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Adaptation challenges and opportunities for the European energy system

Building a climate-resilient low-carbon energy system

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European Environment Agency

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Executive summary

Key messages

- The European energy system increasingly needs to adapt and become more climate resilient in the context of continuing climate change, modern societies' increasing dependence on a reliable energy supply and an increasing share of climate-sensitive renewable energy sources.
- Climate change and extreme weather events increasingly impact all components of the energy system. They affect the availability of primary energy sources (in particular renewable energy sources), the transformation, transmission, distribution and storage of energy, and energy demand. It is crucial that these impacts are considered in the clean energy transition.
- Key EU climate and energy policies and strategies promote the mainstreaming of climate change adaptation into energy policies. The development of the Energy Union — which aims to make energy more secure, affordable and sustainable — provides important opportunities for further integrating climate change adaptation in European and national energy planning.
- Most European countries have addressed the energy sector in national climate change impact, vulnerability and risk assessments, national adaptation strategies and/or action plans. Further action is needed to consider the impacts of climate change in the development of national climate and energy plans and long-term strategies under the Energy Union, and in the update of national adaptation strategies and action plans. Governments can further facilitate adaptation through the regulation of energy markets and other policy interventions, as well as through 'soft' measures that focus on information provision and exchange.
- Many energy utilities, network providers and other stakeholders in the energy sector are already addressing adaptation needs. All market actors in the energy sector, including business associations, should consider strengthening climate resilience as an integral part of their business.

Chapter 1 – Purpose and scope of this report

This EEA report identifies the challenges of, and opportunities for, climate change adaptation and climate resilience in the context of a decarbonising energy system in Europe. It intends to support the efforts of the European Commission, national governments and non-state actors involved in planning, reporting, reviewing, implementing and revising relevant policies. The report provides information on the climate impacts and adaptation challenges associated with different energy technologies, gives an overview of the state of adaptation related to the energy system in Europe and presents good practice adaptation examples. The report concludes by identifying opportunities for further action by key adaptation actors and enablers in Europe.

Chapter 2 – The European energy system now and in the future

The key driver for changes in the global and European energy system is the need for a clean energy transition that drastically reduces greenhouse gas emissions. The EU has adopted several quantitative targets related to the energy system in its 2030 climate and energy framework. The European Commission has proposed a strategy for a climate-neutral economy by 2050, including several long-term decarbonisation scenarios up to 2050.

The share of renewable energy sources in primary energy supply has more than tripled and their share in electricity generation has more than doubled since 1990. All global and European decarbonisation scenarios agree that these shares will continue to increase rapidly. Furthermore, the role of electricity as an energy carrier is increasing in all decarbonisation scenarios. These developments require the strengthening of electricity grids, enhancing the level of interconnection and increasing electricity storage.

The energy sector is a large user of water and land, both of which can be impacted by climate change. **The clean energy transition in Europe presents both opportunities and challenges for climate change adaptation.** On the one hand, replacing coal-fired power plants by photovoltaics and wind power radically reduces greenhouse gas emissions and water consumption, thus contributing to mitigation as well as adaptation in water-scarce regions. On the other hand, biofuels, and carbon capture and storage need more water and/or arable land than many conventional energy technologies.

Chapter 3 – Climate change impacts on the European energy system

Anthropogenic climate change has already significantly affected the European climate, and further change is inevitable. The most important changes for the energy system include increases in mean and extreme air and water temperatures, and changes in annual and seasonal water availability, extreme climate-related events, and coastal and marine hazards.

Warming temperatures decrease energy demand for heating, but increase energy demand for cooling. They can also affect electricity generation and transmission, as well as fossil fuel extraction and transport. Water availability is generally projected to increase in northern Europe and decrease in southern Europe, but with marked seasonal differences. These changes can affect cooling water availability for thermal power plants, hydropower and bioenergy potential, river-borne fuel transport and energy demand for water provision. Climate change can also affect the potential for wind and solar power, but available projections are associated with significant uncertainty.

Many extreme weather events, including heat waves, heavy precipitation events, storms and extreme sea levels are projected to increase in frequency and/or magnitude as a result of climate change. Without appropriate adaptation measures, direct economic losses to the European energy system could amount to billions of euros per year by the end of the century, with much larger indirect costs. Climatic risks to the energy system can be further aggravated by the combination of different climatic hazards or by extreme events that affect several components of the energy system simultaneously.

Climate change impacts and related adaptation needs vary significantly across energy system components and European regions (see Map ES.1). Some impacts can be economically beneficial, such as reduced energy demand for heating. However, many impacts are adverse for the energy sector and/or society as a whole, such as reduced cooling water availability for thermal power plants in many regions and increasing risks for energy infrastructure from extreme weather events and sea level rise. **Northern Europe experiences both beneficial and adverse impacts on its energy system, whereas southern European regions face overwhelmingly adverse impacts.**

Chapter 4 – Building a climate-resilient energy system

Building climate resilience comprises addressing the impacts of weather hazards on existing energy infrastructure and its operation, as well as considering the impacts of long-term climate change on newly planned infrastructure. Given the diversity of adaptation challenges across regions and energy system components, careful assessment of the relevant risks and options, as well as coordinated action by a wide range of public and private stakeholders, is necessary to ensure the clean energy transition is also climate-resilient.

There are both synergies and trade-offs between climate change adaptation, mitigation and wider sustainability objectives. The important connections between energy policy and other policy areas call for a comprehensive policy approach that considers multiple societal and policy objectives jointly.

Businesses are key actors in strengthening the climate resilience of the energy system. However, market actors in the energy system face a number of barriers that may impede the implementation of effective adaptation actions. Well-designed European and national policies can play a key role in overcoming these barriers.

Key EU climate and energy policies and strategies promote the mainstreaming of climate change adaptation into energy policies. These include the EU adaptation strategy, the Regulation on the governance of the Energy Union and climate action, the Commission proposal for a long-term strategy 'A Clean Planet for All' for a climate-neutral economy by 2050 and the Regulation on risk-preparedness in the electricity sector. The EU also supports building climate resilience in the energy system by requiring climate-proofing of major new energy infrastructure,

Map ES.1 **Selected climate change impacts on the energy system across Europe**

British Isles

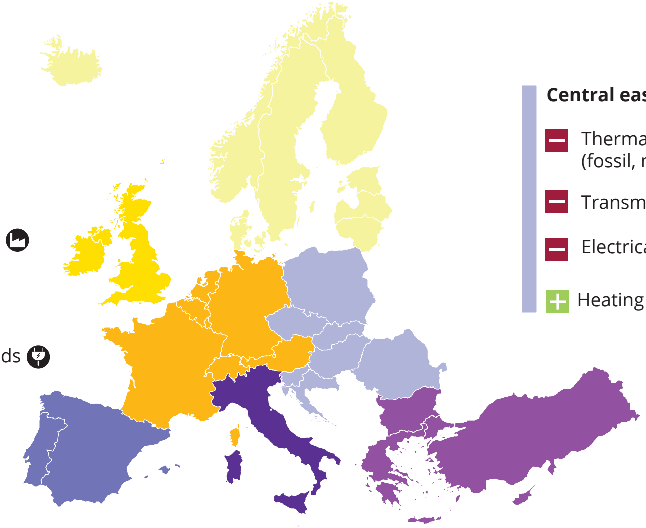
- − Offshore energy production infrastructure (wind, oil, gas) 🏭
- − Coastal energy infrastructure (power plants and refineries) 🔌 🏭
- − Transmission and distribution grids 🔌
- − Electrical susbtations 🔌
- + Heating and cooling demand 🔌

Northern Europe

- + Hydropower ✺
- + Offshore wind power ✺
- + Biomass energy ✺
- ▣ Oil and gas extraction 🏭
- − Offshore energy production infrastructure (wind, oil, gas) ✺ 🏭
- − Coastal energy infrastructure (power plants and refineries) 🔌 🏭
- ▣ − Oil and gas transport 🏭
- − Transmission and distribution grids 🔌
- + Heating and cooling demand 🔌

Central western Europe

- − Offshore energy production infrastructure (wind, oil, gas) ✺ 🏭
- − Thermal power plants (fossil, nuclear and biomass) 🏭 🔌 ✺
- − Transmission and distribution grids 🔌
- − Electrical susbtations 🔌
- + Heating and cooling demand 🔌



Central eastern Europe

- − Thermal power plants (fossil, nuclear and biomass) 🏭 🔌 ✺
- − Transmission and distribution grids 🔌
- − Electrical susbtations 🔌
- + Heating and cooling demand 🔌

Iberian Peninsula, Apennine Peninsula and South-eastern Europe

- − Hydropower ✺
- − Concentrated solar power ✺
- − Biomass energy ✺
- − Thermal power plants (fossil, nuclear and biomass) 🏭 🔌 ✺
- − Transmission and distribution grids 🔌
- − Pumped hydro storage 🔌
- − Peak electricity demand 🔌
- − Energy demand for desalination 🔌

+ Predominantly beneficial impacts

− Predominantly adverse impacts

▣ Impacts not classifiable as beneficial or adverse due to complex economic and environmental effects

✺ Renewable energy sources

🏭 Fossil energy sources

🔌 Other energy sources and carriers (nuclear, electricity, heating and cooling)

funding relevant research and innovation projects, and developing climate services for the energy sector as part of the Copernicus services.

Almost all European countries have concluded a national climate change impact, vulnerability or risk assessment that covers the energy sector. Most countries also include energy as a relevant sector in their national adaptation strategies and/or plans. However, **available government documents provide only limited evidence for the implementation of adaptation actions in the energy sector**. Individual countries are facilitating adaptation in the energy system by providing guidelines for vulnerability assessment and resilience planning, through support for the development of weather and climate services, and through reporting obligations for infrastructure providers.

Many energy utilities and network providers are already adapting their activities to the observed and projected impacts of climate change.

Some of these activities have been triggered or facilitated by government policies and regulation. Various international governmental and sectoral organisations are supporting these actions by providing guidance, developing information sharing platforms, facilitating communities of practice and acting as catalysts for the development of relevant services.

Chapter 5 – Conclusions and outlook

Many asset owners and managers, as well as policy-makers at the EU, national and regional levels, and other stakeholders are already addressing adaptation needs in the energy system. However, some stakeholders are only beginning to acknowledge the relevance of climate change impacts on their activities, or they are experiencing barriers to taking action. **More can and should be done to ensure that the energy system in Europe is climate resilient now and in the future**.

