2016 study estimated the volume of construction materials required to protect the world's top 221 seaports from stronger storms due to sea-level rise. In cases of high sea-level rise, less than 10% of the ports analysed would require approximately 436 million m^3 of materials, led by concrete.

Slow-onset climate impacts could require more frequent infrastructure replacement and maintenance

Rising temperatures could cause more "wear and tear" and damage to structures over time (e.g. sinking foundations, roads and steel), requiring more frequent replacement of construction materials. Although construction materials, such as cement, iron and steel, are relatively resilient to external conditions, some are more vulnerable to certain types of climate impacts. Asphalt, steel and clay are sensitive to heat extremes. Asphalt roads can become soft as temperature rise and deform when heavy vehicles run over them. Steel, used as structural support in most building and energy infrastructure, can experience thermal expansion, leading to heat buckling when designed tolerance is exceeded. High temperatures were partially blamed for causing a skyscraper in Shenzhen, China, to shake in 2021 as the steel frame stretched in the heat, forcing evacuation. Extreme temperatures can even cause materials to melt, resulting in roads "bleeding" as the surface layer of bitumen softens, as happened in India in 2019. Concerning transport infrastructure, concrete roads can expand and contract as temperatures fluctuate, and higher than expected temperatures may lead to cracked concrete. For reconstruction purposes, there is an increased demand for concrete resistant to higher temperatures (See Box below).

Changes in rainfall patterns and humidity could also cause damage to the built environment. In certain areas, especially clay soils or in permafrost thawing regions, building and infrastructure foundations could be affected by changing rainfall patterns and temperatures, leading to sinking of the ground below the structure and causing collapse. Over the next 50 years, this could affect more than 10% of properties in the United Kingdom.

Concrete and climate change

Concrete plays a major role in building climate-resilient infrastructure, as its durability makes it better able to survive disasters. In case of severe floods, concrete structures can withstand much more water and debris pressure than steel or wood. The Global Cement and Concrete Association estimates that concrete structures have 50% or more survival rates when facing an 8 m wave, as opposed to 5 m for steel and 2 m for wood structures. Indeed, concrete represents the most used material in floodwalls, and it comes first among the construction materials required to protect the world's top 221 seaports from sea level rise-enhanced storm surges. Nevertheless, structures containing concrete are not invulnerable to climate impacts. For instance, steel inside concrete can rust and expand when it gets wet, potentially cracking the concrete and weakening the structure. Higher CO_2 concentrations in the atmosphere could also affect the steel through the process of carbonation, lowering the pH of the concrete and making the steel more prone to corrosion.

Energy demand for water supply in the context of climate change

The provision, transport and distribution of freshwater require energy. Seawater desalination and wastewater treatment are the most energy-intensive processes associated with water supply, requiring up to almost 100 kWh per m^3 of water treated. Globally, more than half of the energy used for water supply is in the form of electricity for the extraction of groundwater and surface water, and for wastewater treatment. The rest is thermal energy for diesel pumps and natural gas for desalination.

In countries where water scarcity is projected to increase, energy demand will also increase for water supply. For instance, energy consumption for water supply is increasing in the Middle East and North Africa (MENA) region, one of the most water scarce region of the world, for water desalination. If climate change is not mitigated, most MENA countries will see a further decrease in freshwater availability. Sea-level rise would lead to saltwater intrusion, and droughts could reduced recharge rates. Increased temperatures and aridity could result in higher evaporation rates, worsening the water crisis in the region, where water demand is likely to increase with near doubling of the population by 2050. To meet the water demand, energy-intensive seawater desalination is being increasingly used in the region. MENA countries are already producing 48% of the world's desalinated water and increasing their investment in desalination plants. In the Middle East, seawater desalination contributes more than 90% of all daily water requirements, consuming a substantial amount of electricity, mostly produced from fossil fuels.

To cope with the energy demand increase for water supply, the MENA region is exploring solutions. Given the region has tremedous solar energy potential, solar-powered desalination has been a topic of interest since the early 1980s, when the first-ever commercial pilot plant was commissioned in the MENA region. The Al Khafji desalination plant, the world's first large-scale desalination plant powered by renewable energy, was completed in 2018 in Saudi Arabia. The plant is connected to a solar PV system and has a production capacity of 60 000 m^3/d, a sufficient freshwater supply for a city of about 150 000 people. The MENA region is also looking for more efficient use of water resources and re-use of wastewater. For instance, wastewater re-use is increasingly adopted for irrigation, with 86% of the water withdrawn for different water-user sectors used in crop production in the region.

Transport

Transport accounts for 37% of global CO_2 emissions from end-use sectors and is the sector with the highest reliance on fossil fuels. Global transport demand and emissions have been growing steadily for the past two decades, until the Covid-19 pandemic hit the sector severely in early 2020. Covid-19 had a big impact on transport demand. Road transport in particular, which represents 57% of global oil demand, declined on an unprecedented scale in early 2020, with a 50% global average drop between 2019 and 2020. As of July 2022, energy demand from each transport sub-sector is recovering at varying speeds, generally rebounding and continuing to grow. The transport sector and its energy demand are affected by climate change in several ways. Rising global temperatures, more frequent heatwaves and extreme weather events can increase the energy demand in many transport sub-sectors. This sub-section illustrates examples from aviation, road transport and railways, noting that other important sub-sectors, such as shipping, may also suffer from increased climate-induced energy demand.

Aviation

Rising global temperatures and extreme heat may lead to increased energy use in aviation

Rising temperatures and more frequent heatwaves due to climate change could particularly affect energy demand in aviation. Extreme heat requires aircraft to consume more energy per flight. Surface air density, which depends on air temperature and airport altitude, can significantly influence the maximum allowable takeoff weight. Hotter air is less dense, meaning that higher temperatures result in less lift and require more engine thrust for takeoff.

Moreover, there are temperature thresholds above which an airplane cannot take off at its maximum weight. Above this threshold, an aircraft's weight needs to be restricted to be able to take off, especially at airports with short runways. A flight from Phoenix to New York, for example, is able to fly with all the seats filled when the ground temperature is 38°C. If the temperature rises to 43°C, the flight's capacity decreases by six seats. That is, with the same amount of energy thrust, the aircraft must carry less weight. If the temperature rises to 49°C, the aircraft's maximum seating capacity would be reduced by more than 20% (35 seats out of around 160). Thus, more frequent extreme heat events at some airports may require restricting seat availability, more flights for the same number of passengers or the use of aircraft with greater engine thrust. These impacts combined could lead to an increase in energy demand in the aviation sector, which accounted for around 12% of the energy use in the transport sector in 2019.

In some extreme cases, when temperatures go beyond a certain level, aircraft are unable to take off. In Phoenix, more than 40 flights were cancelled in 2017 due to extreme heat (50°C). Some studies project that, in the United States, the number of spring and summer days when temperatures will be too hot for aircraft to fly at normal weights could double by 2050, compared to today. Hence, in certain times of year, aviation activity may decline because of increased extreme heatwaves.

Aviation and changing wind patterns

Changing winds patterns (near-surface winds and en-route winds) associated with climate change can also affect the aviation sector. Near-surface winds are relevant for takeoff and landing because changing wind direction or reduced wind speed can require more energy, all other factors being equal. A long-term change in the trends of en-route winds can also affect fuel consumption and journey time. A scenario in which the atmospheric CO_2 concentration is doubled, compared to pre-industrial levels, leads to strengthened en-route winds. This significantly shortens transatlantic flights between London and New York eastbound, leading to lower-than-usual fuel consumption, and lengthens westbound flights, leading to higher-than-usual fuel consumption, in all seasons. However, the shortening and lengthening do not cancel out: overall round-trip journey times would increase. Hence, with higher atmospheric CO_2 concentrations, aircraft on the London-New York route could consume an extra 7.2 million US gallons of jet fuel annually due to the effect of climate-induced strengthened en-route winds.

Road transport and railways

A warmer climate and more frequent heatwaves would affect fuel and battery efficiency in road transport, while railways would remain relatively robust, despite added stress

Raising global temperatures will affect energy demand in passenger road transport, particularly EVs and hybrid electric vehicles (HEVs). Extreme variations of surface temperatures have a direct impact on increasing the fuel consumption of all types of road vehicles. For instance, car cooling systems have to work much harder with increasing ambient temperature in order to keep all parts of the engine within operating range, requiring more energy. Extreme heat may cause the air inside tyres to expand, causing over-inflation, which increases rolling resistance and therefore decreases efficiency – also requiring more energy. The higher the ambient temperature, the quicker the reduction of number of recharging cycles of EV and HEV batteries, meaning that the life span of the batteries would decrease quicker. Higher global temperatures may require more frequent changes of EV and HEV batteries. At the same time, rising global temperatures may help overcome one of the problems of Lithium-ion (Li-ion) batteries in some places. At sub-zero temperatures, the Li-ion cell's capacity and its best state of charge are reduced, effectively reducing the efficiency of the battery, hence requiring more energy for the same number of kilometres.

Analyses of the vulnerability of railway systems to climate change show that they are relatively robust, with the exception of some extreme weather events. Railways are generally able to continue to operate even if slow-onset climate conditions evolve, as they are planned with large security margins. For instance, recent drainage systems are designed to cope with at least a one-in-a-hundred-year flood event, and stabilised renewed railways can withstand temperatures of up to 60°C. However, steel rails tend to be around 20°C above the surrounding air temperature, which in extreme heatwaves, can lead rails to expand, bend, flex or buckle. Such events could lead to disruptions, as per warnings issued by the UK Network Rail in July 2022.

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Chapter 5. Measures to build climate resilience for energy security

Building and strengthening the climate resilience of energy systems is increasingly important, given the hazards faced and the impacts on energy security. Climate resilience is the ability to anticipate, absorb, accommodate and recover from the effects of a potentially hazardous event related to climate change. A climate-resilient energy system is one that can prepare for changes in climate, adapt to and withstand the slow-onset changes in climate patterns, continue to operate under the immediate shocks from extreme weather events, and restore the system's function after climate-driven disruptions.

Enhancing climate resilience requires actions from all stakeholders. Energy suppliers, consumers and authorities are key actors, while science communities, international organisations, civil society and businesses in other sectors are all involved. **Energy suppliers**, including generators and operators of transmission and distribution systems, have primary responsibility for and direct interest in protecting their own assets and providing reliable energy services to their customers. They can improve resilience to climate change by conducting climate risk and impact assessments, implementing physical system hardening, switching to a water-efficient and heat-resilient production process, diversifying the energy supply chain and introducing better climate monitoring systems for early warning and emergency response.

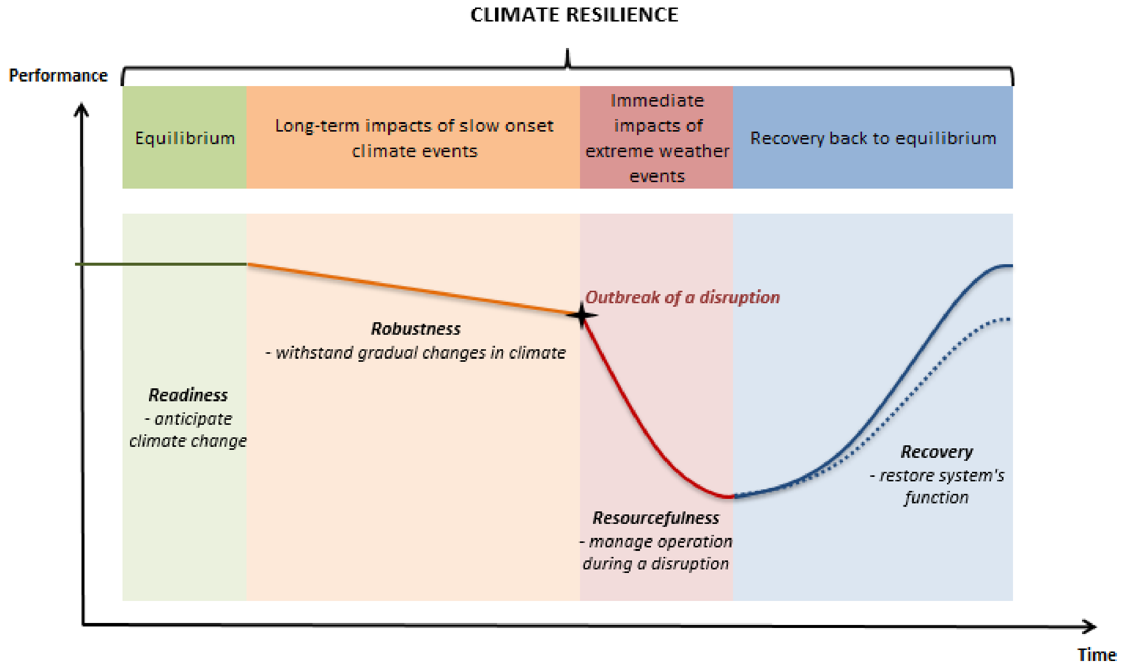
Energy consumers can contribute to climate resilience by adopting demand-side measures in the main end-use sectors (buildings, industries and transport). Although demand-side measures may seem to have only indirect impacts on the resilience of the energy system, they actually play a key role in enhancing the flexibility of and managing peak load in power systems. Demand-side measures that are already proven effective include climate-proofed designs, choices that reduce energy use, improved energy efficiency, new technologies, nature-based solutions and climate-resilient materials.

Energy authorities, which include national and sub-national governments and regulators, have a critical role in building energy-sector climate resilience by establishing an enabling policy and market environment. Energy authorities can facilitate actions from energy suppliers and consumers, addressing barriers that could discourage actions for climate resilience. Such barriers include high upfront costs versus long-term benefits, uneven distribution of costs and benefits, and limited knowledge and awareness about climate impacts and risks. In addition, monopolistic market conditions may require greater policy and regulatory measures to enable climate resilience actions and investments among energy suppliers. Energy authorities can catalyse actions by energy suppliers and consumers by enhancing knowledge about climate risks and impacts; establishing appropriate policy frameworks; mainstreaming climate resilience into relevant regulations, standards and guidelines; mobilising financing and investment; supporting adequate risk-sharing mechanisms to cope with potential costs from climate impacts; and ensuring an efficient and co-ordinated disaster risk preparedness and response system.

This chapter provides a non-exhaustive overview of measures that can improve the overall resilience of the energy system to climate impacts, looking at supply, demand and cross-cutting actions from energy authorities. These measures can be applicable to various stages of climate resilience: readiness, robustness, resourcefulness and recovery (see Figure and Table below).

- **Readiness** is the ability to assess, anticipate and prepare for changes in climate in advance.
- **Robustness** is the ability of an energy system to withstand the gradual, long-term changes in climate patterns and continue operation.
- **Resourcefulness** is the ability to continue operation during immediate shocks, such as extreme weather events.
- **Recovery** is the ability to restore the system's function after an interruption resulting from climate hazards.