The development of the Energy Union and the EU long-term strategy on climate action provide important opportunities for mainstreaming climate change adaptation in the planning and implementation of a decarbonised energy system in Europe through more coordinated actions, reporting and mutual learning among all involved actors.

National (and sub-national) governments play an important role in facilitating climate change adaptation in the energy system. National climate change impact, vulnerability and risk (CCIV) assessments of the energy system, with a strong forward-looking component, are essential for making the clean energy transition climate-resilient. Countries that have not addressed energy as a priority sector or policy area in their national CCIV assessment are encouraged to do so in the future. Furthermore, **all countries should consider the impacts of climate change on the current and future energy system in the development of their national climate and energy plans and long-term strategies under the Energy Union**, and in the development and update of their national adaptation strategies and action plans.

Countries can facilitate building climate resilience in the energy system through regulation of energy markets and 'soft' measures that focus on information provision and exchange. Such activities can be supported by reporting requirements on climate change risks and adaptation actions for critical infrastructure providers, in particular, where such information is not available from other sources.

All market actors in the energy sector should consider strengthening climate resilience as an integral part of their business. Business associations in the energy sector can support their members in doing so.

1 Introduction

Key messages

- The overarching objective of this EEA report is to identify the challenges of, and opportunities for, climate change adaptation and strengthening climate resilience in the European energy system.
- All parts of the energy system, from energy production and transformation through to transmission, distribution, storage and demand, can be impacted by weather extremes and long-term climate change. It is crucial that these impacts are considered in planning the clean energy transition.
- The European Union is building the Energy Union, which aims to make energy more secure, affordable and sustainable. The goal of climate change adaptation in the energy system is to ensure that the goals of the Energy Union can also be achieved in a changing climate.

1.1 Purpose and content of this report

1.1.1 Purpose and target audience

The overarching objective of this report is to identify challenges and opportunities for climate change adaptation and strengthening climate resilience in the context of a decarbonising energy system in Europe. The focus is on how policies at the European, national and — in some cases — subnational levels can support the transformation to a climate-resilient energy system now and in the future.

Since 2004, the EEA has regularly published reports on climate change impacts and vulnerability in Europe, addressing a broad audience (see EEA, 2017b for the latest report). This report is the second to address adaptation needs and opportunities for specific systems and sectors in Europe that are sensitive to climate change and play a key role in the decarbonisation of the economy. The first report addressed the transport system (EEA, 2014). A third report, to be published soon after this report, will address agriculture. Climate change impacts and adaptation will also be addressed in the forthcoming SOER report — The European environment — state and outlook 2020.

This report primarily targets European, national and subnational policymakers in the field of climate change and energy. Additional target audiences are relevant international organisations, regulators and standardisation organisations, business organisations and individual businesses from the energy sector (including producers, transmission system operators and traders). The information may also be relevant for investors, climate service providers, consultancies and researchers addressing the energy system, as well as civil society and the general public.

1.1.2 Multiple challenges facing the European energy system

The European energy system faces several important challenges. First, the energy sector is currently the largest emitter of greenhouse gases in Europe owing to its large reliance on fossil fuels. Therefore, the decarbonisation of the energy sector will play a central role in achieving a climate-neutral economy in Europe. The **clean energy transition** requires wide-ranging changes in how energy is produced, transported and used (EC, 2018j, 2018q). Many, but not all, decarbonisation measures can also reduce other environmental impacts, such as air pollution. Second, Europe's energy supply is highly dependent on imports from outside Europe, including from politically unstable regions. As a result, **geopolitical tensions** can threaten the security of the energy supply in Europe (EC, 2014). Third, **modern societies and economies are increasingly dependent on a reliable energy supply**, in particular with regard to electric power. Most economic and financial activities, transport, water supply and the provision of health services and disaster relief support rely on information and communication technologies powered by electricity. Therefore, even short interruptions in electricity supply can lead to high economic and social costs.

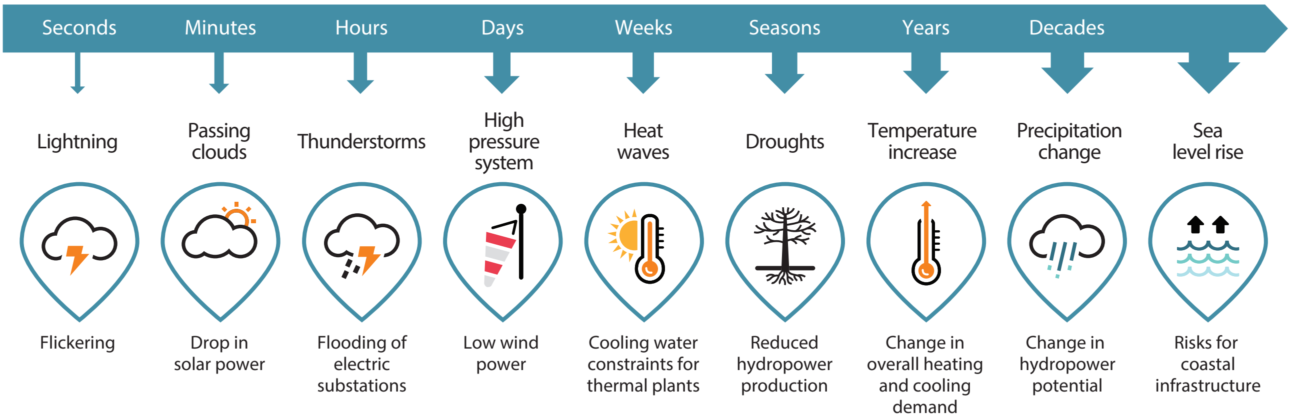
In addition to these challenges, **all parts of the energy system, from energy production (1) and transformation to its transmission, distribution, storage and demand, can be affected by weather and climate, including long-term climate change** (see Figure 1.1 for selected examples). Gradual changes in the climate can affect the availability of important resources such as water for hydropower and for cooling thermal power plants. They can also affect energy demand, in particular in relation to heating, cooling and water supply. Weather extremes such as floods and storms can lead to blackouts due to flooding electric substations or windfall on power lines. Sea level rise can threaten coastal and offshore energy infrastructure.

The clean energy transition increases the need for the energy sector to consider climate variability and climate change due to the increasing share of climate-sensitive renewable energy sources (RES) and the stronger role of electricity as an energy carrier. Considering the important role of secure and affordable energy for European economies and societies, and the massive investments planned in the European energy system, **it is crucial that the impacts of climate variability and change on the current and future energy system are considered in the clean energy transition.**

1.1.3 Policy context

The European Union (EU) is building the Energy Union, which aims to make energy more secure, affordable and sustainable. Several important pieces of legislation have already been adopted and others are currently in the legislative process. Of particular relevance is the Regulation on the governance of the Energy Union and climate action (EU, 2018d), which strengthens the coordination role of European institutions and creates new planning and reporting requirements for national governments. The underlying planning and reporting processes provide an opportunity to address climate change mitigation and adaptation in the energy sector in an integrated manner. The proposal for a revised regulation on risk-preparedness in the electricity sector (EU, 2018c) can play an important role in preventing, preparing for and managing electricity crises resulting from extreme weather events, even though climate change is not explicitly mentioned. Furthermore, the long-term strategy 'A Clean Planet for All' puts forward a vision for steering the EU towards a CO_2 emissions-free future in 2050 (EC, 2018j), in line with the objectives of the Paris Agreement (UNFCCC, 2015). In response to the challenge from climate change impacts, **the EU adopted an EU adaptation strategy in 2013, which was evaluated in 2018** (EC, 2013b, 2018v). For further information on relevant EU policies, see Section 4.2.

Figure 1.1 Weather and climate impact the energy system on all time scales



Source: EEA, adapted from Troccoli (2018).

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(1) From a physical perspective, energy can be neither produced nor consumed; it can only be transformed from one form (e.g. solar radiation) to another (e.g. electric power). Nevertheless, international energy statistics use the term 'energy production' and 'energy consumption' to describe usable energy entering or leaving the economy. In the interest of coherence with these established terminologies, this report uses the terms 'energy production' and 'consumption' instead of the more exact terms 'energy supply' and 'energy use'.

1.1.4 Outline

This report is structured as follows.

Chapter 1 describes the context, purpose and scope of this report. It also defines key terms used throughout the report.

Chapter 2 provides an overview of the current status of the energy system in Europe, including its interaction with other systems and sectors. It also discusses how global and European policies and other drivers are expected to affect the energy system in the future, and includes relevant scenarios.

Chapter 3 gives an overview of past and projected climate change across European regions, and describes the main impacts of these changes on the European energy system. The chapter concludes with a summary of the main adaptation needs and opportunities for each energy system component and related adaptation options.

Chapter 4 discusses the adaptation challenge of the European energy system from an actor's perspective. It starts with an overview of the main types of adaptation action and the key actors involved, and then discusses the role of governments in facilitating adaptation in the energy system. The remainder of the chapter is devoted to a review of the main adaptation policies and actions by the EU, national governments, international organisations and selected other actors. The chapter concludes by presenting adaptation case studies from various infrastructure providers from the European energy sector.

Chapter 5 presents the main policy-relevant conclusions of this report.

1.2 Scope of the report

1.2.1 Thematic scope

This report looks at the energy system and focuses on climate change adaptation and strengthening climate resilience (see Section 1.3 for a definition of these terms). Considering that climate change mitigation and adaptation in the energy system need to be addressed jointly, this report also addresses the synergies (i.e. where mitigation activities also have adaptation benefits, or vice versa) and trade-offs (i.e. where an adaptation action increases the mitigation challenges, or vice versa) between these two policy objectives. However, the focus of this report is on the additional challenges created by a changing climate.

This report covers the whole energy system, from primary energy production to energy use, and includes all energy sources and carriers. The definition of the energy system applied here includes the 'traditional' energy sectors, such as oil and gas extraction, transport and distribution; electricity generation (from all sources), transformation, transmission, storage and distribution; and heating and cooling production and distribution. However, it also comprises activities and actors outside the 'traditional' energy sector that can play an increasing role in a decentralised energy system, such as biomass production and transport for energy production, and electricity production and storage by individuals. Particular attention is given to components and technologies that are highly sensitive to climate change and variability and/or that are expected to become more important in the context of the clean energy transition. As a result, there is a strong focus on low-carbon technologies and on the electricity system. Energy use for various purposes is considered only insofar as the demand is climate sensitive (in particular heating and cooling) and may require adaptation actions within the energy sector. The use of energy carriers for non-energy purposes is outside the scope of this report.