Conceptual framework of energy-sector climate resilience



Measures to build climate resilience for energy security by stakeholder

Types	Measure	Readiness	Robustness	Resourcefulness	Recovery
Supply side	Conduct climate risk and impact assessment				
	Implement physical system improvement				
	Switch to water-efficient and heat-resilient production process				
	Diversify energy supply chain				
	Better monitor for early warning and emergency response				
Demand side	Ensure climate proofing in design and performance				
	Increase awareness and promote behavioural changes				
	Improve energy efficiency				
	Use smart and advanced technologies for better management				
	Adopt nature-based solutions				
	Switch to climate-resilient materials				
Authorities and governments	Enhance knowledge about climate risks and impacts				
	Establish appropriate policy frameworks				
	Mainstream climate resilience into relevant regulations				
	Mobilise financing and investment				
	Support adequate climate insurance				
	Ensure emergency preparedness				

Supply-side measures

Comprehensive climate risk and impact assessments help identify appropriate sites and technologies

The increasing climate impacts on energy systems highlight the importance of climate risk and impact assessments. Project developers and investors can avoid potential losses by taking climate risks and impacts into account and adopting appropriate measures in advance. Some governments already recommend that energy suppliers assess climate-related risks and provide tools. For instance, the US Department of Energy established guidelines in 2016 and supported 17 energy companies in conducting climate change vulnerability assessments.

Climate risk and impact assessments are increasingly being used for investment decisions. More and more energy-related companies are disclosing the results of climate risk and impact assessments, following the guidelines of the Task Force on Climate-related Financial Disclosures (TCFD). The TCFD was created in 2015 to promote awareness of reliable information on climate-related risks and opportunities. It recommended that companies disclose information on the chronic and acute physical risks of climate change and their impacts, comparing various climate scenarios, as one of the components of "Climate-Related Risks". It emphasises that this analysis will help companies improve their resilience to the potential impacts of climate-related risks, prepare for contingencies and implement more rapid responses to emerging risks and opportunities. The TCFD guidelines are also welcomed by governments. The European Commission announced the European Guidelines on Reporting Climate-related Information supporting the TCFD guidelines and encouraged companies to integrate the information on the physical effects of climate change.

TCFD guidelines on the disclosure of physical risks of climate change

<table>
<tr><th>Physical risks</th><th>Potential financial impacts</th></tr>
<tr><td rowspan="3">Acute
(increased severity of extreme weather events, such as cyclones and floods)</td><td>Reduced revenue from decreased production capacity</td></tr>
<tr><td>Reduced revenue and higher costs from negative impacts on workforce</td></tr>
<tr><td>Write-offs and early retirement of existing assets</td></tr>
<tr><td rowspan="4">Chronic
(changes in precipitation patterns and extreme variability in weather patterns, rising mean temperatures, rising sea levels)</td><td>Increased operating costs</td></tr>
<tr><td>Increased capital costs</td></tr>
<tr><td>Reduced revenues from lower sales/output</td></tr>
<tr><td>Increased insurance premiums and potential for reduced availability of insurance on assets in high-risk locations</td></tr>
</table>

Source: TCFD (2021b).

Following the TCFD guidelines, some energy suppliers have already conducted climate risk and impact assessments. For instance, Ørsted, a Danish renewable energy company, conducted a climate scenario analysis in 2019 to identify and assess the potential impacts of a warming climate with a focus on offshore wind power generation. It qualitatively assessed impacts from changing wind patterns, sea-level rise and extreme waves.

Such climate scenario-based assessments help energy project developers identify proper sites. For instance, the AES Corporation, a power generation and utility company, did a stress test against wind, flood and wildfire based on two climate scenarios with a 2040 timeframe. Based on the result, the AES Corporation planned to reduce the proportion of its assets in medium- and high-risk locations from 37% in 2020 to 27% by 2040, with growth in new renewable capacity in low-risk locations.

Climate impact and risk assessments can also help energy suppliers select the more resilient production technology. For instance, Enel, an Italian energy utility, adopts a scenario framework to assess chronic and acute physical risks under three climate scenarios, supporting the definition, planning and implementation of adaptation solutions. An example of these analyses is the assessment that led to the use of climate data elaborated up to 2050 to manage projected climate impacts on power generation and to assess potential risks for grids. Estimation of extreme wind speed, based on historical data progressively integrated with climate data, helped the company select the most suitable wind technology. Similarly, site-specific assessments for hydropower plants were used to assess flood risk and identify risk mitigation actions.

Despite some progress, many energy suppliers still struggle to conduct comprehensive climate risk and impact assessments. As of 2020, only 44% of the 267 energy companies participating in the TCFD submitted climate-related metrics, including the information on the physical risks of climate change. Although the response rate of the energy sector was higher than that of banking, insurance, transport, and technology and media, it was still lower than that of the material and buildings and the agriculture and food sectors. Some companies point out difficulties in obtaining appropriately granular, business-relevant data and tools for scenario analysis, determining scenarios and quantifying climate-related risks and opportunities, and characterising resilience.

To address these challenges, climate projection data and scenarios need to become more accessible. In the past, some utilities used only historical climate data in their risk and impact assessments due to challenges in accessing and interpreting climate projection data. However, relying solely on historical data may lead to an underestimation of future climate change risks and impacts. In order to support the use of future climate scenarios in risk assessments, the TCFD Knowledge Hub provides information on scenario analysis, listing existing tools and resources. The United States Environmental Protection Agency also introduced a list of tools for climate change adaptation, including a Climate Scenarios Projection Map.

Climate risk and impact assessments for energy suppliers would benefit from an extended time horizon. Currently, a majority of the existing scenario analyses conducted by energy suppliers go to 2040 or 2050, which may not capture the entire lifetime impacts of climate change on energy systems. Given that many parts of the energy system in general operate for a minimum of 20 years and up to 100 years, a longer time horizon for climate risk and impact could improve insights for managing the security of supply.

Life span of power plants by technology

Technology	Life span (years)	Technology	Life span (years)
Coal	30-60	Hydro	50-100
Natural gas	15-60*	Solar PV	25-40
Oil	20-60	Wind	20
Nuclear	40**	Biomass	20-30

*15-40 years for gas turbines and combined-cycle units and 30-60 years for steam turbines.
**Potential extensions of additional 20-40 years not considered.
Sources: NREL; S&P Global (2019).

Physical system improvement could prevent and withstand damages from climate change

Physical system improvement can help energy systems withstand the physical impacts of extreme weather events, such as floods and tropical cyclones. It can significantly reduce the probability of damage from floods, which are expected to become more frequent in many regions. For instance, improving the floodwall and dikes of generation assets and relocating substations to higher ground can help power plants prevent flood damages. Particularly for hydropower generation, which is directly affected by floods, hardening and redesigning infrastructure can be useful for dam security. Measures can include enhancing reservoir capacity, increasing dam height, increasing flood fences around power stations, relocating powerhouses to higher ground, modifying canals or tunnels, building upstream sediment control facilities and modifying spillway capacities. According to a Word Bank analysis, increasing hydropower plants' spillway capacity can reduce the probability of damage from floods by 50% while increasing total project cost by only 3%. Enhanced hydropower plants can also bring benefits in protecting communities from floods and droughts.

Technical and structural improvements of power generation assets and electricity networks can also enhance resilience against tropical cyclones. The projected intensification of tropical cyclones could have negative impacts on wind power generation and electricity networks, which already suffer from these climate hazards. Advancing wind power plant design with stronger towers, customised rotor sizes and reinforced foundations will help cope with the intensification of tropical cyclones. Improving electricity networks with underground lines, replacing concrete and wooden poles with galvanised steel poles, installing battery storage solutions and upgrading towers and insulators can reduce damage to transmission and distribution networks. In some places, designing strongly meshed networks, which include redundant lines as backups in case of failure in the main line, may help avoid loss of load and enhance resilience to tropical cyclones.

Physical system hardening can also enhance the resilience of energy systems against slow-onset events, such as sea-level rise and permafrost thaw. Many oil and natural gas facilities, as well as thermal power plants, are located along coasts, since they rely on imported fuels or seawater for cooling. Electricity networks are also heavily concentrated along coastlines because a high number of cities are located on the coasts, consuming three-quarters of global energy. However, energy systems situated on coasts can be vulnerable to sea-level rise and its associated events, such as storm surges, erosion and flooding. According to the United States Climate Resilience Toolkit, roughly one-third of the country's petroleum and gas refining facilities are in the coastal plains of the Gulf of Mexico and exposed to storm surge and coastal flooding. In order to build resilience against sea-level rise and its associated events, energy suppliers can build coastal barriers using green infrastructure (e.g. plants, reefs and sand) or grey infrastructure (e.g. seawalls and dikes) to address storm surges and inundation. They can also consider relocating vulnerable facilities out of flood-prone areas.

Upgrading energy infrastructure with additional devices (e.g. braces and thermosyphons) can also reduce damage from permafrost thaw. Thawing permafrost can jeopardise the structural integrity of oil pipelines and raise the potential risk of oil spills in Arctic regions. To protect oil pipelines from potential damage from permafrost thaw, some are built on elevated support systems to keep pipes above ground. However, the faster temperature rise in the Arctic region is making such braces twist and bend. To keep the ground frozen, more and more thermosyphons – tubes that suck heat out of permafrost – are installed in the ground to cool the permafrost below the pipeline. A layer of insulating materials on top of the permafrost can be added as well. Alyeska, United States, added about 100 thermosyphons with a layer of insulating wood chips in 2021 to protect the Trans-Alaska Pipeline, one of the world's largest oil pipelines, which already uses 124 000 thermosyphons.

Switching to a water-efficient and heat-resilient production process makes energy supply more robust

Developing and switching to innovative water-efficient technologies can improve the climate resilience of fuel supply and mining. For example, water use can be cut by controlling water losses (e.g. minimising wet areas or filtering tailings) or using dry processing technologies. In copper mining, a better ore sorting system can reduce water consumption for processing waste, which has increased 60%, compared to twenty years ago, due to the depletion of high-grade mineral ore deposits. New developments in lithium mining, such as direct lithium extraction technologies, can also cut water use in the initial steps of production.

Switching to alternative water sources could be an option for extractive industries. Alternative water sources, such as water from mine dewatering and surface runoff, recycled process water, produced water, treated wastewater or seawater, can reduce business risks related to freshwater shortage. Wastewater for hydraulic fracturing in shale production is being used or explored in some countries, such as Mexico, South Africa and some parts of the United States, where climate change is projected to make less freshwater available. Use of seawater and wastewater is also actively being discussed in the mining industry. According to Cochilco, a Chilean copper commission, copper mining's use of seawater – desalinated and direct from the ocean – will increase 167% by 2032 in Chile, while freshwater use will decline 45%, making the industry rely on around two-thirds of water from the ocean. Already, seawater mixed with tailings dam water in the industrial storage pond is occurring in Chile, as seen at the Las Luces copper-molybdenum beneficiation plant.

Further deployment of dry or hybrid cooling systems for thermal power plants may reduce their dependence on water and decrease the risk of climate-induced disruptions. A dry cooling system in general has higher construction and operation costs and a 7-8% lower efficiency than a conventional wet cooling system. The application of dry cooling systems has therefore been limited to high water stress regions or natural gas combined-cycle power plants, which require less cooling water per MWh. For instance, in South Africa, where water stress is rapidly increasing, Eskom embarked on dry cooling systems at the Matimba, Majuba Kusile, Medupi and Kendal power plants for water conservation, despite their higher cost. In the United States, dry and hybrid cooling systems are increasingly adopted for natural gas combined-cycle power plants, from 13 620 MW net summer capacity to 20 221 MW in 2020, although they are rarely used for oil and coal power plants due to their cost.

Wastewater for cooling thermal power plants could be an alternative but may require more affordable and reliable wastewater treatment. Attempts to use reclaimed water from municipal wastewater has already started in some countries. Palo Verde, the largest nuclear power plant in the United States, relies on reclaimed water (220 ML per day) piped from Phoenix, 70 km away. However, the soaring cost of treated wastewater, projected to be around USD 300 per acre-foot in 2025, compared to USD 53 in 2010, is posing a challenge to the operation, making the plant seek other sources of water. Similarly, India's endeavour to make all thermal power plants within 50 km of a sewage treatment plant use treated wastewater faces financial cost issues, since the reclaimed water cost is projected to increase by more than three times, compared to the current price. Innovative technologies that can significantly reduce the cost of wastewater treatment could help thermal power plants in countries with scarce freshwater sources.

Another major climate-related concern in the energy sector is the increase of extreme heat. Innovative technologies can make electricity generation, particularly from renewables, more resilient against extreme heat and thus more reliable and stable. Given that standard wind power plants designed to operate below 35°C need to shut down at temperatures above 45°C, there have been efforts to improve wind power plant design. For instance, a new design with enhanced wind turbine ventilation was adopted for the 50 MW Dhofar Wind Power Project in Oman so that it could operate in conditions of 45°C.

Continuous operation of solar PV also requires improvement in solar PV cooling technologies. A projected increase in heatwaves is likely to reduce solar PV efficiency and generation output. Although passive cooling systems based on natural convection and active water-cooling techniques are being used at most solar PV plants, these methods have a low efficiency or require an external supply of power and water. Further improvement of cooling technologies, such as enhanced and combined phase change materials and combined heat pipe and sink cooling, can help maintain solar PV performance against temperature rise.

Technological and geographical diversification in energy supply contributes to climate resilience

Diversification of resource production will contribute to global energy security, enabling energy suppliers to continue operation despite shocks to one production site. For instance, critical minerals, essential for clean energy transitions, are concentrated in a small number of countries. Thus, climate impacts on key producer countries can become a major threat to global energy security. Indeed, floods in Indonesia, the world's biggest supplier of nickel ore, led to an immediate increase in global nickel prices in June 2019 due to the closure of around 75% of nickel mines.

Diversifying production sites of critical minerals could enhance energy security in the face of increasing climate impact and rapid demand growth. For example, increasing lithium and nickel production in Africa by developing untapped potential could reduce the global reliance on Australia, Chile and China for lithium production and on Indonesia, the Philippines and Russia for nickel production. Already, some lithium mining projects are under development in Ghana, the Democratic Republic of the Congo, Mali, Namibia and Zimbabwe, and nickel production is taking place principally in Botswana, South Africa and Zimbabwe with the potential development of the East African nickel belt. Further exploration of critical minerals resources could help energy suppliers cope with disruptions in leading suppliers and continue operation during climate-related shocks.

Diversifying power generation technologies could also improve climate resilience by reducing dependence on vulnerable sources. Climate change could make certain power generation technologies more vulnerable than others. In some parts of North Africa, hydropower is likely to see a significant drop in generation output and an increase in year-to-year variability due to decreasing streamflow and increasing droughts. Reducing the region's reliance on hydropower and raising the share of other power generation technologies would help enhance its climate resilience.

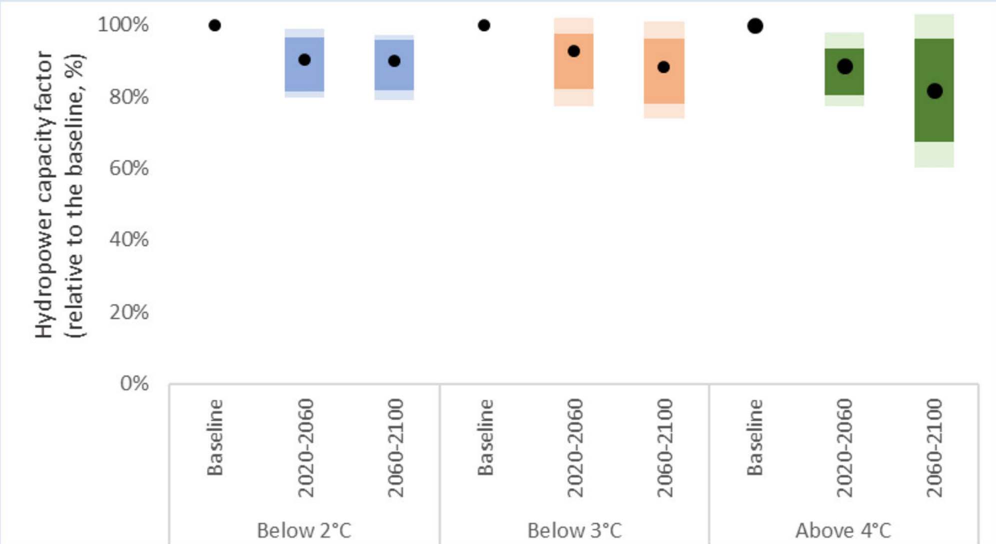
Geographical diversification of power sources with more distributed energy systems, batteries or interconnections can also improve energy-sector climate resilience. Microgrids with distributed energy resources can be used for backup generation when the central power source is damaged by climate hazards. Microgrids generally include a small-scale thermal generator with local fuel storage (e.g. diesel generators and small natural gas turbines) or variable renewables with batteries. Microgrids can function separately from the main grid in the event of outages, ensuring local power reliability. In other locations, more interconnections to link diverse energy sources (e.g. regional power pools) and redundancies can be a better solution for improving reliability. For instance, the interconnection between the United Kingdom and Belgium allowed the United Kingdom to import electricity from Belgium to cope with power supply strains during the record-breaking heatwaves in July 2022.

Diversification of power generation technologies and climate resilience in Brazil

A strong historical reliance on hydropower for electricity generation in Brazil has raised concerns about exposure to the adverse impacts of climate change. In 2020, hydropower provided almost two-thirds of electricity generation. However, climate change is disturbing hydropower operation by increasing variability in streamflow and augmenting evaporation losses from reservoirs, adding stresses to the changes in land use in watershed areas. Climate change is expected to have more impacts on hydropower generation in the future. Eastern Brazil has already experienced a decrease in mean precipitation and is likely to see a further drop with increasing aridity. The changes in precipitation patterns could shift the total availability of and seasonal variations in water and consequently hydropower generation capacity.

IEA analysis of climate impacts on major hydropower plants in Brazil shows that the hydropower capacity factor of Brazil is projected to decline for the rest of the 21st century, compared to a 1970-2000 baseline. A higher GHG emissions scenario is projected to bring a larger decrease in the hydropower capacity factor than a lower GHG emissions scenario, although the estimated levels of impacts vary across river basins and among climate models. For instance, the results show that some hydropower plants located in southern Brazil, such as Barra Grande and Machadinho, could be less affected by climate change in all three scenarios, while others experience a notable change in their hydropower capacity factors in a majority of climate models.

Climate change impacts on hydropower in Brazil, 2020-2100 compared to 1970-2000

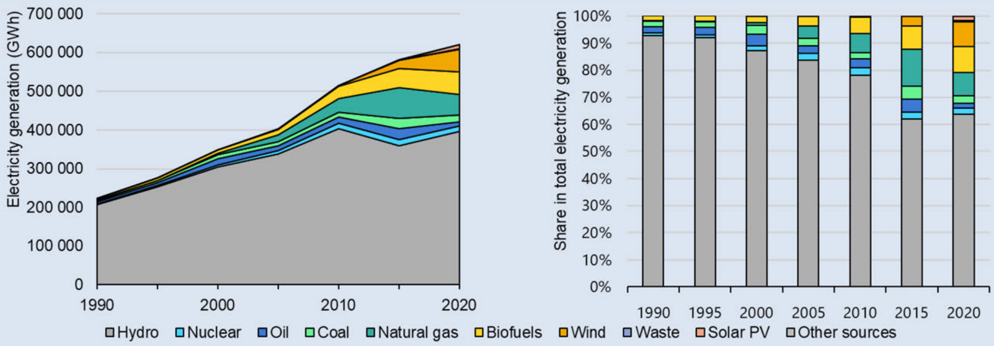


Notes: Assessment of climate impacts on 88 hydropower plants in Brazil using five GCM, four GHM and three Representative Concentration Pathways. Black dots indicate the average hydropower capacity factor for the selected Brazilian hydropower plants based on results from 20 combinations of GCMs and GHMs for each scenario. Coloured bars indicate the range of the results; darker colours in the bars show the range of 80% of the results.

Source: IEA (2021i).

In order to cope with the projected decrease in hydropower capacity, Brazil has been working on diversifying electricity generation technologies. It reduced the share of hydropower in electricity generation from 93% to 64% between 1990 and 2020 while significantly raising the share of natural gas, wind and biofuels. Shares of both natural gas and wind increased, from 0% to 9%, over the past three decades, while the share of biofuels also escalated, from 2% to 9%. The growth in diverse generation technologies helps the country reduce its reliance on hydropower and thereby cope with changes in hydropower generation due to climate change impacts.

Diversification of electricity generation technologies in Brazil, 1990-2020



Source: IEA (2022c).

Better climate monitoring systems enable early warning and improve emergency response

The deployment of smart grid technologies provides system operators with increased visibility into real-time operation and can help them minimise damage from climate hazards. For instance, in cases of outages, smart grid technologies can automatically alert the utilities and help them fix problems. Smart grid technologies can also enable energy suppliers to reroute power around the detected problem, preventing a lengthy outage. Their ability to diagnose problems is particularly useful when multiple outages happen simultaneously due to extreme weather events, such as tropical cyclones. For example, when Hurricane Irma led to massive outages in 2017, smart grid infrastructure accelerated power restoration in Florida, bringing benefits of nearly USD 1.7 billion of avoided customer interruption costs with 112 million fewer interruption hours.

Smart metering can restrict the impact of climate-driven outages. Advanced metering infrastructure, which is becoming more commonly applied, enables the communication of energy usage across the distribution network in close to real time. Distribution system operators benefit from extensive visibility into the condition of their systems, allowing them to develop the most effective solutions to cope with the impact of outages on the distribution network. For example, when an electricity system is impaired by an extreme weather event, the energy company can use smart metres to implement targeted load shedding while limiting the likelihood of large-scale outages.

Real-time climate monitoring with early warning systems helps energy suppliers prevent and manage climate change risks. However, current energy supply chains are not appropriately covered by climate monitoring systems. According to a 2021 report released by the US Government Accountability Office, roughly 14 000 km of active oil and gas pipelines are not being sufficiently monitored. To fill the gap, some initiatives and actions are being implemented by energy suppliers in collaboration with international organisations and academia. For instance, nuclear power plant operators are participating in the IAEA's External Events Notification System, which is based on a real-time multi-hazard monitoring platform (DisasterAWARE) to enable timely responses to events that could threaten the safety of nuclear facilities, such as floods and wildfires.

Technical innovation is also enabling better monitoring of climate and weather conditions. For instance, energy suppliers can reduce the risk of wildfires by installing improved monitoring options, such as unmanned aerial vehicles, a global system for mobile communication technology combined with smoke and temperature sensors, high-resolution video cameras with automatic alert systems, and Internet of Things solutions supported by satellite imagery. Indeed, in August

2021, Pacific Gas and Electric Co.'s high-definition camera, supported by artificial intelligence analytics, spotted a wildfire north of Sacramento in its early stage and helped limit the fire.

Innovative technologies for monitoring climate and weather conditions can also contribute to regular operation practices. For instance, Iberdrola adopted an integrated system for the prediction of medium- and long-term meteorological variables (MetoFlow system) using weather forecasting techniques, machine learning, artificial intelligence and big data technologies. It can predict extreme meteorological phenomena, such as storms and frost, and allows the activation of emergency plans in advance.

Demand-side measures

Ensuring climate proofing in infrastructure design could reduce potential climate risks

Considering climate risks and impacts in the design of assets and infrastructure can help with the security of energy supply when it comes to transport infrastructure, as well as reduce energy demand for infrastructure by reducing the need for reconstruction. For instance, Avatiu Port in the Cook Islands modified its project design in 2011-2014 so as to allow for future adaptation to the anticipated impact of sea level rise, spending USD 800 000 (4.4% of total project cost). The revised design involves the strengthening of pilings to raise the wharf level by up to 0.5 m. The Central Mekong Delta Connectivity Project in Viet Nam also changed its design after a study assessing the vulnerability of the project to climate change. One of the climate-proofing options identified was to raise the design height of the road embankment by 0.3 m to make it less vulnerable to sea level rise-related impacts. The cost of adaptation represents only 0.5% of the total project cost.

Regular performance assessment of key infrastructure in end-use sectors could also ensure resilience against extreme weather events. Monitoring the operations of infrastructure, such as regular observation and recording of the performance of the asset, can support the identification of needs for maintenance and upgrades. Timely and proper maintenance and upgrades help assets and infrastructure in end-use sectors prepare for changes in climate and withstand adverse climate impacts (e.g. breakdown by climate disasters). They can also help avoid the significant costs and energy use associated with reconstruction.

Developing frameworks for adaptive decision making that address climate impacts, energy security and service continuity will be increasingly critical in the next decades because of the essential dependence of several vital infrastructure systems, such as healthcare infrastructure, on energy infrastructure. Climate variability is also expected to bring in a great degree of variability in demand for energy services. Future energy assets will need to be designed not only to consider future climate impacts but also to withstand variability in the demand for energy services.

Energy consumers can contribute to climate resilience by managing their energy consumption

Energy consumers can help the energy system respond to climate change in various ways, including by changing their behaviour patterns and shifting to climate-resilient alternatives. For instance, during heatwaves or cold spells, adjusting the thermostat for buildings to levels closer to outside temperatures can help manage peak energy demand. Setting thermostats at no more than 19-20°C in homes, offices and other commercial buildings in winter can reduce electricity demand by 160 TWh globally in 2030, with over 70% of the reduction occurring in advanced economies.

The use of a “smart default” can take advantage of consumer inertia while still enabling users to select a different option if they prefer. India's regulation for ACs, approved in 2020, requires establishing a 24°C default temperature settings for devices, which could reduce electricity consumption by 18-24%, compared with the previous default temperature of 20-21°C. The Spanish government imposed a lower limit of 27°C for AC in summer for offices, stores and hospitality venues in 2022 until November 2023.

Using a white roof instead of a dark roof, which can cool the top floor of a building by 2-3°C, can also reduce energy demand for cooling. One analysis found that the net annual energy use for a building with AC can be reduced by up to 20% upon raising the solar reflectance of the roof from 10-20% to 60%. Using solar reflective roofs can also contribute to limiting urban heat. A University of New South Wales study shows that the outdoor air temperature in major Australian cities can be reduced by 2.1-2.5°C with this solution. Supportive government regulations and civil society initiatives can accelerate uptake. For instance, the New South Wales government’s ban on dark roofs and the Million Cool Roofs Challenge, which aims to deploy 1 million m^2 of cool roofs in countries suffering heat stress, could catalyse the deployment of roofs that use less energy and are more resilient to climate impacts.

Consumers can also select more climate-resilient options in the transport sector. Aviation is not only energy intensive but also vulnerable to climate-driven disruptions, such as tropical cyclones and extreme heat, causing flights to be cancelled. Where available and a viable option, train alternatives tend to be more resilient to extreme weather events while consuming less energy. Such behavioural changes can be turned into or supported by legislation. In 2021, France approved a bill to end air routes also covered by train journey in under 2.5 hours. The Spanish government adopted a policy to develop a 4 000 km high-speed rail network to provide an attractive alternative to short-haul domestic flights. In an urban context, shifting to active mobility, such as walking and cycling, can reduce energy demand while providing important benefits for human health and the environment.

Energy consumers can reduce their energy consumption through various communication activities (e.g. media, campaigns, meetings and online promotion) and training. For instance, energy-saving competitions and community-based initiatives can leverage social comparisons among consumers of the same energy utility and engage participants through real-time feedback, as well as set milestones and targets that trigger rewards. In the Cool California Challenge, households in each city earned points based on their self-reported energy consumption behaviour. In the San Diego Energy Challenge, households that opted in to use online software to encourage energy reduction decreased their electricity consumption by 20% over three months. In general, the energy savings that can be achieved through competitions and community-based initiatives are around 14% for electricity and 10% for gas. Providing consumers with data tracking their domestic energy consumption, comparing this with their previous consumption or that of their neighbours and informing them of potential savings was found to lead to around 2% energy savings in the United States, Malaysia and Japan.

The production of synthetic fertilisers currently relies heavily on fossil fuels – mostly natural gas and coal, with ammonia production accounting for approximately 2% of total final energy consumption. Switching to biological fertilisers is an effective alternative to reduce energy consumption. Moreover, the overuse and/or long-term application of synthetic fertilisers can lead to degradation of soils and surrounding water bodies. Biological fertilisers are made up of live bacteria and microorganisms that help improve soil fertility and plant development. These bacteria aid in the nitrogen fixation process, which produces the nutrients required for plant development. Bio-fertilisers enhance nutrient availability while increasing yields by 10-25%.

Besides being less energy intensive, bio-fertilisers increases plants resilience to weather-related stress. They contain ingredients that help plants cope with abiotic stresses, including drought, extreme cold, water surplus or shortages, and salty soils. They are also less expensive and do not cause air and underground water pollution, soil acidification or loss of soil fertility.

Energy efficiency can reduce energy demand and relieve the climate-related strain on energy systems

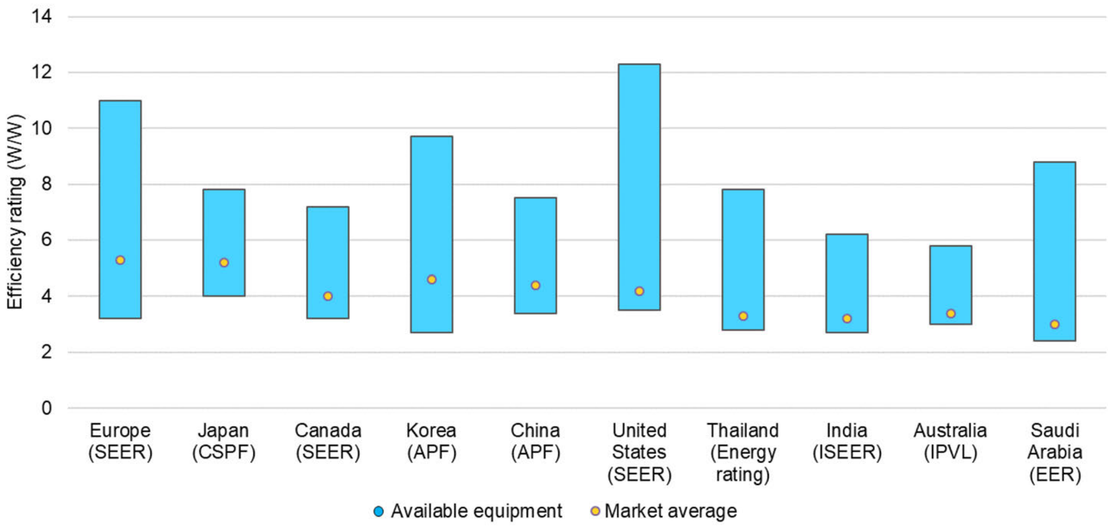
Reducing the absolute level of energy demand or mitigating the projected increase of energy demand due to climate change is an important way to build climate resilience and enhance energy security and is something energy efficiency improvements can help support. Efficient cooling systems can reduce the strain on electricity supply during heatwaves. Doubling AC energy efficiency by 2050 would reduce the need for 1 300 GW of additional electricity generation capacity to meet peak demand. More efficient transport systems can help manage fuel shortages due to supply disruptions during tropical cyclones or wildfires.