This report applies the following categorisation of the energy system into components (IEA, 2016b):

1. **Primary energy production:** the extraction or production of energy resources as inputs to energy transformation processes. It includes the extraction of the main fossil energy sources (coal, oil and natural gas) and of uranium. It also includes renewable energy sources such as hydropower, bioenergy, solar power and wind energy.

2. **Energy transformation:** the transformation of energy resources into secondary energy carriers. This includes electric power and heat generation technologies, including renewable (e.g. biomass-based) and fossil energy, and fuel refining.

3. **Transport, transmission, storage and distribution:** this component comprises power grids, gas and oil pipelines and their supporting infrastructure, such as storage facilities, substations and logistical assets. It further includes pumped hydropower storage, batteries and other storage technologies. It also includes transport of fuels and carbon capture and storage.

4. **Energy demand:** this covers the use of energy in buildings, households, industry, businesses and transport (i.e. the power, heating and cooling

demand of all consumers). The non-energy use of energy sources (e.g. oil use for plastic production) is outside the scope of this study.

An overview of key actors and enablers that play a role in climate change adaptation in the energy system is provided in Section 4.1.2.

The European Atomic Energy Community (also known as **Euratom**) is legally separate from the EU, and issues relating to nuclear safety are outside the mandate of the EEA. Adaptation challenges that nuclear power plants have in common with other thermal power plants (e.g. cooling water availability) are addressed in this report. In contrast, potential adaptation challenges relating to the safety of operating nuclear power plants and to nuclear waste disposal are not addressed in this report.

1.2.2 Geographical scope

The geographical scope of this report comprises the 33 member countries of the EEA. They comprise the 28 EU Member States (as of May 2019) as well as Iceland, Liechtenstein, Norway, Switzerland and Turkey. The EEA's Western Balkan cooperating countries are not explicitly addressed in this report. However, they are strongly interconnected with EU power and gas networks, and many of the findings in this report also apply to them. Upstream activities (e.g. oil and gas extraction) outside Europe are beyond the scope of this report, but the import of energy carriers is briefly discussed, as it may generate adaptation needs for infrastructure located within Europe (e.g. pipelines or sea terminals).

This report presents information for the largest group of countries for which this information is readily available. As a result, there is some variation in the geographic coverage between and within chapters. For example, Section 2.1 relies strongly on energy statistics from Eurostat, which are most readily available for EU Member States. Similarly, Section 4.2 focuses on EU policies, which are not directly applicable to the non-EU member countries of the EEA. In contrast, Section 2.2 relies largely on the EU long-term strategy 'A Clean Planet for All', which covers several countries that are neither EU Member States nor EEA member countries.

There are considerable differences across Europe in climate change impacts as well as in the physical assets, ownership and management of energy infrastructure. These differences in adaptation needs and opportunities require adaptation policies, strategies and actions that are tailor-made for a specific country or region. To support regionally specific adaptation planning, Chapter 3 analyses climate change and its main impacts on the energy system in seven European regions. Considering the particular focus of this report on electricity supply and demand, the **regional country groupings** used in Chapter 3 are based on the regional wholesale electricity markets of the EU (including Switzerland) (EC, 2018u). The non-EU member countries of the EEA were added to those regions to which they are most closely connected. The island countries of Cyprus and Iceland, which are not connected to the European electricity grid, were added to the regions with the most similar climatic conditions. The resulting regionalisation is as follows:

1. Northern Europe: Denmark, Estonia, Finland, Iceland, Latvia, Lithuania, Norway, Sweden.

2. British Isles: United Kingdom, Ireland.

3. Central western Europe: Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Netherlands, Switzerland.

4. Central eastern Europe: Croatia, Czechia, Hungary, Poland, Romania, Slovakia, Slovenia.

5. Iberian Peninsula: Spain, Portugal.

6. Apennine Peninsula: Italy, Malta.

7. South-eastern Europe: Bulgaria, Cyprus, Greece, Turkey.

Chapter 4 gives a brief overview of the national-level adaptation policies relating to energy; it also presents various examples of policies and actions at national and subnational level. However, a systematic assessment of adaptation needs and actions in the energy system for all countries is beyond the scope of this report.

1.3 What do adaptation and climate resilience mean?

Different communities of policymakers, practitioners and scholars use somewhat different terms for managing the impacts of climate variability and change. The United Nations Framework Convention on Climate Change (UNFCCC) (UN, 1992), as well as EU climate change policy, distinguishes two fundamental policy options to limit the risks of climate change for societies: mitigation and adaptation. Energy policies and practice commonly use the term climate resilience

Box 1.1 Definitions of key terms used in this report

Mitigation (of climate change): 'a human intervention to reduce emissions or enhance the sinks of greenhouse gases.'

Adaptation (to climate change): 'In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities.'

Maladaptation: 'actions that may lead to increased risk of adverse climate-related outcomes, including via increased GHG emissions, increased vulnerability to climate change, or diminished welfare, now or in the future. Maladaptation is usually an unintended consequence.'

Hazard: 'the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources.'

Vulnerability: 'the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.'

Risk: 'the potential for adverse consequences where something of value is at stake and where the occurrence and degree of an outcome is uncertain.'

Resilience: 'the capacity of social, economic, and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation.'

Source: IPCC (2018).

Climate-resilient infrastructure 'is designed, built and operated in a way that anticipates, prepares for, and adapts to changing climate conditions. It can also withstand, respond to, and recover rapidly from disruptions caused by these climate conditions.'

Source: OECD (2018).

for reducing the negative impacts of climate-related hazards, which is closely related to adaptation. Box 1.1 provides definitions of these and other relevant terms.

Although the original concepts and definitions of the terms 'adaptation' and '(climate) resilience' differ, they are now often used in connection with each other (e.g. EC, 2018q). **In this report, the expressions 'adaptation to (climate change)' and strengthening 'climate resilience' are used broadly, and largely interchangeably, for all efforts that address climate-related challenges to the energy system, relating to both short-term climate hazards and long-term climate change.** It should be stressed that adaptation and resilience in the energy system not only refer to the design and building of infrastructure but also include the management and operation of energy infrastructure and the underlying policies and institutions. Further information on different types of adaptation is provided in Section 4.1.

The goals of climate change adaptation and resilience building in the energy system are to ensure a secure and affordable energy supply now and in the future while supporting the clean energy transition and other societal objectives (EC, 2018c). More specifically, adaptation aims to ensure minimal disruption to energy production, transformation, transport and consumption in the long term, while also protecting the value of public and private investments in the sector and the interests of society and the economy overall (Boston, 2013). It can also address risks to public safety that could originate from energy infrastructure during extreme climate conditions, such as sparking wildfires (see Box 3.1). Failing to adapt energy systems to climate change could result in severe consequences such as blackouts, which have a significant impact on modern economies that are reliant on stable access to energy.

The energy system has strong links with other systems and sectors due to its use of water and land (see Section 2.1.5 for further information on the energy-water-food nexus). Therefore, a sustainable energy supply should minimise conflicts, and exploit synergies, with other relevant policy areas, such as water and flood management, biodiversity protection and agricultural policy. Adaptation actions with substantial negative impacts on other policy goals or societal objectives are often referred to as maladaptation, which should be avoided. Synergies and trade-offs between adaptation, mitigation and other policy objectives are discussed further in Section 4.1.4.

1.4 Development of this report

This report has been developed by a team of authors from the EEA, two of its European Topic Centres, and external consultants engaged under a framework contract with the EEA. The key methods used were literature review, and stakeholder and expert consultation.

Literature review has been central to all parts of the report. This report draws on numerous publications by international organisations, EU institutions, national governments, sector associations, academic research institutions and other relevant organisations.

Stakeholder and expert consultation has also been a key element in the development of this report. The EEA convened a stakeholder group for this report, which comprised representatives from international organisations, the European Commission, national governments, regulators, sector associations and infrastructure operators from the energy sector, and research projects. These stakeholders were first invited to comment on the annotated outline of the report and to suggest additional literature sources. In September 2018, the EEA organised a stakeholder workshop where the scope and content of this report was discussed further. Finally, the stakeholders were invited to provide comments on the draft report in parallel with the European Environment Information and Observation Network (Eionet) review.

Adaptation case studies in this report show examples of how energy producers and infrastructure providers throughout Europe have addressed climate-related challenges and opportunities in their planning and operation. Section 4.5 of this report includes five in-depth case studies that are based on literature review and interviews with relevant stakeholders. They have also been published on the European Climate Adaptation Platform (Climate-ADAPT) (2), a data and information-sharing platform co-managed by the Commission and the EEA. Shorter illustrative case studies, based on literature review only, are included as text boxes in the main text.

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(2) https://climate-adapt.eea.europa.eu

2 The European energy system now and in the future

Key messages

- The key driver for changes in the global and European energy system is the need for a clean energy transition that drastically reduces greenhouse gas emissions. The EU has adopted several quantitative targets related to the energy system in its 2030 climate and energy framework. The European Commission has proposed a long-term strategy that includes several long-term decarbonisation scenarios up to 2050.
- Energy supply in Europe is still dominated by fossil fuels, the majority of which are now imported. However, the share of renewable energy sources in primary energy supply has more than tripled and their share in electricity generation has more than doubled since 1990. All global and European decarbonisation scenarios agree that these shares will continue to increase rapidly.
- The energy sector is a large user of water and land. The interdependencies represented by the energy-water-land nexus are expected to intensify due to climate change impacts and an increasing share of renewable energy sources. Some low-carbon energy technologies have the potential to contribute positively to this nexus, whereas others may increase competition for scarce water and/or land resources.
- The interconnection between European electricity grids has increased in recent years. Electricity storage is becoming increasingly important for managing the growing share of intermittent renewable energy sources in electricity generation. The role of electricity as an energy carrier, and of electricity grids and storage, is further increasing in all decarbonisation scenarios.
- Final energy consumption in Europe has remained largely constant since 1990. The decarbonisation pathways in the EU long-term strategy place a strong focus on decreasing overall energy demand through increasing energy efficiency and, possibly, changes in consumer behaviour.

The energy sector is of high economic importance in Europe. According to provisional estimates, it comprises more than 110 000 enterprises, employs around 1.6 million people and has a turnover of around EUR 1.9 trillion along the supply chain in the EU (Eurostat, 2018c). However, the relevance of the energy sector for overall society is much greater than these numbers suggest. Energy enables a multitude of services, including heating and cooling, lighting, telecommunication, information technology and transport. Energy has therefore been characterised as the 'lifeblood' of modern societies.

This chapter outlines the current energy system in Europe, as well as scenarios for its future development, which are driven to a large degree by the need for a clean energy transition.

2.1 The European energy system

This section examines the key components of the European energy system. It provides a descriptive and quantitative characterisation of each component and the most relevant developments. It also reviews the interaction of the energy system with other sectors. This report applies the Eurostat terminology of energy aggregates (see Box 2.1), and this section relies largely on Eurostat energy balances data. Most of these data are also available for three of the five non-EU member countries of the EEA — Iceland, Norway and Turkey — but not for Switzerland and Liechtenstein. However, some statistics (in particular those relating to the import of energy carriers) are available only for the 28 EU Member States (EU-28), and data reporting from non-EU countries is sometimes delayed. For reasons of consistency and to avoid any confusion about which countries are covered in a particular figure or statement, all quantitative data in this section refer to the EU-28. Relevant information on particular circumstances in non-EU member countries of the EEA is provided in the text.

Box 2.1 Main energy aggregates according to Eurostat

Primary energy: the first energy form in the production process for which various energy uses are in reality practised. Eurostat's methodology is based on the physical energy content method. For directly combustible energy products (e.g. coal, crude oil, natural gas, biofuels, waste) it is their actual energy content measured by their net calorific value. For products that are not directly combustible, the application of this principle leads to the choice of heat as the primary energy form for nuclear, geothermal and solar thermal power and to the choice of electricity as the primary energy form for solar photovoltaic, wind, hydro, tide, wave and ocean power.

The choice of the physical energy content method for determining the primary energy equivalent of fuels can give a distorted picture of the relative importance of different energy carriers. For example, in a hypothetical scenario in which 50 % of electricity is produced from nuclear fuels and 50 % from wind energy, nuclear energy would be described as having a primary energy share of 75 % and wind as having only a 25 % share. Hence, the importance of most renewable energy sources in the overall energy system is under-represented by their primary energy equivalent.

Primary production: this refers to any kind of extraction or exploitation of energy products from natural sources. For fossil and other fuels, it refers to the extraction from the environment. It also includes electricity and heat according to the choice of the primary energy form (electricity generation using hydro, wind and solar photovoltaic power).

Final energy consumption: the total energy consumption in all end-use sectors (including industry, transport, services and others). By and large, it accounts for the amount of energy delivered to final consumers.

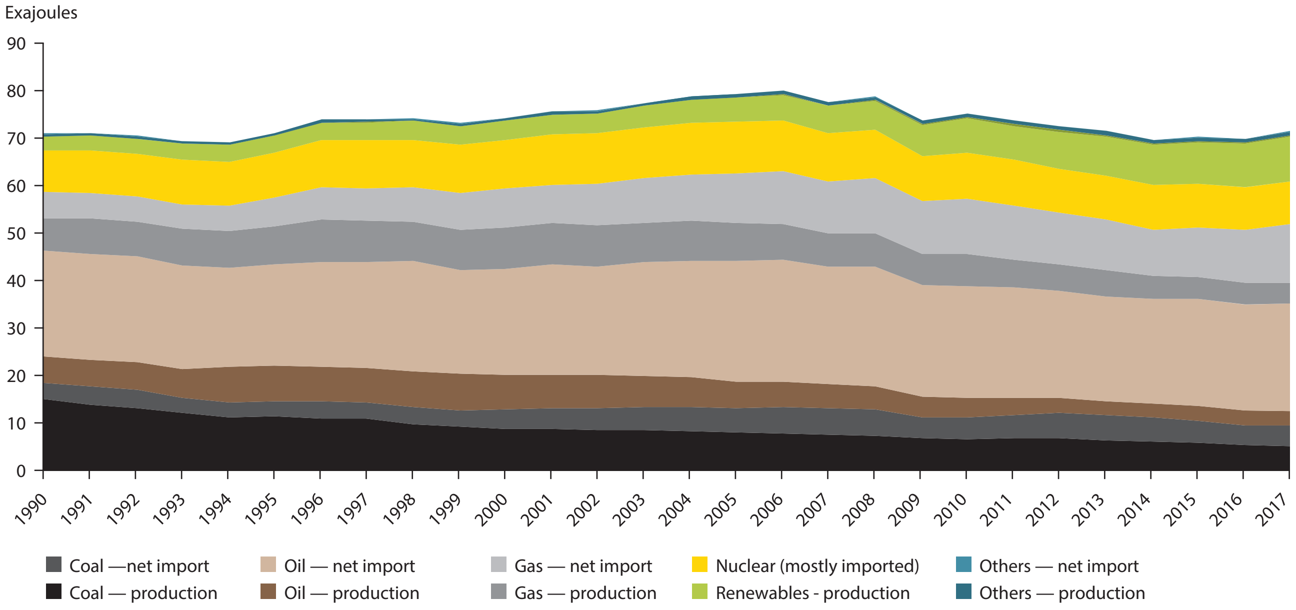
Source: Adapted from EU, 2008b; Eurostat, 2018e.

2.1.1 Primary energy supply

Figure 2.1 shows the development of the primary energy supply in Europe (EU-28) over time for different energy carriers, distinguished by domestic production and net imports. Eurostat data do not distinguish between domestic production and imports of nuclear fuel. According to data from the Euratom Supply Agency, the share of domestic uranium production in overall uranium supply has been consistently below 10 % since 1995 (ESA, 2019, Indicator 5).

Europe relies on a broad range of energy sources. **Fossil fuels still dominate the primary energy supply in Europe** (74 % in 2017). However, **the share of renewable energy sources (RES) in the primary**

Figure 2.1 Production and net imports of primary energy to the EU-28 by fuel type



Notes: Electricity imports are not shown in this figure because net extra-EU energy imports were negligible. Nuclear fuel is mostly imported.

Source: EEA, based on data from Eurostat (2019b).

energy supply of the EU-28 has grown significantly, from 4 % in 1990 to 14 % in 2017. Oil, used primarily as a transport fuel, and natural gas remain the most important energy sources in Europe, accounting for 36 % and 23 % of the total primary energy supply in 2017, whereas the share of coal declined from 26 % in 1990 to 13 % in 2017. The share of nuclear energy remained more or less constant at 12 %. The interpretation of these numbers should consider the limitations of the physical energy content method used to determine the primary energy content of different energy carriers (see Box 2.1). Further information on the increasing role of RES for electricity production is provided in the next section.

The domestic production of fossil fuels in Europe has decreased, from 39 % of the EU primary energy supply in 1990 to 18 % in 2017. Most of the decrease is due to declining coal production, but Poland and Germany, among other countries, still have significant coal production. Extraction from North Sea natural gas fields is carried out by the Netherlands, Norway (not included in Figure 2.1) and the United Kingdom. Norway and the United Kingdom are also significant oil producers in Europe.

Europe's energy supply is strongly dependent on imported fuels. The share of imported fuels in the primary energy supply of the EU-28 increased from 44 % in 1990 to 56 % in 2017, with most of the increase occurring before 2007. The large decline in the production of domestic fossil fuels was compensated in almost equal parts by increasing shares of imported fossil fuels (from 44 % to 55 %), mostly from increasing gas imports, and of domestic RES (from 4 % to 13 %). The share of imports would be lower if Norway were included, as it is an important producer of oil and gas and also an important source of imports into the EU. More than 80 % of the EU's natural gas imports originate from four countries (Russia, Norway, Algeria and Qatar). Oil and coal imports come from a more diverse range of countries (Eurostat, 2018c). In recent years, the EU has spent about EUR 1 billion every day on energy imports, with considerable fluctuations depending on the price of crude oil (Eurostat, 2019c). The annual spending on energy imports to the EU amounts to approximately 2 % of the total gross domestic product.

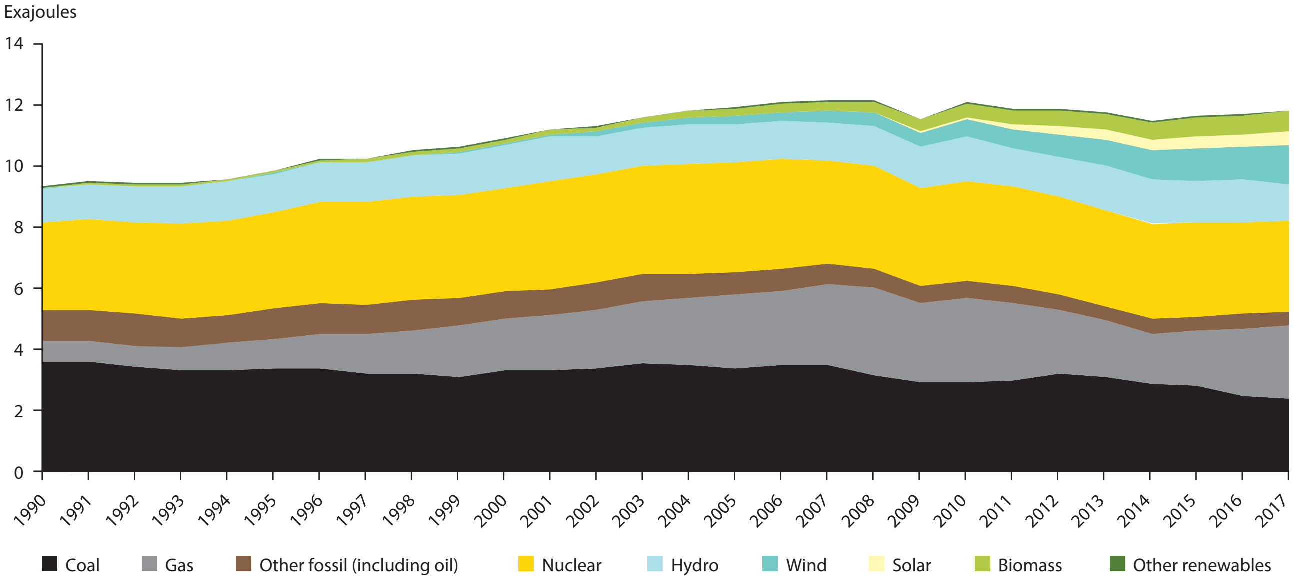
2.1.2 Energy transformation

Electricity generation

Figure 2.2 shows the development of gross electricity generation in Europe (EU-28) over time for different energy sources.

Electricity generation in Europe remains dominated by fossil fuel-based thermal power plants, but their share has dropped from 57 % in 1990 to 44 % in 2017. The share of nuclear power has also declined, from

Figure 2.2 **Gross electricity generation in the EU-28**



Source: EEA, based on data from Eurostat (2019b).