Energy efficiency is particularly important to limit the climate-induced energy demand in the buildings sector. In all future scenarios, climate change is projected to increase cooling needs in buildings and would require better insulated and more efficient buildings to manage. However, roughly 75% of the current EU building stock is estimated to be energy inefficient. Renovating existing buildings could reduce the European Union's total energy consumption by 5-6%. Currently, less than 1% of the national building stock is renovated each year, on average. In order to meet the European Union's climate and energy objectives, current renovation rates should at least double.

Improving the energy efficiency of appliances can also help relieve the strain on electricity demand during extreme weather events. Improving the efficiency of AC appliances or switching to more efficient appliances, such as heat pumps, could reduce the projected increase in the electricity demand of buildings. Without major efficiency improvements to cooling equipment, electricity demand for cooling could increase by as much as 40% globally by 2030, resulting in potentially large strains on the power grid at peak times during heatwaves. Using rooftop solar PVs could smooth cooling demand peaks, as AC demand is usually temporally and geographically correlated with high levels of solar irradiation.

However, an analysis of AC systems across countries shows that, nearly everywhere, people are buying ACs that are significantly less efficient than what is available, as people tend to buy the less expensive products. The average product across the major cooling markets is usually two times less efficient than the global best available products. IEA analysis has also shown that, in many markets, consumers could purchase more efficient AC equipment than the average without an increase in price. Policy measures, such as minimum energy performance standards, are important to ensure that available appliances become more efficient and to prevent the least efficient options by limiting the maximum amount of energy consumed by an appliance.

Energy ratings of air conditioners already available in markets by regional metrics, 2020



Notes: SEER = seasonal energy efficiency ratio. ISEER = Indian seasonal energy efficiency ratio. EER = energy efficiency ratio. CSPF = cooling seasonal performance factor. APF = annual performance factor. IPVL = integrated part load value. An AC's efficiency rating refers to the ratio of heat removed from a space to the amount of energy the equipment requires to condition it. The higher the rating, the more efficient the equipment. Efficiency rating indicators differ by country, depending on climate weighting, which can be altered by, for example, assuming different temperature bins (ranges) or requesting different numbers of testing data points.

Sources: IEA (2020c) and national product registry information.

New technologies can help limit climate impacts on households and businesses

"Smart" and advanced digital technologies provide energy users with options to control their energy use remotely or automatically, which can help reduce the stress and risks to energy systems during climate-driven disruptions. For instance, the installation of controllable switches enables the network operator to manage network stresses and serve critical clients, allowing control of the network at a distance. These controllable switches have the ability to limit the impact of lost grid capacity to a small area, preventing potential damages from extreme weather events (e.g. wildfires and tropical cyclones). Intelligent automated switches could also allow the operator to switch the grid to a "hazard configuration" mode in the case of detection of extreme weather events. The use of small-scale distributed energy sources, particularly solar PVs with batteries and grid-forming capabilities or islanding technologies, can also provide backup power when electricity is not available from the grid due to climate-induced disruptions.

Smart and responsive ACs and thermostats can help reduce peak electricity demand during heatwaves. Occupancy-reactive temperature control is a commercially available smart thermostat that uses sensors to detect when a zone is occupied and applies a temperature setback when it is unoccupied. Occupancybased control can reduce heating, ventilation and AC system run time during the cooling season by 5.9% ± 46%, on average. Alarm systems, remote fault indicators and control centres can help preventively disconnect electrical equipment to avoid intensive damages. In the case of floods, these technologies allow for disconnecting electric equipment, reducing fire risk for equipment and the risk of hydrocution for humans. These technologies also allow for disconnecting elements in a controlled manner and isolating the parts of the system that will be at risk, to avoid a system-wide impact (or blackout). Resilience is increased due to reduced equipment damage and the ability to restore affected areas quicker.

Nature-based solutions can reduce the negative impacts of climate change on energy assets and consumption

Nature-based solutions have gained momentum in recent years to address climate change impacts based on an improved understanding of how ecosystems produce a diverse range of services that contribute to human welfare. Nature-based solutions can provide multiple benefits: minimising disaster risk, protecting coasts against erosion and floods, reducing flood impacts, mitigating extreme heat and improving water availability and quality.

Multiple benefits of nature-based solutions

Examples of nature-based solutions	Associated ecosystem services		
	Coastal protection	Reduction in flood impacts	Heat mitigation
Protecting/restoring coastal habitats (e.g. mangroves, salt marshes, coral and oyster reefs)	O		
Protecting/restoring upland forests		O	O
Creating parks and open green space		O	O

Note: The list of examples and services is not exhaustive. It depends on the selected nature-based solutions intervention, its location and the scale of implementation.
Source: OECD (2020).

Nature-based solutions can help manage energy demand by preventing and reducing climate impacts. Nature-based solutions, such as green roofs (roofs partially or completely covered with vegetation over a waterproofing membrane), can support adaptation to extreme weather events. Typically, a green roof design consists of three layers: vegetation, growth media and drainage. Each layer has advantages for climate change adaptation. The vegetation layer provides shading and reduces the temperature during daylight hours in summer, reducing heat stress and cooling demand. In peak tropical temperatures, green roofs were recorded to reduce temperature by approximately 1.70°C, and a hybrid green-blue roof in the range of 5-9°C.

The growing media and drainage layer supports storm water management by storing excess rainfall, while vegetation transpiration restores water storage capacity to the media. Given these multiple benefits, the installation of green roofs has been encouraged through legislation at the local level. The local government of Toronto, Canada, has required the installation of green roofs for new developments larger than 2 000 m^2 since 2009; Copenhagen, Denmark, requires green roofs for all structures with flat roofs built after 2010. In the United States, New York, San Francisco and Washington, D.C. encourage green roofs as well.

Preservation and restoration of riverbed and coastal wetlands can reduce flood risk to the key infrastructure of end-use sectors (e.g. ports, railways, roads and the industrial complex) and therefore help enhance energy-sector resilience. In coastal areas, restoring ecosystem services is estimated to be two to five times cheaper than constructing submerged breakwaters to deal with wave heights of up to 0.5 m. In the north-eastern United States, protected coastal wetlands are estimated to have helped prevent over USD 600 million in direct property damages during Hurricane Sandy. In addition to coastal flooding, natural coastal habitats, such as coral reefs, salt marshes, sea grass or mangroves, sandy beaches and dunes, can provide effective defences against storm surges and chronic stressors, such as sea-level rise and coastal erosion. One of the main nature-based solutions available to reduce urban flooding is planting trees and hedges to increase water absorption, catch rainfall and slow down surface water runoff.

A shift to climate-resilient materials could reduce the adverse impacts of climate change

Materials that are more resilient to certain climate impacts could reduce destruction risks and reduce the repair costs of climate-related extreme weather events. This is particular important for critical infrastructure. Through improved climate risk and impact assessments, a better understanding of the conditions under which infrastructure will need to operate, coupled with a better understanding of the full-service curve for any material or system, would be of great benefit. This would enable projection of the expected service life of the selected materials, taking into account the environment to which it is or will be exposed. This could then guide the innovation needed in material science and building products to improve resilience to climate hazards. For instance, since one of leading causes of deterioration of concrete or steel bridges is corrosion, a possible solution is to cover or encase the metal parts with paint or a polymer wrap, which would provide a protective barrier to keep the chlorides from contacting and corroding the reinforcing bars.

In the transport sector, the development of sodium-ion batteries could be advantageous, given the natural abundance and lower cost of sodium compared to lithium. This type of battery would be less affected by water stress-related impacts affecting critical minerals production (especially lithium), reducing the risks of supply chain disruptions. Moreover, on the basis of the information currently available, we can project the cost of sodium-ion batteries to be about 10-20% less than that of their lithium-ion counterparts.

Permeable pavements are one solution to prevent floods in urban areas. They are composed of a porous urban surface of open pore pavers, concrete or asphalt, with an underlying stone reservoir. They allow rainwater to infiltrate where it falls, thereby reducing storm water runoff. Installation costs are roughly two to three times higher than for regular asphalt or concrete. However, some applications have demonstrated a 90% reduction in runoff volumes.

Measures for energy authorities and governments

Energy authorities can support collection and diffusion of climate data, risks and solutions

Accessible, accurate and comprehensive weather and climate data are essential to enable energy suppliers to conduct proper climate risk and impact assessments, and energy consumers to adopt climate proofing in design and performance. Governments can support such activities through **collecting and distributing scientific data and projections.** The availability of adequate weather and climate data through public and open sources is a precondition for climate-smart energy planning and investment. Project developers and investors can make decisions to select the most appropriate energy option based on the data. Energy system operators can adjust their schedules and take preparatory actions using high-resolution weather and climate forecasts. Weather and climate information allows them to estimate accurately their future power output and optimise decisions about when to sell electricity to the market or when to schedule maintenance works. In addition, energy consumers can adopt demand-side measures, such as efficient cooling systems for heatwaves and watershed area management against flooding, to cope with potential changes in climate.

Despite notable progress in climate science and projections over the past two decades, energy suppliers and consumers still have difficulties in using climate data and models. One of the major reasons is the lack of availability of climate information at smaller geographic and temporal scales, important for energy planning and investment. Even if they are available, sometimes the information is not publicly available, hard to find and challenging to interpret. Even when energy suppliers and consumers have access to such information, it remains challenging to link the complex probabilistic information to industry-specific applications and management tools while addressing a significant level of embedded uncertainties in climate models.

Energy authorities can use their understanding of the specific data and information needs of the sector and work with national meteorological and hydrological services to ensure that relevant data are publicly available, sufficiently downscaled and translated into variables that are relevant to energy-sector stakeholders. Recent analysis by the WMO has shown that, while most countries provide climate services for energy, few of them provide tailored products for the energy sector or its sub-sectors (e.g. for renewable energy).

In addition to supporting weather and climate information, energy authorities can also support the understanding **of projected climate impacts**. Energy authorities can build and diffuse tools that help energy-sector stakeholders (e.g. fuel suppliers, transmission system operators and consumers) better anticipate likely climate impacts on their strategy, assets, activities or services. The US government, for example, provides diverse tools for exploring climate hazards and assessing risks in the US Climate Resilience Toolkit, covering all sectors. The United States has also developed a guide for climate change vulnerability assessments to support electricity utilities in assessing vulnerabilities to climate change and identify a portfolio of resilience solutions (including through a step-by-step approach to determine the costs and impacts of each solution). More recently, a risk mapping tool has been developed for Jamaica to help identify the areas and sectors of its infrastructure networks (energy, water and transport) that are most vulnerable to climate risks.

Energy authorities can also help improve knowledge about **available adaptation options** and their costs and benefits. Climate risk reporting requirements can help energy authorities collect information from key actors about their strategies and activities to enhance resilience. In the United Kingdom, energy regulators, utilities and network operators are obliged to report on their climate change risks, adaptation actions and plans, including barriers encountered. In addition, public research and development funding can help develop effective resilience options or reduce the costs of specific options for individual actors.

In many cases, energy authorities will need to support businesses, communities and households in **building the capacity** needed to understand and appropriately use available climate risk data and tools and to implement measures that increase resilience. Experience from various countries has revealed that skills gaps can constitute a considerable barrier to resilience-building activities, even when clear climate projections and assessment frameworks (and a sound policy framework) are available. In the United Kingdom, energy stakeholders reported that decision makers often lack adequate skills and knowledge to enhance resilience, especially at the local level, where much resilience-building activity takes place. Energy authorities can support the development of necessary skills and capacity among key energy-sector stakeholders by, for example, providing training workshops and building communities of practice.

The need for investment in climate information and capacity building is particularly high in developing countries. In many African countries, climate forecasting and early-warning systems are constrained due to the lack of capacity and resources. In Mozambique, the absence of a well-functioning early warning system and the limited capacities of key central and local government authorities to respond to emergencies was identified as one of the major weaknesses after Cyclone Idai hit the country in March 2019. Improving the availability of high-quality climate data should be a priority, given that it is a very cost-effective investment that could generate large benefits (e.g. by improving investment in long-lived infrastructure assets). Joint capacity-building programmes for multiple entities could provide an opportunity to strengthen the communication of the latest climate information among stakeholders and to learn from each other's experience.

Governments need to establish a policy framework for energy-sector resilience

Governments are responsible for setting the policy framework that supports investments and actions to strengthen resilience in industry, businesses and households. Many countries have started to build a policy framework by integrating climate resilience considerations into their national energy and climate plans. According to recent IEA analysis, three out of four IEA member and association countries included a dedicated section on the climate resilience of energy systems in either their national energy or climate plans, with detailed steps for implementation. In addition, almost all EU member countries included a section on the energy sector in their national adaptation strategies.

Nevertheless, in some cases, national plans may be insufficient to cope with the estimated level of climate risks. A country with a high level of climate hazards should consider prioritising climate resilience measures, while a country with a lower level may pay less attention to the issue. In terms of policy preparedness against the level of climate hazards, around 30% of IEA member and association countries may be insufficiently prepared for the climate risks they may be expected to face. As of March 2022, only 40% of the 194 submitted NDCs prioritise adaptation in the energy sector.

Having a high-level national policy framework or strategy for energy-sector resilience is important to identify the climate risks, vulnerabilities and resilience needs at a system level that risk assessments and resilience planning at an asset or local level cannot capture. The development of energy-specific resilience strategies also offers an opportunity to deliberate and build consensus on questions around an "acceptable level of risk", as well as equity and justice (e.g. who would be affected by this risk). They can also help identify synergies and trade-offs with other policy objectives and avoid maladaptation.

To maximise its effectiveness, a national resilience framework should provide clear goals, strategies and commitments; set clear responsibilities for various actors; and be accompanied by concrete measures and instruments that encourage action. Spain's second National Climate Change Adaptation Plan, for example, has a section on energy that proposes measures, assigns responsibilities and defines performance indicators and sources of funding for four priority areas of action (incorporating climate impact considerations on energy supply, planning and management; preventing climate impacts on electricity generation; preventing climate impacts on energy transport, storage and distribution; and managing electricity demand changes associated with climate change). In the United Kingdom, a nationwide climate change risk assessment is undertaken every five years; a National Adaptation Programme, also revived every five years, sets out actions that the government and others will take; and the Adaptation Committee biennially monitors progress.

Mechanisms for the monitoring and evaluation of adaptation progress should be an integral part of an energy-sector resilience framework. National adaptation monitoring and evaluation is a relatively recent activity in many countries, and there is limited experience with mid-term and end-term evaluations of adaptation policies at the national level. Many monitoring and evaluation systems rely on a combination of indicators that provide information on climate hazards and climate impacts, adaptive capacity, and adaptation actions and outcomes. Italy developed a list of climate change impact indicators under the framework of its National Adaptation Strategy (including, for example, gross hydropower production and the gradient of natural gas heating consumption). In the United Kingdom, the Adaptation Reporting Power gives the government the power to require relevant actors (such as electricity transmission and distribution companies) to report on how they predict climate change will affect them and to propose ways of managing the impacts. Such reporting requirements not only provide the government with information on resilience but can also help raise awareness and organisational capabilities in the private sector.

Resilience needs to be mainstreamed into regulations, guidelines and project approval processes

By developing technical **standards and guidelines**, energy authorities influence the investment, operation and maintenance of several assets in the energy supply value chain, from the design and siting of infrastructure to rules regarding asset performance. Many of these standards and guidelines have been in place for some time, and some will need to be revised and updated to assist energy infrastructure and service providers in alleviating the adverse impacts of climate change on their operational, financial, environmental and social performance. Japan Railways, for example, raised the standard for the estimated maximum performance temperature of its railroads, from 60°C to 65°C, to guide future investments. The European Union recently introduced new ambitious policies to help steer member states towards better energy efficiency in buildings, revising the Energy Performance of Buildings Directive and the Energy Efficiency Directives that propose measures for the modernisation of the building stock and the digitalisation of energy systems. Furthermore, in Europe, the two standardisation organisations, CEN and CENELEC, have been mandated to review existing infrastructure standards with adaptation relevance, including in the energy sector. CEN and CENELEC published a guide that provides a checklist and decision tree to ensure that standards support and enhance climate resilience.

Governments can also maximise the use of key infrastructure by conducting regular performance assessments. Performance assessments can help avoid the destruction of infrastructure by improving its readiness against extreme climate impacts. However, many countries still do not undertake them regularly. According to an Organisation for Economic Co-operation and Development survey, in 2017, performance assessment was only mandated in half of the countries, and ex-post audits by the Supreme Audit Institution regarding infrastructure assets are mainly conducted on a case-by-case basis. Maintenance of infrastructure suffers from insufficient measurement. Data on assessments of past and current conditions are often not available. This includes data on past construction and repairs and an asset's usage and performance. Keeping records on public assets up to date is a technically demanding task, involving valuation and revaluation of non-financial assets.

Governments can also **integrate climate risks into standard policy and project appraisal processes**. The European Union, for example, has required that climate risks be considered in environmental impact assessments (EIAs) since 2014. EIAs must consider the impacts that climate change may have on the project itself and the extent to which the project will be able to adapt to possible future climate changes over the course of its lifetime. A guidance document provides information about the legal aspects of understanding climate change adaptation in EIAs and guidance on how to take account of trends, drivers of change and risk management approaches in EIAs. Similar requirements could also be developed for strategic environmental assessments, while zoning laws can restrict the development of energy infrastructure in flood- or storm-prone areas.

Governments can take measures to incentivise private investment in resilience

To enhance the resilience of the energy sector, investments are needed by a variety of actors, requiring a variety of financing models. Investment made by utilities will mainly rely on traditional corporate financing channels, while investments by individuals (e.g. in building renovations) may require specific public incentives. In some cases, governments or public institutions will directly finance all or part of an investment. The cost of a given resilience-building investment will very much depend on the physical, market and overall policy context. However, the incremental cost of implementing resilience measures could be negligible if resilience is considered early on in the project development and design phases. Using tools for decision making under uncertainty can reduce the need for costly retrofitting while reducing upfront costs.

Even when the benefits of resilience-building investments clearly outweigh the costs, market barriers can impede such investment. This may be the case, for example, when climate resilience measures require high upfront costs but yield benefits that become tangible only after several years or even decades. A private actor may also be discouraged from investing in resilience if the benefits occur broadly and are difficult to value privately. Investment could also be restricted when the benefits of a resilience measure are difficult to assess and quantify (as this reduces the bankability of projects), resilience benefits are not valued, or where measures do not create revenue streams that are attractive to investors.

There are some measures that governments can take to facilitate or promote investment in resilience building. **Encouraging climate information disclosure** can support the bankability of resilience-building investments and thereby improve access to finance. In addition to increasing transparency in financial markets, the process of reporting can also be valuable in raising awareness within companies about their exposure to climate risks and in stimulating action and investment to reduce such risks. Such disclosure should ideally cover risks resulting from both climate-related extreme events and longer-term shifts while allowing governments to monitor progress in the implementation of resilience building. France's 2015 Energy Transition Law, for example, required listed companies to report on climate change impacts or explain why they have not done so.

Where public banks or institutions co-finance investments, governments can require climate risks to be considered. The Asian Development Bank requires that climate risk screening be undertaken for all investments and that a more detailed risk and adaptation assessment be applied to projects that are assessed to be at medium or high risk. Similarly, large infrastructure projects co-financed by some European funds are required to undertake a climate risk and vulnerability assessment and to include appropriate adaptation measures when needed. The

European Commission published a technical guidance that aims to support project promoters and experts involved in the preparation of infrastructure in climate-proofing projects, while the European Investment Bank developed a Climate Adaptation Investment Advisory platform to provide technical and financial advice to EU clients that have the potential to strengthen climate resilience. The World Bank also screens its lending for exposure to climate and disaster risks and has developed a set of tools to support that process.

Governments can also **provide direct financial support**, such as grants or loans, to finance all or part of investment costs. In the United States, in response to Hurricane Sandy, the New Jersey government created a facility that co-finances energy resilience measures in critical infrastructure assets and services, to enhance their reliability during future hurricanes. In Latin America, public investment has played a central role in modernising ageing hydropower plants that tend to be more vulnerable to climate change impacts (see Box below).

In regulated sectors, such as electricity, regulation can promote or act as a barrier to investment in resilience. Traditional approaches based on cost-of-service compensation models may be inappropriate to stimulate investment in demand-side measures. The regulatory framework needs to recognise the value of resilience investment (both to the asset and to the energy system at large) and to ensure that adequate renumeration mechanisms encourage such investments. Performance-based regulation, where network operators are remunerated based on their performance in specific criteria and metrics, is one way to achieve this. Italy’s network regulator, ARERA, has been using an output-based incentive scheme since 2017 to encourage smart grid rollout and resilience investment plans among distribution system operators.

The role of public investment in enhancing the climate resilience of ageing hydropower plants in Latin America

The wide presence of ageing hydropower plants in Latin America makes its electricity system more vulnerable to climate change. Over 50% of the installed capacity in Latin America is over 30 years old. Such ageing hydropower plants are expected to require modernisation to address the projected increase in extreme precipitation events, in addition to general rehabilitation. Some efforts, such as upgrading spillway capacities and increasing dam safety, will protect ageing hydropower plants against future climate hazards and help them adapt to new climate conditions.

The modernisation of hydropower plants needs further investment, with access to financing considered the main barrier. A 30-year rehabilitation plan to extend the life span and improve the efficiency of the Salto Grande hydropower facility in

Argentina and Uruguay would need USD 960 million. The modernisation of Itaipu hydropower plants in Brazil and Paraguay will require an investment of USD 500 million.

Public investment has been playing a major role in financing the modernisation of hydropower plants against increasing climate concerns in some Latin American countries. An announced USD 500 million project to upgrade and rehabilitate Yacyretá hydropower plant will be funded by the Yacyretá Binational Entity, a joint entity between the governments of Paraguay and Argentina. The project will add 276 MW and increase production by 9% with three new turbine generator units, and extend the life span of 20 existing units. Similarly, the Inter-American Development Bank offered a USD 125 million loan for the modernisation of the Acaray Hydropower plant.

Governments can strengthen climate risk insurance

Investments in climate resilience need to be accompanied by **risk-sharing and financing mechanisms**, such as insurance, to manage residual climate risks. An effective climate risk insurance market can significantly improve preparedness against climate hazards while helping avoid excessive financial burdens on individual stakeholders and/or taxpayers. At the same time, the insurance sector can support risk assessment and reduction by encouraging the quantification of climate risks and by imposing higher premiums on risky behaviour.

The market for private weather and climate risk insurance has become more sophisticated over the years. Parametric (or index-based) insurance, where pay-outs are made when certain pre-determined thresholds are surpassed, is increasingly used for disasters affected by climate change, such as drought, hurricane damage or flooding. In the energy sector, index-based insurance has also been developed to cover, for example, weather-related changes in energy supply (e.g. due to changes in wind flow, lack of solar irradiation or variation in water levels) or demand (e.g. due to mild winters or cool summers). Overall, however, natural disaster insurance in the private sector remains limited. In Europe, 65% of the losses caused by extreme weather and climate-related events are not insured; in some parts of the European Union, the share is as high as 95%.

To promote private risk insurance, governments can require certain activities to be covered by insurance protection. In France, natural disaster coverage is compulsory in all property insurance policies. Where insurance markets are less developed, governments can also consider opening public risk pools (discussed below) to the private sector. The Caribbean Catastrophe Risk Insurance Facility has been offering insurance coverage to electricity utilities for damage to transmission and distribution systems due to storms since 2020. The facility was set up due to the difficulties faced by many utilities in purchasing traditional indemnity insurance because of limited availability and uneconomical pricing.

Even if private insurance covers the damage to physical assets and lost revenue after a disaster, the damage and cost to society and the national economy can hardly be compensated by private insurance. For example, the costs of a power blackout for a society are much higher than the immediate revenue losses to the power producers or network operators responsible. Some countries have adopted **national disaster risk financing strategies** to strengthen financial resilience in such instances. Often, this takes the form of a national **contingency fund**, which sets aside public funds for early response and recovery. **Regional public insurance pools** have been set up in developing and emerging economies, where market-based insurance coverage and fiscal response mechanisms are often less developed. These pools, often supported by international development assistance, have built joint reserve funds that retain some of the risk through joint reserves and capital first while transferring excess risk to the international reinsurance markets on competitive terms.[30] Four sovereign catastrophe risk pools are up and running, protecting about 40 low- and middle-income countries.[31] More recently, Germany announced the intention to create a "global shield" against climate risks to help the most vulnerable developing countries strengthen insurance, risk pooling and social protection schemes.

Energy authorities need to ensure effective emergency preparedness, responsiveness and recovery

Energy authorities have always played an important role in ensuring a secure, stable and affordable energy supply. Most countries have in place an emergency preparedness and response framework to help the energy sector better absorb, accommodate and recover from energy supply shocks. Emergency preparedness for climate risks implies a robust early warning system but also includes establishing provisions (and potentially requirements) for key actors to develop preparedness and response systems for extreme weather and climate emergencies, as well as creating a clear legal and institutional structure to enforce such provisions. Japan, for example, strengthened its disaster preparedness legislation, requiring electricity businesses to collaborate in disaster responses, after it was hit by a series of typhoons and earthquakes that caused long and large-scale power blackouts in 2019 and 2020.

[30] Transferring excess risk to the international reinsurance market means that a private reinsurer indemnifies (or compensates) the pool for losses that exceed a specified limit.
[31] The Caribbean Catastrophe Risk Insurance Facility (the biggest to date), the Pacific Catastrophe Risk Insurance Company, the African Risk Capacity, and the Southeast Asia Disaster Risk Insurance Facility.

Once a disaster occurs, energy authorities need to co-ordinate recovery efforts among various actors to minimise the magnitude of interruptions and restore normal operation as quickly as possible. Often, this will require co-ordination across multiple sectors, such as information and communications and transport. There may also be a need to reallocate resources, including human resources. For instance, a shortage of skilled labour in distribution companies was considered one of the reasons behind the prolonged outages after the heavy rainfall and flash flooding in Sydney, Australia, in February 2020. Reallocating resources from other parts of a region or country and using new technologies, such as pre-inspection by drones, could be part of the response. Executing regular response exercises can help identify potential resource gaps and increase stakeholders' capacity to act quickly and adequately in case of climate disasters.

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Chapter 6. Cost-benefit analysis of climate resilience for energy security

Investment in climate change adaptation and resilience in the energy sector likely remains far below what is required, and the lack of information to make investment decisions is considered a major hurdle. A cost-benefit analysis (CBA) for energy-sector climate resilience could facilitate investment decisions; however, it would need to be somewhat adjusted, considering the characteristics of climate resilience investment. First, it would need to have a longer time horizon than traditionally used, given that the benefits of climate resilience become tangible after a comparatively long period. Second, it needs to consider various climate scenarios in addition to traditional sensitivity analyses. Third, a CBA for climate resilience should be inclusive, because a narrowly designed CBA focusing only on direct return on investment might fail to capture the indirect socio-economic impacts of climate resilience that usually spread across the energy value chain.

Many governments, institutions and organisations are working on designing CBA methodologies specifically adapted to investments in energy-sector climate resilience. The United Kingdom released a Green Book on how to appraise the societal costs and benefits of policies, programmes and projects, accounting for climate change effects. The European Network for Transmission System Operators Electricity (ENTSO-E) adopted guidelines for the power-sector climate impact CBA. The guidelines cover not only the direct socio-economic impact of climate change on a single energy infrastructure project but also evaluate its influence on the energy system itself, taking into account the structural changes that would occur. In the United States, guidelines for the energy sector were developed to provide standardised measures for each step of a CBA (e.g. how to determine a discount rate and how to calculate benefits and costs).

Studies conducted by international and research organisations have also used CBA to demonstrate the benefits of investments in climate resilience. For instance, the World Bank's Lifelines report found that investing in more resilient power infrastructure is clearly a cost-effective choice in low- and medium-income countries; the incremental cost of increasing the resilience of exposed assets in the power sector would be less than USD 30 billion per year, a 3% cost increase on average across the spending range. At a country level, the Canadian Climate Institute conducted a bottom-up analysis with simulations of the macroeconomic impacts of climate-driven damages to seven sectors (including energy infrastructure) from 2015 to 2095. The study shows that proactive adaptation and mitigation actions will reduce the total real GDP losses by 75% and that every dollar spent on adaptation measures today will bring direct benefits of five dollars and economy-wide benefits of ten dollars. The study also shows that, even in the short term, investments in climate resilience bring overall economic benefits and that the benefits increase substantially over the century. Moreover, the Global Centre on Adaptation showed that investing USD 1.8 trillion between 2020 and 2030 in adaptation could generate USD 7.1 trillion in total net benefits.