31 % in 1990 to 25 % in 2017. However, nuclear power still plays an important role in electricity generation in half of the EU-28. France alone is responsible for around half of the nuclear power production in the EU. Nuclear power is being phased out in Germany.

Electricity generation from renewable sources has grown substantially in the EU, from 13 % in 1990 to 31 % in 2017. The share of hydropower has remained largely constant over time, in the range of 10-13 %. Wind and solar power have grown considerably, from almost nothing in 1990 to 11 % and 4 % of the power supply, respectively, in 2017. That was the first year in which wind power production exceeded hydropower production in the EU. The share of biomass in power production has increased from less than 1 % in 1990 to more than 5 % in 2017. The share of RES in general would be considerably higher if data from the non-EU member countries of the EEA, where hydropower is often the dominant source of electricity generation, were included.

The growth in renewables, in particular wind and solar power, is the major development in the European power system. In 2016, renewables accounted for 86 % of the newly installed electricity generation capacity in Europe (EEA, 2017e). This growth is expected to continue as policies focus on decarbonisation and on promoting renewable energy production (see Section 2.2). Further increases in the growth in renewable generation capacity are expected as onshore and offshore wind power and utility-scale photovoltaics (PV) increase their cost-competitiveness compared with electricity generation from fossil fuels (IRENA, 2018c).

Heating and cooling

Heating and cooling represent an important share of Europe's energy consumption. Energy consumption for heating is clearly dominant in most countries. It comes from a variety of sources, including solid, liquid and gaseous fossil fuels and biofuels, electricity and solar thermal energy. Energy consumption for cooling is much lower in most countries, but it is increasing due to socio-economic changes and climate change.

The EU's **heating and cooling strategy** was launched in 2016 (EC, 2016e). Significant progress has been made across Europe in terms of increasing the share of RES in the energy mix for heating and cooling. However, the majority of heating and cooling energy is still generated from fossil fuels (66 % in total, 42 % from natural gas). Electricity and district heating account for 21 %, which is mainly based on fossil fuels. Biomass is used in about 12 % of heating and cooling production, notably in Austria, Finland and Sweden. Solar thermal and geothermal power, and heat pumps are still marginal in most European countries. However, biogas and heat pumps have had high annual growth rates since 2005 (Eurostat, 2018f; Camia et al., 2018; Heat Roadmap, 2019).

The decarbonisation of industrial and domestic heating processes still presents a challenge (Steinbach et al., 2017). Meeting decarbonisation targets will require a combination of energy efficiency improvements (including insulation in buildings) and new or innovative heating and cooling solutions. These include combined heat and power generation, heating and cooling from renewable sources, power-to-heat and/or district heating and cooling. Suitable solutions will differ across regions, partly reflecting regional variations in heating and cooling demand.

2.1.3 Transportation, transmission, storage and distribution

Energy is provided to final consumers through transmission and distribution networks or transport services (e.g. for solid fuels). These networks and services are reinforced and supported by storage facilities and technologies. This infrastructure provides the backbone of Europe's energy system, linking energy supply and demand. **Energy transport, transmission, storage and distribution generally involves large-scale infrastructure that can be disrupted by extreme weather events related to climate change.** Damage to infrastructure can cause long-lasting and costly supply disruptions, such as power outages, as well as costly equipment repairs or replacement.

European electricity grids have increased their level of interconnection in recent years. There are plans to further enhance cross-border electricity transmission capacity — most notably through the EU's Trans-European Networks for Energy (TEN-E) Regulation and strategy (EC, 2018w; EU, 2013b) and the projects of common interest (EC, 2019d). The TEN-E Regulation has recently been evaluated, and it would be repealed by the proposed Regulation establishing a Connecting Europe Facility (Rademaekers et al., 2018; EC, 2018s).

In 2014, the European Council formulated the objective that EU Member States should have a cross-border electricity transmission capacity that is equal to at least 10 % of their domestic electricity generation capacity by 2020 (EC, 2018l). This target was later raised to 15 % by 2030 (EU, 2018d). Seventeen Member States are on track to reach the targets, while Cyprus, Poland, Spain and the United Kingdom are not expected to meet the interconnection target for 2020 (EC, 2017f). A more interconnected EU grid can increase both vulnerability and resilience, depending on the particular situation and the management of the overall system.

Recent developments in EU energy market legislation include network improvements to support the connection of renewable energy generation to local distribution grids (EC, 2016b, 2018r). Smart grids and other innovations play a role in increasing the resilience of electricity networks and the integration of renewable energy (Schaber et al., 2012; Becker et al., 2014; EDSO for Smart Grids, 2018). Innovations in the area of offshore wind energy include the expansion and improvement of long-distance transmission networks through the development of specialist insulation and superconducting materials for subsea cables.

The European **gas network** can be subdivided into long-distance transport pipelines and distribution grids. Long-distance gas transport is strongly influenced by Europe's dependence on gas imports from Russia. The EU is aiming to reduce its dependence on Russian gas for political and strategic reasons. It has started to do this with the construction of reverse-flow pipelines (in which gas can flow in both directions, thereby increasing capacity) and by increasing connectivity between Member States. However, Germany is currently planning to expand import capacity from Russia through the Nord Stream 2 project (Nord Stream 2, 2018).

Liquefying and transporting natural gas (**liquefied natural gas** or LNG) has had a large impact on the global gas market in recent years, by enabling significant natural gas imports from places such as Algeria and Qatar. This also reduces EU import dependency on specific gas pipelines, thereby increasing overall system resilience. Various Baltic Sea states have plans to build new LNG storage terminals. The shale gas boom in the United States provides another source of LNG imports, at least as long as current long-term market prospects remain the same. Conventional gas and LNG terminals and refineries are largely based in coastal areas. Their infrastructure and operation is therefore vulnerable to storms, storm surges and sea level rise.

Oil infrastructure in the EU is largely owned by private energy companies. A large number of oil refineries in Europe are located on coasts where they are vulnerable to storm surges and wave activity. Pipelines and associated oil infrastructure may also be vulnerable to strong winds.

Energy storage is an increasingly important part of the energy system. Traditionally, this has focused on facilities for the **storage of oil**, as all EU Member States are obliged to have oil stocks equivalent to 90 days of oil consumption. Norway, Switzerland and Turkey are bound by similar rules as Member States of the International Energy Agency (IEA). This obligation stems from the oil shocks of the 1970s and is intended to prevent supply disruptions. **Natural gas storage** is not regulated in the same way as oil storage (i.e. there are no quantitative requirements for emergency stocks). Gas storage is vital to guarantee the continuity of gas supply in winter when demand is highest, thereby contributing to security of supply.

Electricity storage improves the resilience and flexibility of power supply. This is becoming increasingly important to network operators that need to manage the increasing share of intermittent RES in electricity generation. The need for electricity storage capacity is expected to boom in coming years (EC, 2013c). **Pumped hydroelectricity** has been the main form of large-scale electricity storage employed in Europe. It has generally been used for electricity generation during daily peak hours and pumping during low-demand nightly hours in thermal electricity-dominated systems. In Norway, however, electricity needs have been covered by hydropower with sufficient reservoir capacity to meet demand in cold winters. This capacity has also led to studies on how Norwegian large reservoir hydropower can deliver balancing capacity across Europe, and on the technical, economic and environmental challenges that are linked to the operation of hydropower plants for long-term storage. There remains significant potential to develop pumped hydropower in Norway and elsewhere if the business case is sufficiently strong (EASE/EERA, 2017). For variation over hours, large-scale **battery storage** has very recently started to be deployed successfully as the cost of batteries declines and the technology improves. This technology will compete with the traditional pump storage hydropower that has reservoir capacity for a few hours of operation only. The growth in the use of electric vehicles and residential batteries, combined with smart devices and contracts, has the potential to greatly increase the availability of electricity storage and consequently to improve system resilience. However, such growth may be limited with current battery technologies as a result of resource limitations including cost, space and rare minerals. **Hydrogen storage** is just starting to become part of the energy system, but it may experience substantial growth in the future.

Heating and cooling storage in underground aquifers is receiving increasing attention as a way to optimise the thermal conditions of buildings. Several such systems have been installed in the Netherlands, where it is becoming a standard for new buildings; it has a large potential for application in other countries as well (Bloemendal and Jaxa-Rozen, 2018).

The vulnerability of storage technologies to climate change impacts varies by type. The vulnerability of above-ground storage facilities is similar to that for other key fossil fuel infrastructure. Subterranean storage infrastructure should be largely unaffected. Pumped hydropower storage needs to be distinguished by technology. Closed-loop pumped storage plants are rather insensitive to climate variability and change, whereas open-loop plants have similar susceptibilities as run-of-river and reservoir hydropower systems. The novelty of other storage technologies presents some uncertainties regarding their potential climate vulnerabilities, although temperature is known to affect the effectiveness of batteries.

2.1.4 Energy demand

Energy demand is the fundamental driver behind the energy system. Aggregate energy demand in Europe appears to have stabilised in recent years, but important shifts in demand are still taking place between and within sectors. Energy demand is also affected by climate change, primarily through changes in ambient temperature, which determine the demand for heating and cooling in buildings.

Final energy consumption

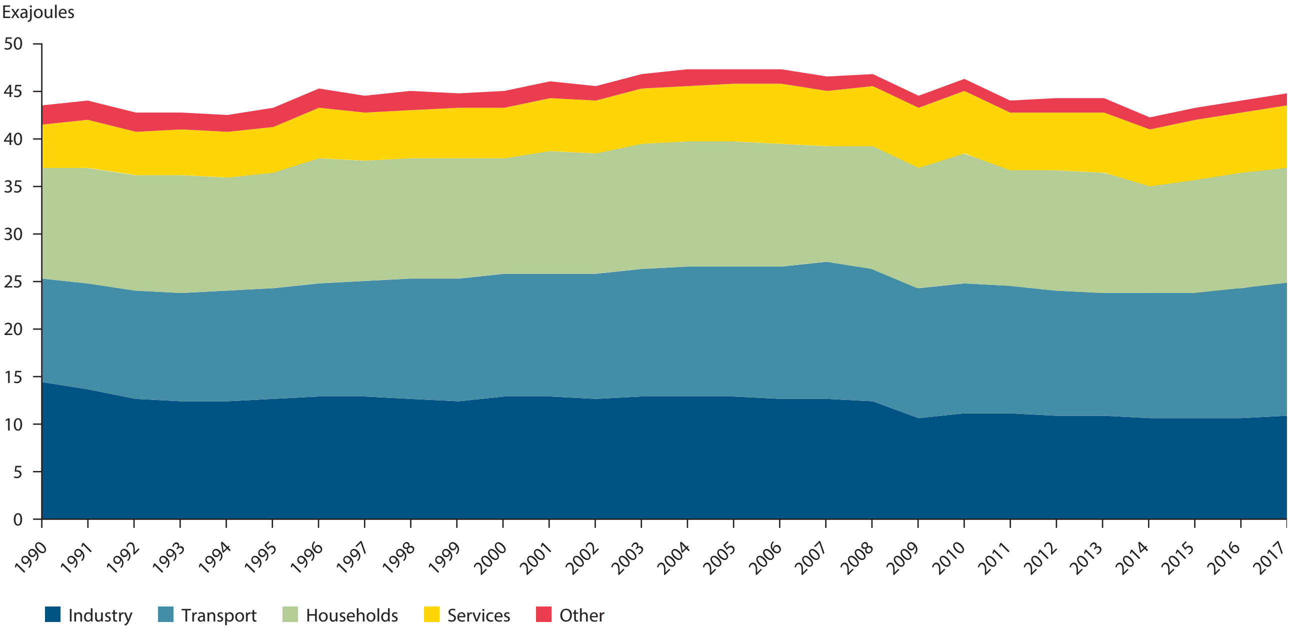
Figure 2.3 shows the development of final energy consumption in Europe (EU-28) by sector.

Final energy consumption in Europe (EU-28) has remained largely constant since 1990. It mostly grew until 2006, then declined until 2014, and started increasing again afterwards. Industry is the only sector with an overall declining trend in energy use. Most of the energy savings in industry are due to increasing energy efficiency and structural change towards less energy-intensive industries (Voigt et al., 2014). This includes the relocation of carbon-intensive production outside Europe, also known as carbon leakage (Paroussos et al., 2015). The recent economic crisis also played a role by reducing industrial output and thereby the total energy demand (EC, 2017b). Energy use by households does not show a clear trend, and energy demand in the services and transport sectors is still increasing. Rising energy demand in the services sector can be explained by economic growth and structural change. The growth of energy use in transport is primarily driven by an increase in air travel and road freight transport.

Fuel mix in the transport sector

The transport sector is still strongly dominated by oil use. Oil accounts for 94 % of the sector's energy consumption, and the sector accounts for 80 % of the total oil consumption in the EU. Alternative fuels, particularly liquid biofuels, liquefied petroleum gas and natural gas have emerged as a small but increasing share of the transport energy mix since 2006. Driven by biofuel targets in the Renewable Energy Directive, the share of biofuels in the energy mix of the road transport sector has increased from a negligible level in the early 2000s to 3.5 % in 2016 (Eurostat, 2018b). Electricity has remained a small

Figure 2.3 Final energy consumption by sector in the EU



Source: EEA, based on data from Eurostat (2019b).

part of the transport fuel mix. Sales of hybrid and electric vehicles have grown in the past decade, but they still represent only around 1.5 % of all new vehicles sold in the EU in 2017. In Norway, their share is already more than 30 % (EEA, 2018b). Current and expected growth in electric vehicle uptake across Europe will significantly increase the share of electricity in the energy mix of the transport sector.

Heating and cooling demand

Space heating and cooling account for roughly half of the total final energy demand in the EU (Heat Roadmap, 2019). A large share of the energy consumption in the built environment and in industry is for heating purposes. The use of low-temperature heat for heating in the built environment accounts for 27 % of the total final energy consumption in the EU. Gas is the primary fuel used for this purpose. An additional 16 % of the final energy consumption is used for process heating in industry (Heat Roadmap, 2019). Process heat is primarily produced from natural gas (39 %), coal (17 %) and other fossil fuels (19 %); the remainder comes from renewable sources. For high-temperature process heating, hardly any renewable sources are used. Cooling, whether for industrial processes or for use in buildings, is currently a relatively small part of final energy demand. Cooling demand in the EU has undergone a large increase, from 63 TWh in 1990 to 152 TWh in 2016, but it still accounted for only 1.2 % of the energy use in buildings in 2016 (IEA, 2018a).

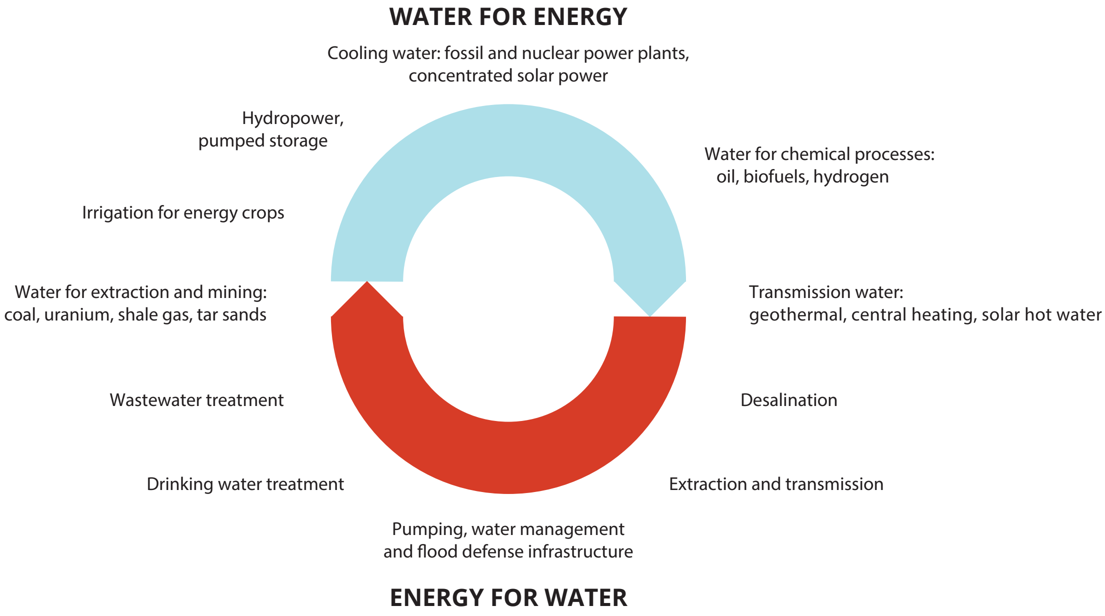
2.1.5 The energy-water-land nexus

The energy sector uses significant amounts of water and land. Hence, it may be in competition with other sectors and systems that use these resources, such as agriculture and natural ecosystems. These links are important considerations in the development of energy strategies.

Energy-water nexus

The energy sector is a large user of water both globally and in Europe. Consumptive water use by the energy system can directly compete with other water users, such as agriculture and industry. Non-consumptive water use can have substantial ecosystem impacts, in particular when thermal power plants discharge cooling water back to the environment at above ambient temperature or when storage hydropower plants can affect the seasonality of river flows. **At the same time, the water sector is a major energy user**, accounting for around 4 % of global electricity consumption (IEA, 2018b). The term 'energy-water nexus' is used to describe the interdependence between these two key systems underpinning economic and social development (see Figure 2.4).

Figure 2.4 Energy-water nexus



Source: EEA, based on EP (2012).

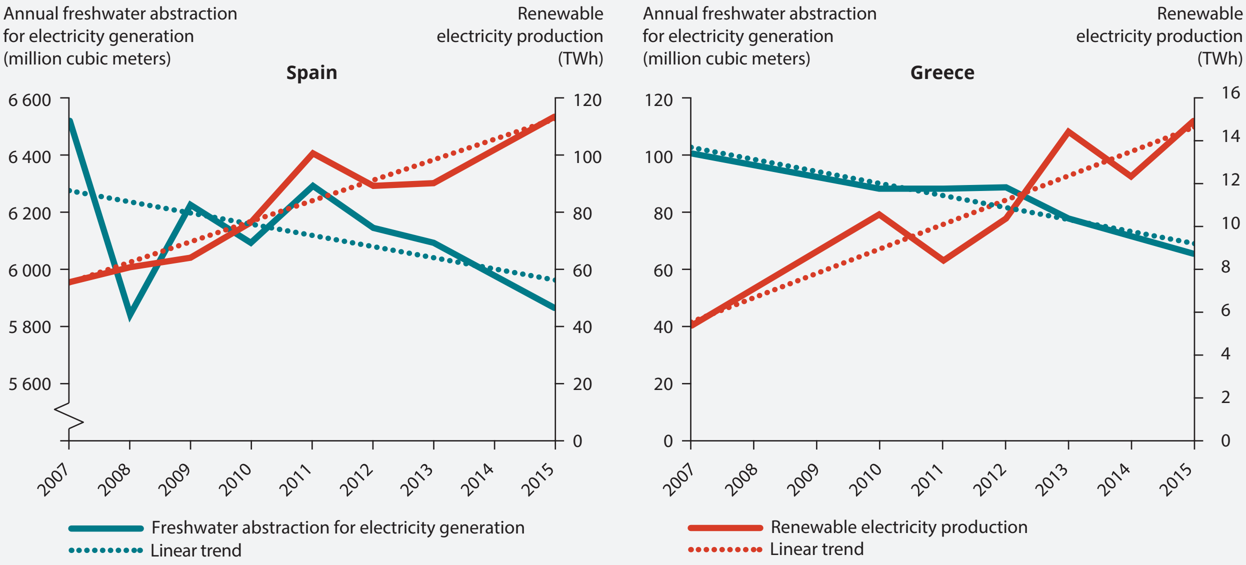
The interdependencies represented by the energy-water nexus are expected to intensify over time as a result of climate change impacts, changing consumption patterns and population growth (Eurostat, 2018d). The decline in thermal power generation as envisaged in most decarbonisation scenarios is expected to lead to reduced water withdrawals but higher water consumption by the energy sector in most advanced economies (Fricko et al., 2016). Several studies have pointed out that increasing water stress can constrain energy production in (parts of) Europe (see Section 3.3).

Some low-carbon energy technologies have the potential to contribute positively to this nexus, whereas others may lead to competition or conflict. For example, replacing thermal power generation with solar PV and wind energy reduces freshwater use per unit of energy generated, whereas water use for energy crops and for concentrated solar power (CSP) can be higher than for fossil fuel power plants (see Box 2.2). Therefore, an energy strategy focusing on bioenergy or CSP can increase competition with other water-using sectors (Berrill et al., 2016).