This chapter presents cases of a CBA for measures that build resilience against flooding in the power generation, transmission and distribution sub-sectors in Africa and Asia. As shared in previous chapters, heavy precipitation and floods are becoming more frequent and intense in these two regions, and the increase is particularly notable in a high-emissions scenario. This chapter focuses on the distinct impacts of these rising flood risks and assesses the impact of specific resilience measures. The analysis compares the costs and benefits of building resilience in the power sector in three climate scenarios with assumptions of different states of the world and mitigation efforts by the end of the century. It aims to provide insights into these costs and benefits, as well as into conducting CBA for climate resilience, adding to the growing analyses on the topic to guide those considering investments in climate resilience.

Structure of the cost-benefit analysis

In examining measures to build climate resilience, the **benefits** included in this analysis correspond to the avoided socio-economic impacts of climate-related outages: a combination of the avoided economic impacts and avoided reduction in social welfare. The **costs** represent the investment needs for climate resilience enhancements to adapt power systems to an expected increase in climate hazards over the century.

To calculate the benefits, this analysis focuses on two major components: the avoided economic impacts of climate-driven power outages and the avoided reduction in social welfare, particularly in terms of health care. Although this approach has limitations since it does not fully capture other social aspects, such as environment, gender, youth and indigenous communities, it could provide insights into how climate resilience in the energy system could contribute to enhancing social welfare. The avoided impacts are calculated as the difference between a business-as-usual (BAU) case and a case with climate resilience investments that could prevent additional outages due to increasing climate impacts.

To calculate the avoided economic impacts of weather-driven power outages, this analysis used the following formula:

Avoided economic impacts of climate-driven power outages

$$= \text{Probability (P)} * \text{energy not served (ENS)} * \text{value of lost load (VoLL)}$$

P represents the probability of a disruption occurring, and ENS represents the amount of electricity that is not served due to climate-driven power outages. The probability of a climate-driven power outage occurring is computed through two components: an econometric modellisation using historical data capturing each region's peculiarities, and a calculation of expected increase of climate-driven outages, which depends on the selected climate scenario and region (from a 4% to 23% rise). The VoLL represents the value of lost load, i.e. the value that a final consumer would have been willing to pay for service continuity. The VoLL reflects all of the economic losses faced by final consumers, such as production curtailments, associated foregone revenues and damages, as well as personal disutility based on the relative dependence of affected users of electricity. The VoLL may differ, depending on the consumers, time, location and other conditions (see Annexes C and E).

However, the VoLL will not capture the full costs of social welfare reduction. For instance, the negative impact on public health due to climate-related energy outages could be missing. This can include potential accidental and non-accidental deaths, mainly related to the inability to use medical equipment (e.g. ventilators and oxygen conservers) due to power outages, difficulties in contacting emergency services or a lack of electricity for cooling. For instance, studies on the health effects of the 2003 New York City blackout found that power outages during hot weather increase mortality and hospitalisation significantly, compared with heat alone.

To calculate the benefits of avoided reduction in social welfare, this chapter focuses on the decrease in negative impacts on public health and their associated costs due to climate resilience measures. The benefits are calculated based on the avoided social costs of fatalities, which are monetised using the Value of Statistical Life (VSL) approach, an index that estimates the value of mortality risk reduction that would prevent one statistical death. This means an evaluation of the additional cost that individuals would be willing to bear for improvements in safety, i.e. reducing fatality risk (see Annex D). Similar to VoLL, this index differs according to the socio-economic and regional context. The total social cost of fatalities is computed by multiplying the number of observed fatalities (F) due to climate-driven power supply interruptions by the VSL (USD) specific to the region in which the impact is perceived.

Avoided social costs of fatalities attributed to climate-driven power outages:

$$= \text{F} * \text{VSL}$$

Mainly due to data limitation, other social benefits of climate-resilient energy systems are not fully considered in this chapter, although VoLL covers some parts of them. Thus, the total benefits calculated in this chapter could be lower than the actual benefits and may represent floor values.

To calculate the costs of resilience measures, three components are used: the additional capital expenditures (CAPEX) for existing and future power plants, the additional operational expenditures (OPEX) for existing and future power plants and the additional climate resilience investments for new power transmission and distribution networks against floods. Examples of resilience measures include, among others, infrastructure improvements, such as flood walls, stiff braced structures or riprap for solar farms. The average normalised costs of improving resilience for the power sector for the CAPEX and OPEX of power plants, and the additional investments for electricity networks, are calculated based on the existing literature (see Annex B).

Once benefits and costs are computed, two numbers are calculated: the net present value (NPV, i.e. the difference between the present value of the benefit and that of the cost) and the benefit-cost ratio (BCR, i.e. the ratio between the present value of the benefit to the cost). These can be used to assess the viability of investments in climate resilience; a viable investment is expected to show a positive NPV and a BCR value greater than 1.

In order to convert future costs and benefits to present value in the NPV and BCR calculation, the monetised costs and benefits are first discounted at a chosen discount rate. This analysis uses an average social discount rate[32] of 2.27%, based on the OECD Cost-Benefit Analysis and the Environment report. Such discounting implies that additional investments and avoided costs in the near future will have a larger impact on the NPV, while those made around 2050 would have a lesser impact. They are then evaluated over time against the BAU scenario (i.e. the baseline condition in which no action would be carried out).

$$\text{Net present value} = \sum_{t=1}^{n} \frac{1}{(1+\delta)^t} * \ (\text{benefits} \ \ \text{costs})_t$$

$$= \sum \mathit{Present\ value\ of\ the\ benefits} \ \sum \mathit{Present\ value\ of\ the\ costs}$$

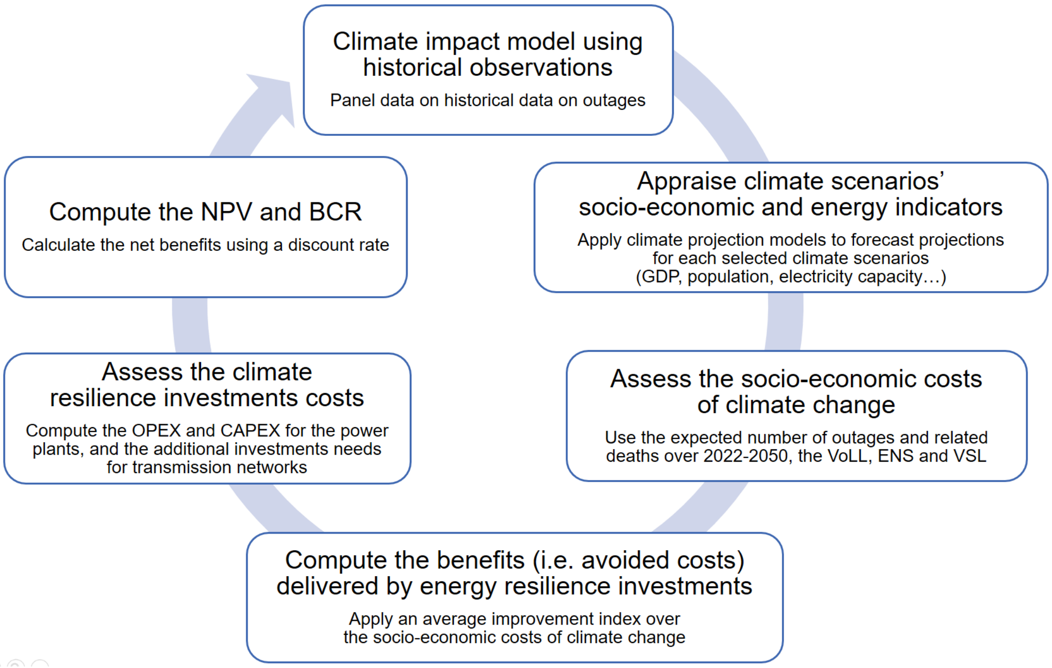
Where δ stands for the social discount rate.

$$\text{Benefit cost ratio} = \frac{\sum \mathit{Present\ value\ of\ the\ benefits}}{\sum \mathit{Present\ value\ of\ the\ costs}}$$

[32] "The social discount rate measures the rate of change over time of the shadow price of the numeraire. A positive discount rate means the shadow price is declining with the time horizon", OECD (2018).

To summarise, the CBA in this chapter follows the five steps depicted in the figure below.

Cost-benefit analysis structure



Note: The figure displays the main steps of this chapter's CBAs. It does not infer a standardised way to lead a CBA on the power sector.

The process is repeated over different potential climate scenarios. The climate and socio-economic development are evaluated over 2022-2050 according to three scenarios derived from the Intergovernmental Panel on Climate Change (IPCC) pathways: Shared Socioeconomic Pathway (SSP)1-1.9, SSP1-2.6 and SSP5-8.5. Each scenario represents a specific development trajectory encompassing population, economic growth, education, urbanisation, GHG concentrations and rate of technological development (see Annex A). Regarding expected outages estimates over the time frame, results are estimated through econometric modellisations for both regions and depend on the climate scenarios i.e. the more intense, the higher the expected increase of extreme events (see Annex C).

Given the high level of uncertainty intrinsic to climate scenarios and the resulting CBA, a sensitivity analysis is used to test the robustness of the results and to investigate the most relevant parameters that could affect the final output. Two main socio-economic factors have been considered as input variables for the sensitivity analysis:

- the VoLL, for which a range of values for each of the macro-regions was retrieved from the available literature (available in Annex E);
- the discount rate, for which a range of values were applied, based on the existing economic literature on social discount rates.

Case studies: Floods in Africa and Asia

Floods are one of the most rapidly growing concerns resulting from increasing GHG emissions. The intensity and frequency of heavy precipitation and floods will increase with every additional degree of global warming. A wetter climate with more frequent and intense heavy precipitation and floods could become a major risk to the power sector by interrupting power generation and damaging power networks. In particular, thermal power plants, hydropower plants and grids are projected to face high risks of flooding (see Chapter 3).

Africa and Asia are among the regions that are already facing more frequent and intense heavy precipitation and floods, and the trend is likely to continue in most parts of these regions in the 21st century. The severe floods in Pakistan in 2022, which damaged 22 power plants and prompted outages and load shedding of up to 15-16 hours, are likely to become more frequent. Moreover, in many developing and emerging countries in Africa and Asia, electricity generation assets and grids are vulnerable to climate hazards due to insufficient connections, limited backup options and poor maintenance. Therefore, when extreme weather events like flooding hit power systems, disruptions could last longer and occur over wider locations. This chapter focuses on comparing the costs and benefits of building resilience in the power sector against floods, with a geographical focus on Africa and Asia, with the aim of providing information on the viability of investments in climate resilience.

These impacts could be mitigated with additional investments in resilience measures. Our analysis examines flood walls, sheet piling, increased spillway capacity for hydropower plants, advanced riprap at solar farms, improved dike construction and extreme event flood design (e.g. reinforcing materials, such as steel, concrete; and reinforcing structures, such as composite tower, poles and elevated components). Additional climate resilience investments for the CAPEX and OPEX for existing and future power plants, and additional investments for new transmissions and distribution networks, are expressed in our analysis by an average improvement cost index over the entire energy expenditures and investments. The annual costs of resilience measures would eventually range from USD 5.9-6.7 billion in Africa to USD 21.0-25.6 billion in Asia, depending on the climate scenario and the embedded assumptions on pathways and additional power generation capacity requirement (see Annex B).

Average additional annual investments requirements for the power sector by region by scenario, 2022-2050

	Africa (USD billion)	Asia (USD billion)
SSP1-1.9	5.9	23.7
SSP1-2.6	6.1	25.6
SSP5-8.5	6.7	21.0

Economic benefits from these additional climate resilience investments are calculated using an average damage probability reduction factor to assess the impact of the specific climate resilience measures mentioned above. These benefits would actually rise over time, as all climate scenarios and assumptions considered in this analysis include more frequent climate hazards by 2050 (4.3-23.0% and 3.7-19.6% in Asia and Africa, respectively). In terms of the benefits of resilience measures against floods, the average annual avoided economic impacts of climate-driven power outages are estimated to be USD 99-259 million in Asia and USD 88-147 million in Africa, depending on the climate scenario. This eventually results in overall benefits over 2022-2050 of USD 1.4-3.5 trillion in Asia and 1.2-2.0 trillion in Africa.

Average annual avoided economic impacts of climate-driven power outages by region by scenario, 2022-2050

Region	Climate scenario*	Averaged annual avoided economic impacts (USD billion)	Averaged annual electricity consumption (TWh)	ENS** (TW)	VoLL*** (USD/MWh)
Africa	SSP1-1.9	87.8	2 417	5.1	1 725.3
	SSP1-2.6	114.3	3 234	7.1	1 725.3
	SSP5-8.5	146.7	5 046	11.5	1 725.3
Asia	SSP1-1.9	99.3	9 873	31.5	696.6
	SSP1-2.6	144.7	14 240	46.3	696.6
	SSP5-8.5	258.9	20 654	70.2	696.6

* Climate scenarios explore possible evolutions of human societies and their implications for the climate. They cover a wide range of future pathways, including a scenario in which GHG emissions decline drastically to net zero by 2050 and are negative in the second half of the century (SSP1-1.9) and another in which emissions continue to rise sharply, doubling from today's levels by 2050 and more than tripling by 2100 (SSP5-8.5). See Chapter 2 and Annex A for more details on scenarios.

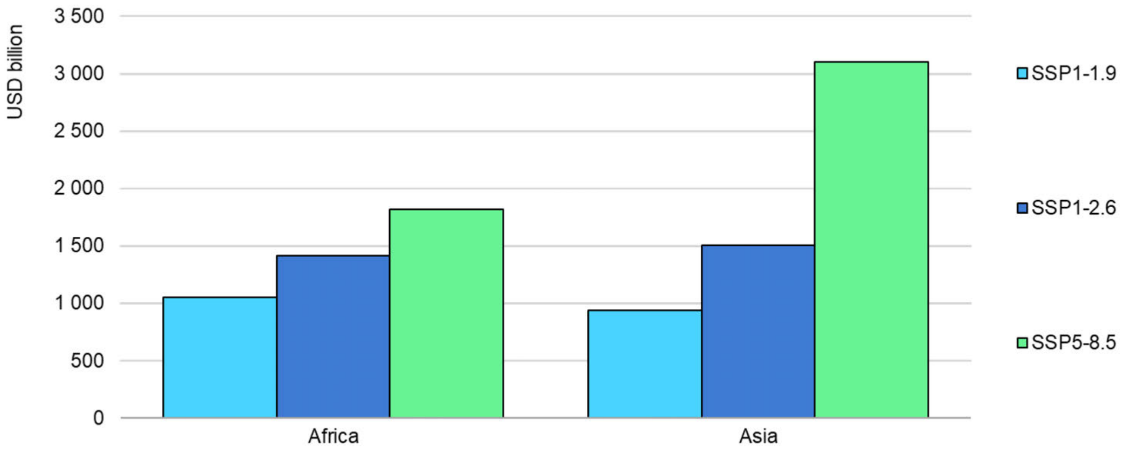
** ENS represents the amount of electricity that is not served due to weather-driven power outages, without additional climate resilience measures in place.

*** Present value. The VoLL reflects all of the economic losses faced by the final consumers. It is context dependent and therefore differs across countries, users and time. The values are obtained from the literature through surveys of the value that a final consumer would have been willing to pay for service continuity.