Box 2.2 Renewable energy sources and water use

The expansion of renewable energy can create synergies at the energy-water nexus, if appropriate RES are chosen. In many regions in southern Europe, water needs for agriculture, industry, energy, tourism and household consumption are increasing while water availability is decreasing due to climate change. In this situation, replacing fossil fuel power plants with renewable energy sources with low water use, in particular wind power and solar photovoltaics, can be a win-win strategy to decrease water scarcity. Figure 2.5 shows that as energy production from renewables in Spain and Greece has increased, freshwater abstractions for power production has decreased. Obviously, the relationship between the two variables depends on the particular choice of renewable energy sources.

Figure 2.5 Water abstractions for power production and primary production of renewable energy in Spain and Greece



Source: Based on data from Eurostat (2018a).

Concentrated solar power (CSP) produces electricity by concentrating solar irradiation to heat a gas or liquid, which is in turn used to drive an electrical generator. CSP is one of the most water-intensive energy production technologies (Frisvold and Marquez, 2014) because of its reliance on large quantities of water for cleaning and cooling the mirrors used in installations. This can lead to scarcity of water resources, particularly in arid regions where such facilities are likely to be situated. While CSP presents a potentially important energy source, its water intensity illustrates significant challenges for the energy-water nexus. Efforts are being made to improve the technology and reduce its water use, for example through the EU-funded MinWaterCSP project. This project is developing solutions such as new cooling systems, heat transfer surfaces and mirror cleaning techniques that aim to reduce CSP water usage. Such advances in technology could reduce water evaporation losses by up to 95 % (INEA, 2018).

The energy-water nexus can also influence the choice of cooling technology for power generation. Once-through cooling systems are the cheapest and most efficient cooling systems, but they require the highest water withdrawals. Dry cooling is the most expensive and least efficient technology, but it uses the least amount of water. Wet cooling towers have intermediate costs and efficiency compared with the first two options. Their water withdrawals are lower than for once-through cooling systems, but their consumption is higher, which can introduce important trade-offs. As a result, the level and type of water stress in a region can play an important role in the choice of the most suitable cooling technology (IEA, 2018b).

Energy is important for the provision of water for a wide range of uses that are crucial for the health and well-being of the population. These uses include the provision of safe and clean drinking water, water desalination, wastewater treatment, and water pumping and distribution for all uses (IEA, 2018b). Failures in the energy system, whether linked to water shortages or not, have the potential to disrupt these vital functions.

The water sector in Europe may be able to reduce its energy use in the future. Some technologies, such as wastewater treatment with energy recovery or biogas production, may even generate more energy than they use (IEA, 2018b). At the same time, energy use may increase in the most water-stressed regions of Europe, where desalination is increasingly used (see Section 3.3.4).

The important system implications of the energy-water nexus are beginning to be taken into account by policymakers (see also Section 4.1.4). Further information on managing this nexus is available in various recent publications from international organisations and academic researchers (e.g. IEA, 2014, 2016c; IRENA, 2015; Pittock et al., 2015).

Energy-land nexus

The term 'energy-land nexus' describes the interaction between energy and other land uses, such as food production and nature protection. **The energy-land nexus is of growing importance, because many RES have a large land footprint.** The land requirement is largest for bioenergy, which relies on plant sources for the generation of energy. The common practice of bioenergy provision from crops is likely to reduce the land available for food production. Innovative initiatives attempt to remedy conflicts between energy and other land uses. For example, agro-photovoltaics (the co-production of food and energy) can significantly increase land use efficiency (Fraunhofer ISE, 2017).

Available studies have produced **very different estimates for the land use requirements of renewable versus conventional energy technologies.** One recent review study found that various RES require about 1-4 orders of magnitude (i.e. factor 10 to 10 000) more land than fossil and nuclear energy sources (van Zalk and Behrens, 2018). However, studies including life-cycle analysis and/or impacts over time come to very different conclusions. A comprehensive review by the International Resource Panel found that the land impacts of RES can be both smaller or larger than those of conventional technologies (UNEP, 2016). One study from the United States has suggested that the cumulative land use impact of fossil energy technologies exceeds that of solar-, wind- and hydropower after a few years or decades (this is even faster for surface coal mining) (Trainor et al., 2016). The only study with a European focus found that the land use intensity of wind power in the EU can be of the same order of magnitude as that of fossil and nuclear energy sources if life-cycle impacts are considered (UNCCD/IRENA, 2017).

The wide range of available results emphasizes that **it can be misleading to directly compare the land use impacts of renewable and conventional energy technologies.** Any such comparison is highly sensitive to methodological choices, such as how to value the impacts of depletive versus non-depletive land uses over time, how to value the use of arable land versus marginal land versus offshore areas, how to value the degree of impact (e.g. mostly visual impact from wind mills versus radical land transformation from surface coal mining or the extraction of non-conventional fossil fuels), how to account for multiple or non-competitive land uses (e.g. roof-top PV, residual forest biomass and wind mills on farmland), and whether to account for upstream impacts in other regions. Rather than attempting to minimise energy-related land use based on any given indicator, the development of clean energy strategies should focus on jointly maximising the various services (such as energy production, food production, nature protection, housing and recreation) that can be provided sustainably by the available land resources in a given region.

Integrated policy perspective

The water and land requirements of the energy system discussed above lead naturally to integrating energy with food and water in the broader perspective of the **energy-water-land nexus** (or **energy-water-food nexus**). This nexus has also gained attention as an overarching global sustainable development policy perspective (Leck et al., 2015).

The cross-sectoral interactions imply that **EU environmental policy legislation plays an important**

role in the energy sector and its adaptation to climate change. In particular, the **Water Framework Directive (WFD)** emphasises the quality of hydromorphological conditions and aims to achieve good ecological status in all water bodies in the EU (EU, 2000). This may prevent energy projects that are liable to influence aquatic ecosystems, such as hydropower and thermal power plants. Preamble 16 states that the energy sector must sustainably manage and protect water, and further integration into various policy areas is encouraged. The WFD requires **river basin management plans** (RBMPs) to be drawn up to protect water environments across Europe. RBMPs should highlight how climate change projections have been incorporated into projects, how monitoring programmes detect climate change impacts, and how robust selected measures are to projected climate conditions. The **Floods Directive**, which complements the WFD, requires Member States to develop **flood risk management plans** (FRMPs) (EU, 2007). FRMPs focus on measures for prevention, protection and preparedness to deal with flooding in both inland and coastal water. They are often combined with RBMPs, and coordination between the two is encouraged in the directives.

2.2 Building a low-carbon energy system

A key driver for changes in the global and European energy system is the need for a clean energy transition. Such a transition needs to drastically reduce greenhouse gas (GHG) emissions, which lead to a changing climate; it should also reduce air pollutant emissions, which are threatening human health and the environment. This section gives an overview of relevant targets and scenarios at the global and European scale.

2.2.1 Global policy targets and energy scenarios

UNFCCC Paris Agreement

The overarching aim of the Paris Agreement under the United Nations Framework Convention on Climate Change (UNFCCC) is to ensure that the increase in global average temperature stays well below 2 °C above pre-industrial levels, while also pursuing efforts to limit this rise to 1.5 °C (UNFCCC, 2015). All signatories have committed to determining, planning and reporting on measures intended to mitigate global warming through nationally determined contributions (NDCs).

The current commitments in the form of the NDCs are not sufficient to reduce global emissions to a level consistent with the goals of the Paris Agreement. The latest United Nations Environment Programme (UNEP) Emissions gap report stated that 'Pathways reflecting current NDCs imply global warming of about 3 °C by 2100, with warming continuing afterwards'. It stressed that 'countries need to strengthen the ambition of NDCs and scale up and increase effectiveness of domestic policy to achieve the temperature goals of the Paris Agreement' (UNEP, 2018).

IPCC SR1.5 pathways

The Intergovernmental Panel on Climate Change (IPCC) Special Report Global warming of 1.5 °C (IPCC, 2018) found that pathways compatible with a global warming of 1.5 °C agreed on a marked increase in the share of renewables, which may cover half to two thirds of global primary energy supply by 2050; a strong decrease in coal use, with the residual to be used only in combination with carbon capture and storage (CCS) by 2050; a rapid decline in the carbon intensity of electricity generation, coupled with a marked increase in the electrification of all end uses; and a sharp decrease in energy demand driven by a pronounced lifestyle shift. All these actions should be supplemented by increased efforts to create negative carbon emissions, for example through the use of sustainable bioenergy combined with CCS.

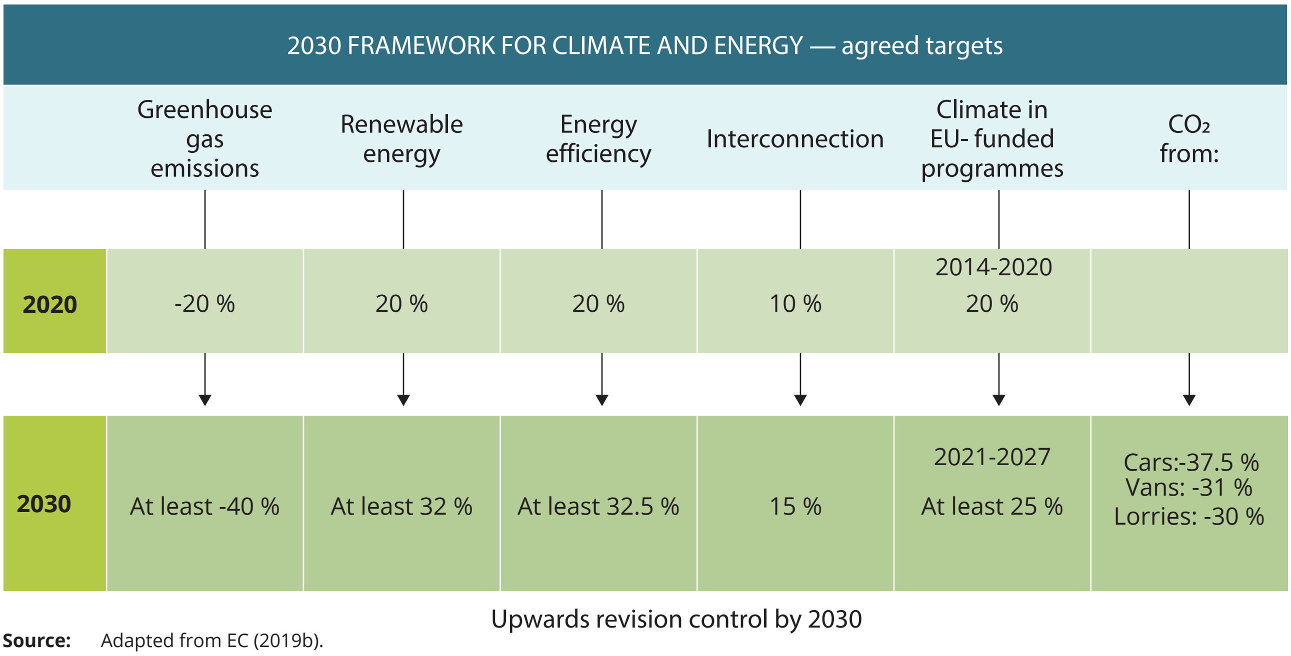
IEA scenarios

The IEA has developed global energy scenarios up to 2040 (IEA, 2018b). Among the three main scenarios are (1) Current Policies, which consider only the impacts of policies already legislated for as of mid-2018; (2) the New Policies Scenario, which also includes the likely effects of policies announced by August 2018, including those to meet the NDCs for the Paris Agreement; and (3) the Sustainable Development Scenario, which presents an integrated approach to delivering on the Paris Agreement, universal access to modern energy by 2030 and improving air quality in order to significantly reduce pollution-related premature deaths. These IEA scenarios, but also the IEA Energy or Reference Technology Scenario (IEA, 2017), illustrate that significant additional action is needed if global emissions are to be made consistent with the goals of the Paris Agreement.