The avoided social costs of fatalities attributed to climate-driven power outages are estimated to be USD 1.3 billion in Asia and USD 1.6 billion in Africa over 2022-50. Similar to the avoided economic impacts of climate-driven power outages, the avoided social costs of fatalities are higher in a high-emissions scenario than in a low-emissions scenario.

The analysis shows that investments in resilience measures against floods will bring more benefits than costs in both regions in all climate scenarios. The NPV for Africa is expected to exceed USD 1 trillion over 2022-2050 for the SSP1-1.9, while the NPV for Asia reaches USD 0.9 trillion. If rapid and steep GHG emissions reductions are not achieved globally, investments in resilience are projected to become even more beneficial. Under the SSP5-8.5, the NPV for Africa is USD 1.8 trillion, and the one for Asia is USD 3.1 trillion.

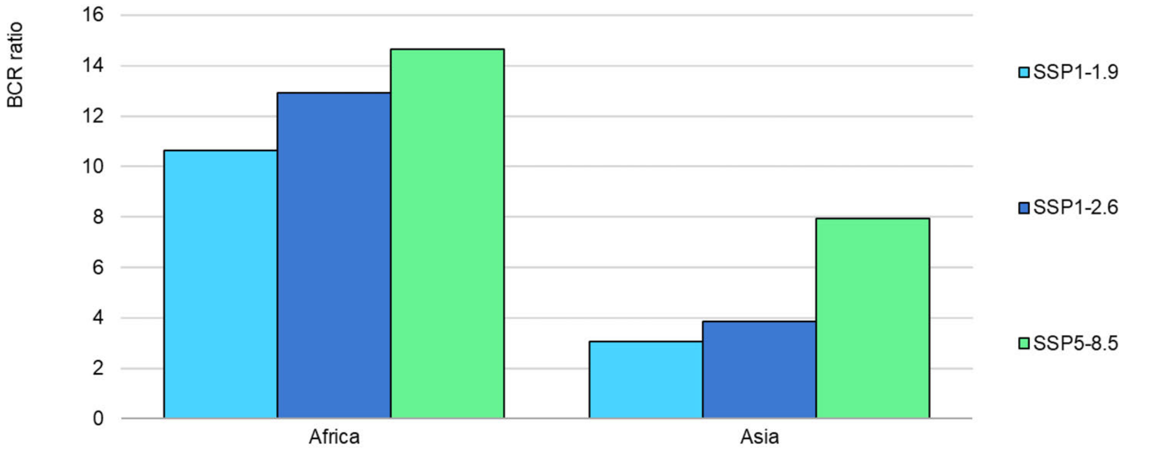
NPV of power-sector flood resilience measures for Africa and Asia, 2022-2050



Source: FEEM, 2022.

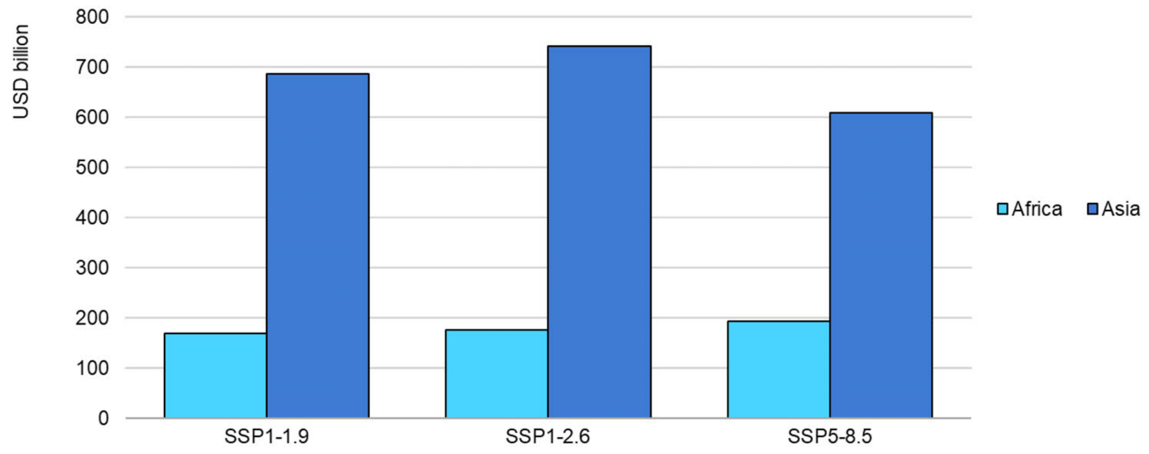
Such investments in resilience are significantly beneficial in both Africa and Asia. The BCR analysis shows that benefits could be three to eight times higher than the costs in Asia, depending on the scenario. In Africa, the BCR is even higher, ranging between 11 and 15, depending on the scenario, meaning that the socio-economic benefits resulting from these investments are up to 11-15 times higher than the costs. Africa's BCR turns out to be higher than Asia's because Africa is expected to have four to five times lower additional costs than Asia in all scenarios (see Figure below). This is mainly due to lower expected additional installed capacity (1.2-1.4 TW in Africa by 2050 and 3.2-4.0 TW in Asia over 2022-2050), thus a lower CAPEX, OPEX and additional needs for power system resilience overall.

Power-sector BCR for Africa and Asia, 2022-2050



Source: FEEM, 2022.

Cumulated costs per region per scenario, 2022-2050

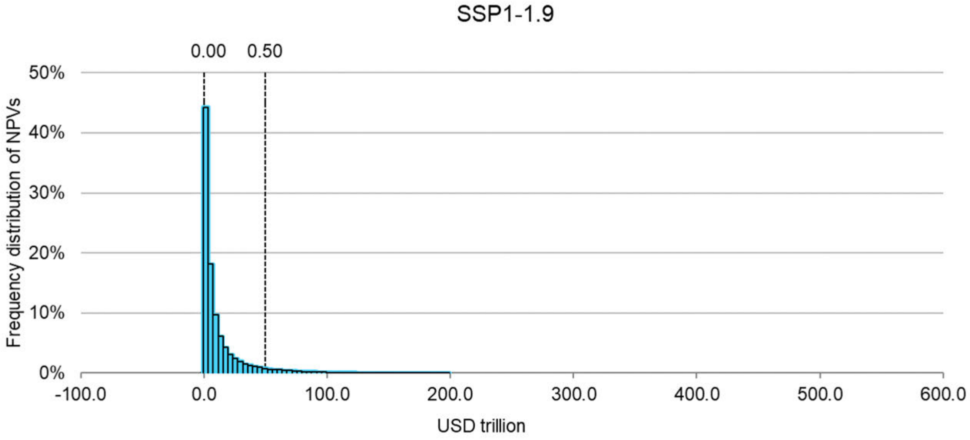


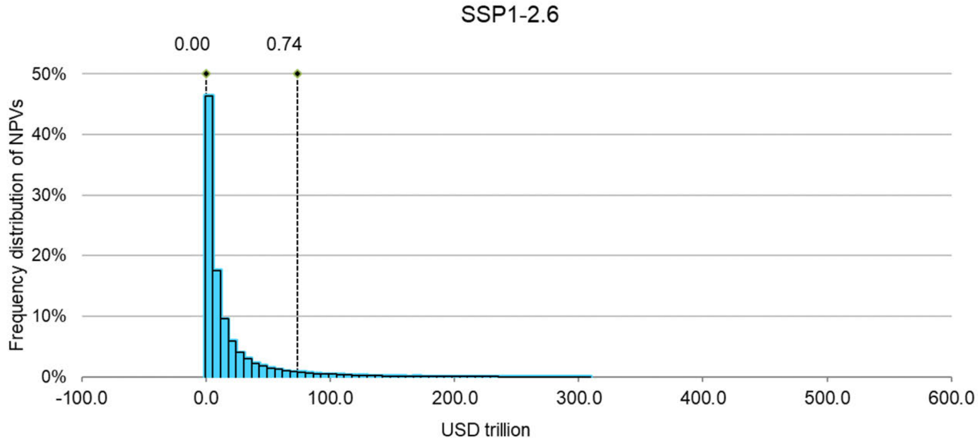
Source: FEEM, 2022.

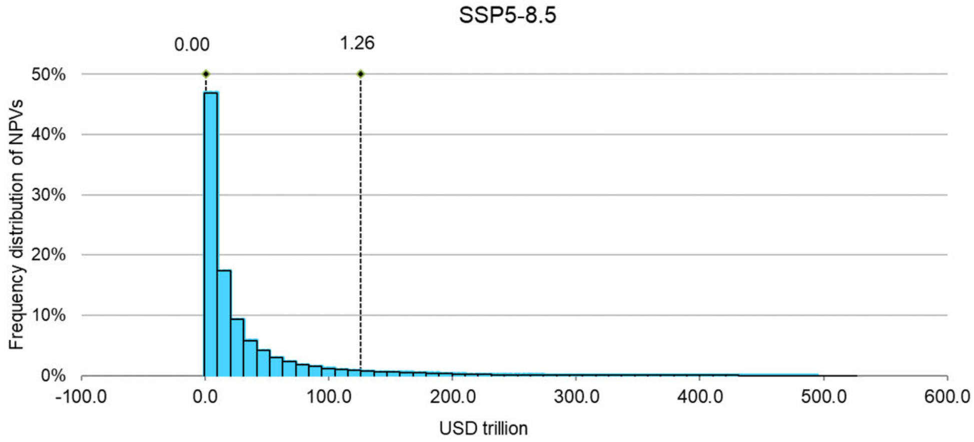
Given the uncertainties intrinsic to CBAs and embedded in climate models, a sensitivity analysis has been carried out to test the robustness of the results and to investigate the most relevant parameters that could affect the final output. The analysis considers Monte Carlo simulations in order to iterate the possible NPV resulting from different VoLL and discount rates.

The sensitivity analysis reaffirms that investment in resilience measures bring more benefits than costs in most cases. In Asia, the result shows an overall confidence for a positive NPV, indicating that climate resilience investments are economically viable over 2022-2050. In Africa, the result also presents an overall confidence for a positive NPV, although there is a slight probability of a negative NPV.

Sensitivity analysis over the Asia region



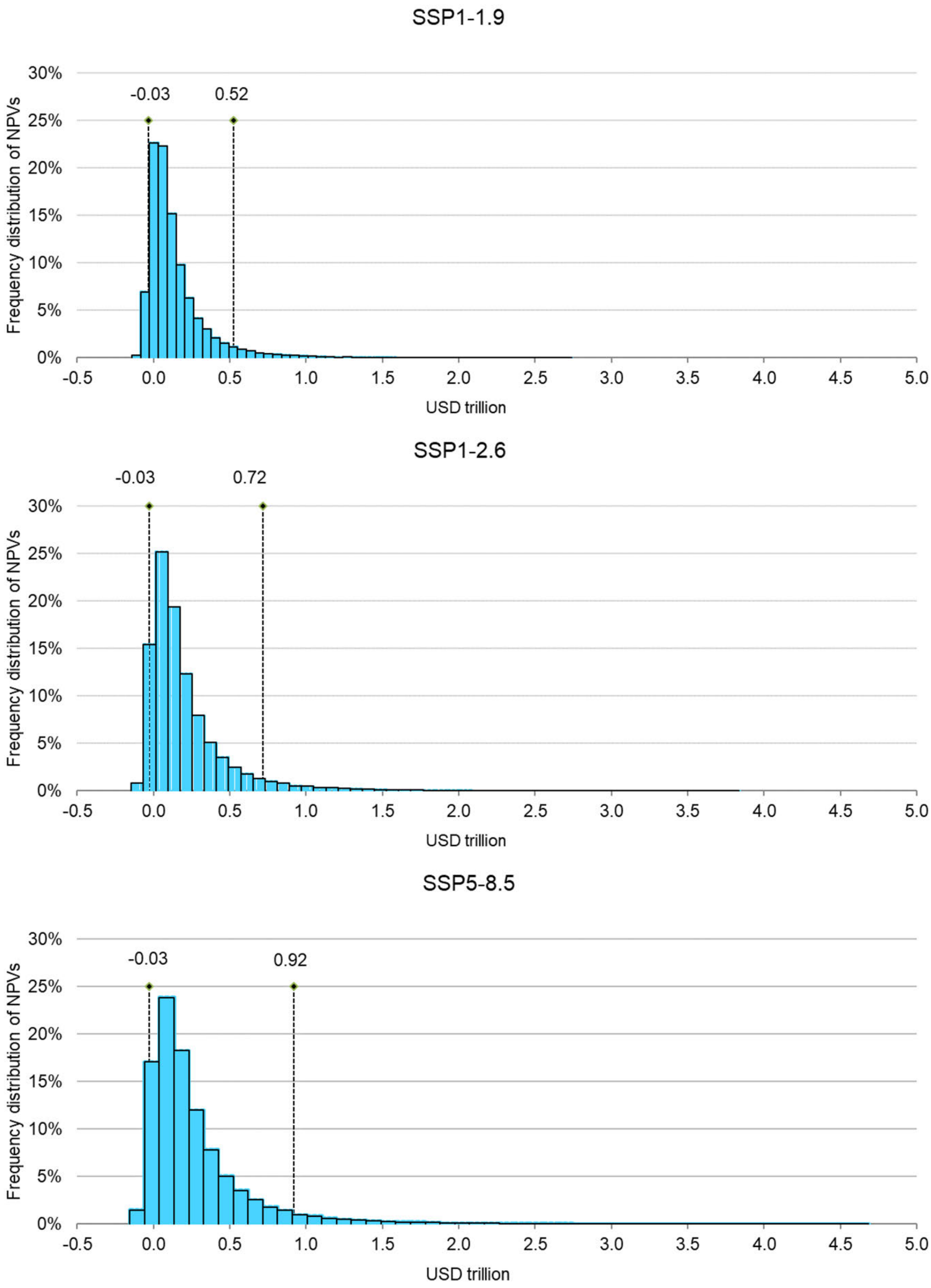




Notes: The numbers above each chart are the NPV thresholds at the border of the lower 5% and upper 5% distribution, while the full range is presented at the bottom of the x-axis. The NPV must be positive for climate resilience investments to be considered economically viable.

Source: FEEM, 2022.

Sensitivity analysis over the Africa region



Notes: The numbers above each chart are the NPV thresholds at the border of the lower 5% and upper 5% distribution, while the full range is presented at the bottom of the x-axis. The NPV must be positive for climate resilience investments to be considered economically viable.

Source: FEEM, 2022.

Overall, the case studies show that investments in resilience measures in the power sector can bring substantial benefits in Africa and Asia. Although this analysis is limited to a specific climate hazard (floods), one part of energy systems (the power sector, including generation, transmission and distribution) and two regions (Africa and Asia), it brings insights for broader investments in energy-sector climate resilience. The analysis shows that the benefits of enhancing resilience considerably are likely to outweigh the costs over the long term in most cases. Despite the embedded uncertainty resulting from the assumptions and data limitations of this exercise, the result of case studies shows the viability of investment in energy-sector climate resilience.

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Annexes on cost-benefit analysis

Annex A. Scope and climate models

The table below shows the countries included in this analysis. Due to data availability, some countries were excluded from the panel data analysis. The modelling shows results at a regional level using IPCC climate models.

Countries considered in the panel data analysis

Region	Countries considered
Asia	Afghanistan, Bangladesh, Bhutan, People's Republic of China (hereafter "China"), Hong Kong (China), India, Iran, Japan, Korea, Maldives, Mongolia, Nepal, Pakistan, Sri Lanka
Africa	Angola, Burundi, Cameroon, Central African Republic, Chad, Comoros, Congo, Democratic Republic of the Congo, Djibouti, Eritrea, Ethiopia, Gabon, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Sao Tome and Principe, Seychelles, Somalia, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

The analysis is conducted considering regional differences among two macro-regions, Africa and Asia, covering 2022-2050.

The climate and socio-economic development of the areas used in this analysis are based on three climate scenarios derived from the integration between two SSPs and three complementary Representative Concentration Pathways (RCPs), as adopted by the IPCC. These define specific global development trajectories (population, economic growth, education, urbanisation and rate of technological development), as well as GHG concentrations leading to specific radiative forcing characteristics.

The narrative pathways were then translated into quantified estimates using Integrated Assessment Models (IAM) outputs. The main scenario characteristics, whose quantitative output was the basis of this analysis, are detailed in the table below.

Summary of the characteristics of global climate and socio-economic scenarios applied

SSP	RCP	IAM markers	Global mean surface temperature	Socio-economic development	Energy details
SSP1	1.9	IMAGE	Below 1.5°C	Sustainable and inclusive development; low population growth	High environmental awareness; low service demand, which is characterised by low energy intensity; weak social acceptance of conventional technologies; rapid conversion towards non-bio renewables
	2.6		Below 2°C		
SSP5	8.5	REMIND-MAgPIE	Above 4°C	Strong preference for rapid conventional development; low population growth; high GDP development and convergence	Low environmental awareness; medium service demand, which is characterised by medium to high energy intensity; high reliance and high social acceptance of fossil fuel energy

Source: FEEM, 2022.

The embedded assumptions of the climate models (SSP1-1.9, SSP1-2.6 and SSP5-8.5) provide the analytical basis of the population, GDP and energy projections used in the CBA. The intensity and the typology of climate impacts addressed are differentiated with respect to the scenario and the region. Due to the limitation of data access, other models for flood or hydrology are not attached to this analysis.

Annex B. Assumptions and methodology for costs

To calculate the investment needs, the additional capital expenditure (CAPEX) and the operational expenditure (OPEX) for power plants, and the costs for building the resilience of transmission and distribution networks, are considered. Generation CAPEX are expressed in average overnight cost per kW of installed capacity, as reported by the IEA (see Table below) and are multiplied by an average improvement cost index for energy resilience infrastructure of 0.094.

Average generation CAPEX per kW of installed capacity

Region	Asia	Europe	North America	Oceania	South America	Africa
USD/kW	1 915	2 125	2 883	2 847	1 452	1 452

Notes: Due to the limited availability in obtaining the African CAPEX value, the South American value has been applied as an approximation.
Sources: IEA (2020); FEEM, 2022.

Values are adjusted considering the average GDP for each region and climate scenario, according to the SSP database. The OPEX for the power sector is then computed, corresponding to 1.3% of the CAPEX value. The additional investments for making the transmission and distribution networks more resilient are computed considering the delta of power utility customers for each climate scenario, based on the SSP database, multiplied by the number of kilometres of network built per customer (see Table below) and the cost of building an additional kilometre of electricity line, adjusted for inflation.

Average value of transmission line built per customer

Region	Africa	Asia
Km/customer	0.02	0.03

Source: Ortiz (2020).

Annex C. Assumptions and methodology for benefits (avoided economic impacts of climate-driven power outages)

The analysis is built as follows: first, the perimeter of the analysis in terms of geographical extension and sectors affected is defined; then, the physical impacts to be addressed are evaluated as a function of the climate scenarios (i.e. of the specific weather events under study) and the socio-economic scenarios (i.e. population, climate policies, energy policies, etc.). An economic value is then attributed to the quantified physical impacts to obtain the total potential costs of climate change if no measures for climate resilience are taken.

These costs are then compared to the costs of the same impacts whenever climate resilience investments are made, obtaining the total avoided costs, i.e. the benefits derived from climate resilience investments.

Data specifications

The actual damages of fast-onset weather extremes are evaluated based on historical data, with the final aim of identifying the factors affecting the number of outages through econometric analysis.

To build the dataset, we draw data from two main sources: the EM-DAT International Disaster Database and the World Bank. For our regression purposes, four sub-regions are considered: eastern Asia, southern Asia, eastern Africa and sub-Saharan Africa. This choice is made to capture regions' peculiarities and to identify the most relevant extreme weather events in the area. For each sub-region, the number of floods, droughts, storms, wildfires and days of extreme temperature are considered, to identify the most impactful hazard to Asia and Africa and observe their causality with climate-related power outages. We gathered data throughout 2006-2021 and organised them into a panel. To preserve the behaviour of units over time, data have been analysed using panel linear regression on RStudio, with a fixed effect model given by country and year covariates.

Econometric specifications

The table below shows significant regression coefficients. It is important to note that all coefficients aim to draw a causal link between the number of climate hazards (storms, floods and droughts) and power outages that are statistically significant at a 0.01 level for each region of interest i.e. there is a 99% statistical confidence that the value is not null.

Regression coefficients (percentage points)

Region	Number of floods	Number of droughts	Number of storms	Number of days of extreme temperature	Number of wildfires
Eastern Asia	0.910***	2.042***	0.956***	1.179***	-
Southern Asia	1***	1.148 ***	1.018***	0.876***	0.986*
Eastern Africa	0.991***	0.933***	0.919***	-	-
Sub-Saharan Africa	0.709***	1.083***	1.025***	-	-

Notes: The number of * represents the significativity of the regression coefficients. If ***, the coefficient is statistically significant with a 99% confidence, i.e. there is a 1% probability that the coefficient is statistically null; ** displays a 95% confidence; and * a 90% confidence.

Source: FEEM, 2022.

In general, an almost perfect one-to-one relationship between extreme events and blackouts can be observed, except in the case of droughts in eastern Asia: if the number of droughts increases by 1, the number of outages is likely to increase by 2, i.e. this kind of extreme event is likely to double blackout numbers.

Our analysis partially controls for the omitted variable problem thanks to the inclusion of two fixed effects in the model: country-fixed effect (controlling for variables that are constant across entities but vary over the region) and time-fixed effect (controlling for variables that are constant across entities but vary over time). In fact, existing literature affirms that there is heterogeneity across countries and time in the case of climate change impact studies. Our model allows studying the change in the response variable considering time and country variation and computing different intercepts, one for each entity.

The main drawback of our model is the high-level regional dimension of the dataset. Higher accuracy and reliability might be reached through additional and detailed data about power outages.

The number of power outages reflects the average number of power outages that a firm experiences in a typical month. Because of the lack of outages data at a residential or an overall level, the model uses power outages in the industrial sector as an approximation of all power outages at a country level. Nevertheless, since the number of people affected by each interruption is provided for by the dataset, the results obtained can be extended to a social perspective. Even if some limitations are present, the model remains valid to understand the basic effects of extreme events on power outages.

Expected increase in outages

Combined econometric results and IPCC climate models are eventually used to estimate the expected number of flood-related outages over 2022-2050. Details on the assumptions for each scenario are summarised in the table below.

Expected increase of outages by 2050 for each climate scenario, compared to 2022

Region	SSP1-1.9	SSP1-2.6	SSP5-8.5
Asia	4.3%	7.7%	23.0%
Africa	3.7%	6.6%	19.6%

Source: FEEM, 2022.

Power outage monetisation

This expected number of outages, computed by region and year as a function of climate change impacts, is multiplied by the System Average Interruption Duration Index (SAIDI) and the expected electricity consumption to get the ENS. Although the SAIDI value could be notably lower than the average duration of interruption caused by extreme weather events (e.g. floods), the SAIDI value is used due to the limited availability of data on the duration of weather-driven disruptions. The ENS is then multiplied by the VoLL to compute the socio-economic cost of the power outage. The SAIDI, which measures the average duration of interruption in the power supply indicated in minutes, is used as an average value with the application of an annual reduction factor of 3%.

Average SAIDI per macro-region

Region	Asia	Africa
SAIDI (minutes)	31.82	27.25

Source: World Bank (2019).

The projection of the electricity consumption measured in MW/minute was computed for each of the three climate scenarios, based on the SSP database. Last, the VoLL was obtained through academic literature review, aiming to consider at least one representative country per macro-region. To verify the results, a sensitivity analysis of the values, as shown in the table below, was performed. Figures have been adjusted each year considering the average GDP per climate scenario and inflation rate of the region. It is worth noting that the VoLL is context dependent and therefore differs across countries, users and time.

Because of limited data availability for specific countries, a benefit transfer approach is applied. It consists in assigning a value already obtained in a specific context to a new case study, performing adjustments required to account for socio-economic differences between the two contexts.

VoLL in USD/MWh, 2022

Region	Asia	Africa
Source	Mukhi et al. (2017)	Oseni and Pollitt (2013)
USD/MWh	740.36	1 860.56

Source: FEEM, 2022.

Annex D. Assumptions and methodology for benefits (avoided social impacts of climate-driven power outages)

The VSL is the commonly used indicator in a CBA to monetise avoided fatalities, in our case due to more investments preventing power outages. The VSL is an estimate of the economic value society places on reducing the average number of statistical fatalities by one and is of common use in the analysis of projects that affect mortality risks. It should be understood as an evaluation of the additional cost individuals would be willing to bear for improvements in safety, i.e. reducing their fatality risk. The standard valuation of this indicator is computed via surveys estimating individuals' willingness to pay in specific situations (e.g. the investment project making roads safer). Due to the subjectivity of this valuation, the VSL can vary widely across regions and sectors.

Total fatalities due to outages take into account the VSL properly adjusted for GDP and inflation multiplied by the expected number of fatalities per minute due to power outage, adjusting the values for population growth rate on the basis of SSP data.

Daily deaths per minute

Region	Asia	Africa
Number/min	25.16	32.23

Source: FEEM, 2022.

Annex E. Sensitivity analysis specifications

Given the high level of assumptions, a sensitivity analysis is needed to test the robustness of the results and to investigate the most relevant parameters that could affect the final output.

The table below lists the VoLLs that have been used to capture the variability of these parameters according to the region and assessment from the literature. The discount rate used to perform sensitivity ranges from 1.4% to 6.0%.

VoLL applied in the sensitivity analysis

Asia				
Country	**Average VoLL**	**Consumer Price Index**	**Final VoLL 2022 (USD/MWh)**	**Source**
South Korea	4 746.73	1.22%	5 230.28	Kim, Jo and Koo (2014)
Israel	0.40	1.99%	537.56	Oseni and Pollitt (2013)
Pakistan	1.02	1.99%	1 370.77	
Japan	50.72	1.99%	68 162.13	
Israel	9.21	1.99%	12 377.23	
Russian Federation	1.21	2.46%	1 742.21	Asian Development Bank (2020)
Japan	4.82	2.46%	6 940.05	
Mongolia	2.21	2.46%	3 182.05	
China	2.05	2.46%	2 951.68	
Nepal	9.35	2.96%	14 482.37	Alberini, Steinbuks and Timilsina (2020)

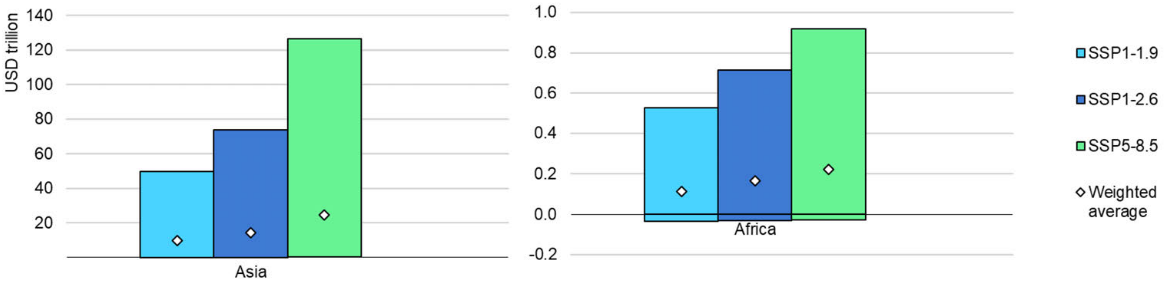
Africa				
Country	**Average VoLL**	**Consumer Price Index**	**Final VoLL 2022 (USD/MWh)**	**Source**
Algeria	0.05	1.99%	67.19	Oseni and Pollitt (2013)
Egypt	0.04	1.99%	53.76	
Gambia	0.25	1.99%	335.97	
Ghana	0.24	1.99%	322.53	
Kenya	0.30	1.99%	403.17	
Mali	0.30	1.99%	403.17	
Morocco	0.24	1.99%	322.53	
Mozambique	0.34	1.99%	456.92	
Nigeria	0.25	1.99%	335.97	
Senegal	0.33	1.99%	443.48	
South Africa	0.18	1.99%	241.90	
Zambia	0.40	1.99%	537.56	

Sensitivity analyses were run for both regions and for all climate scenarios using Monte Carlo simulations to compute NPVs, depending on the other VoLLs and discount rates summarised in the table above. The distribution of the values of these NPVs are then displayed per climate scenario in the figures below.

For the Asia region, the sensitivity analyses show an overall confidence for a positive NPV whichever the climate scenario. Some 90% of the computed NPVs ranges between USD 7.4 billion and USD 49.9 trillion under the SSP1-1.9; between USD 85.0 billion and USD 73.8 trillion under the SSP1-2.6; and between USD 0.5 and USD 125.7 trillion under the SSP5-8.5.

For the Africa region, results slightly contrast: although the sensitivity analyses also show an overall confidence for a positive NPV, in more detail, there is a slight probability for the NPV to be negative. Some 90% of the computed NPVs actually ranges between USD -33.7 and USD 524.9 billion under the SSP1-1.9; between USD -29.8 and USD 715.3 billion under the SSP1-2.6; and between USD -26.9 and USD 920.2 billion under the SSP5-8.5. These results emphasise the variability of parameters and the high level of assumptions needed to run an in-depth CBA over the power sector. Overall, these negative NPV values can be attributed to a low VoLL that could be found in the literature for some specific countries (as seen in the Table above).

Sensitivity analyses results, 2022-2050



Notes: Some 90% of the NPV computed through each run of Monte Carlo simulations is included in the ranges above. For example, for the Asia region, 90% of the computed NPV ranges between USD 7 billion and USD 50 trillion under the SSP1-1.9; between USD 85 billion and USD 74 trillion under the SSP1-2.6; and between USD 0.5 and USD 126 trillion under the SSP5-8.5. Some 5% of the rest of the computed NPV is equally distributed below and above these thresholds.

Source: FEEM, 2022.

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