2.2.2 European policy targets and energy scenarios

This section gives an overview of how the required transition in the energy system is rooted and reflected in EU policies and forward-looking

Figure 2.6 Quantitative targets of the EU Energy Union



2030 FRAMEWORK FOR CLIMATE AND ENERGY — agreed targets

	Greenhouse gas emissions	Renewable energy	Energy efficiency	Interconnection	Climate in EU- funded programmes	CO₂ from:
2020	-20 %	20 %	20 %	10 %	2014-2020 20 %	
2030	At least -40 %	At least 32 %	At least 32.5 %	15 %	2021-2027 At least 25 %	Cars:-37.5 % Vans: -31 % Lorries: -30 %

Upwards revision control by 2030

Source: Adapted from EC (2019b).

scenarios and how these scenarios frame the need for energy system adaptation now and in the future. Relevant EU policies are presented in more detail in Section 4.2.

The **2030 climate and energy framework** aims to cut GHG emissions by 40 % by 2030, compared with 1990 levels (European Council, 2014). The initial framework involved increasing the share of RES to at least 27 % and increasing energy efficiency by 27 %. The last two targets have recently been strengthened, with revised targets of 32 % for RES and 32.5 % for energy efficiency (see Figure 2.6) (EU, 2018a, 2018b).

The proposal for a **EU long-term strategy 'A Clean Planet for All'**, which was published in November 2018, puts forward a vision to steer the EU economy and society towards a (largely) CO_2 emissions-free future by 2050 (EC, 2018j). According to the Commission, the strategy shows how Europe can lead the way to climate neutrality by investing in realistic technological solutions, empowering citizens and aligning action in key areas, such as industrial policy, finance and research, while ensuring social fairness for a just transition. The strategy covers seven strategic areas, proposing joint action in each of these: (1) energy efficiency; (2) deployment of renewables; (3) clean, safe and connected mobility; (4) competitive industry and circular economy; (5) infrastructure and interconnections; (6) bio-economy and natural carbon sinks; and (7) CCS to address remaining emissions. The Commission invites all EU institutions, the national parliaments, the business sector, non-governmental organisations, cities and communities, as well as citizens, to participate in an EU-wide informed debate on the strategy. This should allow the EU to adopt and submit an ambitious strategy to the UNFCCC by early 2020 as requested under the Paris Agreement.

The long-term strategy is based on eight decarbonisation pathways, all of which were developed as a departure from the same baseline scenario (EC, 2018j, 2018q). They cover key features of the energy system (supply, demand, prices and investments) and all GHG emissions for the period up to 2050 (or even 2070) for all EU Member States, all candidate countries, Norway, Switzerland, and Bosnia and Herzegovina.

Table 2.1 **Scenario overview from the proposed EU long term strategy 'A Clean Planet for All'**

	Electrification (ELEC)	Hydrogen (H2)	Power-to-X (P2X)	Energy Efficiency (EE)	Circular Economy (CIRC)	Combination (COMBO)	1.5 °C Technical (1.5TECH)	1.5°C Sustainable Lifestyles (1.5LIFE)
Main Drivers	Electrification in all sectors	Hydrogen in industry, transport and buildings	E-fuels in industry, transport and buildings	Pursuing deep energy efficiency in all sectors	Increased resource and material efficiency	Cost-efficient combination of options from 2°C scenarios	Based on COMBO with more BECCS, CCS	Based on COMBO and CIRC with lifestyle changes
GHG target in 2050	-80% GHG (excluding sinks) ["well below 2°C" ambition]					-90% GHG (incl. sinks)	-100% GHG (incl. sinks) ["1.5°C" ambition]	
Major Common Assumptions	• Higher energy efficiency post 2030 • Deployment of sustainable, advanced biofuels • Moderate circular economy measures • Digitilisation • Market coordination for infrastructure deployment • BECCS present only post-2050 in 2°C scenarios • Significant learning by doing for low carbon technologies • Significant improvements in the efficiency of the transport system.							
Power sector	Power is nearly decarbonised by 2050. Strong penetration of RES facilitated by system optimization (demand-side response, storage, interconnections, role of prosumers). Nuclear still plays a role in the power sector and CCS deployment faces limitations.							
Industry	Electrification of processes	Use of H2 in targeted applications	Use of e-gas in targeted applications	Reducing energy demand via Energy Efficiency	Higher recycling rates, material substitution, circular measures	Combination of most Cost-efficient options from "well below 2°C" scenarios with targeted application (excluding CIRC)	COMBO but stronger	CIRC+COMBO but stronger
Buildings	Increased deployment of heat pumps	Deployment of H2 for heating	Deployment of e-gas for heating	Increased renovation rates and depth	Sustainable buildings			CIRC+COMBO but stronger
Transport sector	Faster electrification for all transport modes	H2 deployment for HDVs and some for LDVs	E-fuels deployment for all modes	Increased modal shift	Mobility as a service			• CIRC+COMBO but stronger • Alternatives to air travel
Other Drivers		H2 in gas distribution grid	E-gas in gas distribution grid				Limited enhancement natural sink	• Dietary changes • Enhancement natural sink

Source: EC (2018q).

Table 2.1 summarises the main features of these scenarios. The Joint Research Centre has provided the global context to the EU long-term strategy in its Global Energy and Climate Outlook 2018, which includes a detailed analysis of sectoral mitigation options towards a global low-emissions economy (Keramidas et al., 2018).

The baseline is largely built on the 2016 EU Reference Scenario (EC, 2016g), but it assumes the achievement of the latest energy and climate 2030 targets. It also incorporates several policy proposals in the field of energy, transport and land use, land use change and forestry, and an update on the prospects of relevant technologies. The scenario assessment encompasses three categories of pathways: the first includes five pathways that rely on a wide range of measures, each exploring a different technological option. Three of these scenarios are driven by the different emphasis on alternative decarbonised energy carriers (electrification, hydrogen or e-fuels), while the remaining two scenarios focus on demand-side measures (enhanced energy efficiency or an enhanced circular economy). All these scenarios attain at best an 80 % emission reduction by 2050 (compared with 1990). The second category includes only the sixth pathway ('COMBO'). This pathway combines all the options considered in the previous five decarbonisation scenarios and reaches a 90 % emission reduction, which is compatible with a 'well below 2 °C' trajectory of global mean temperature increase by the end of the century. The unavoidability of residual GHG emissions from the agricultural sector prevents full decarbonisation (which is necessary for a 1.5 °C trajectory) in the absence of measures to achieve negative emissions. The last category of pathways (seventh and eighth scenarios) explore possible solutions to push the system towards full decarbonisation. They put the emphasis on negative emission technologies ('1.5TECH') and on sustainable lifestyles ('1.5LIFE'), respectively, whereby the latter entails a paradigm shift in consumers' choices and a stronger circularity of the EU economy. The shift towards an increasingly decarbonised future is present in all eight scenarios, but it is most prominent in the last three. All scenarios also assume a marked increase in energy efficiency, whereby the residential and transport sectors are responsible for the largest cuts in final energy consumption.

The main aggregate outcomes for the energy sector in the eight decarbonisation scenarios are depicted in Figure 2.7 and Figure 2.8. The prominent role of renewables is apparent in Figure 2.7, which also highlights the significant role of nuclear energy and the impossibility of fully eliminating fossil fuels. The importance of a widespread electrification of energy uses scenario is highlighted in Figure 2.8, which also points to a virtual extinction of solid fossil fuels and to a significant contribution of biomass and of hydrogen in the fullest decarbonisation scenarios.

2.2.3 Key trends for the future energy system in Europe

The European energy system will experience major changes in the coming decades as it transitions towards a low-carbon energy system. Further to the scenarios from the EU long-term strategy presented in the previous section, several organisations have developed European energy scenarios with time horizons between 2030 and 2050. Relevant scenarios include the REmap scenarios of the International Renewable Energy Agency (IRENA) (IRENA, 2018b) and the 10-year network development plan (TYNDP) scenarios jointly developed by the European Network of Transmission System Operators — Electricity and Gas (ENTSO-E and ENTSO-G) in their TYNDP 2018 scenario report (ENTSOs, 2018).

All available scenarios agree that **achieving the goals of the Paris Agreement requires (1) a highly decarbonised electricity generation sector, (2) the preponderance of renewables in the energy mix, (3) the electrification of most energy uses, primarily transport, and (4) a key role for energy efficiency.** Other developments are dependent on the ambition level of the decarbonisation scenario, socio-economic developments and preferences, and assumptions regarding key technological developments, such as carbon capture and sequestration/use, hydrogen and electric mobility.

This section summarises key trends in the future energy system to assess their implications for climate change adaptation and resilience. Broadly speaking, energy efficiency and water-efficient RES tend to reduce adaptation challenges, whereas increased electrification by climate-dependent and water-intense RES tend to increase adaptation challenges. However, the specific adaptation challenges and opportunities of a particular energy technology differ considerably across Europe depending on the climatic, environmental and other characteristics of a particular region. More detailed information about climate change and its impacts on various components of the energy system, and about related adaptation needs and options, is presented in Chapter 3.

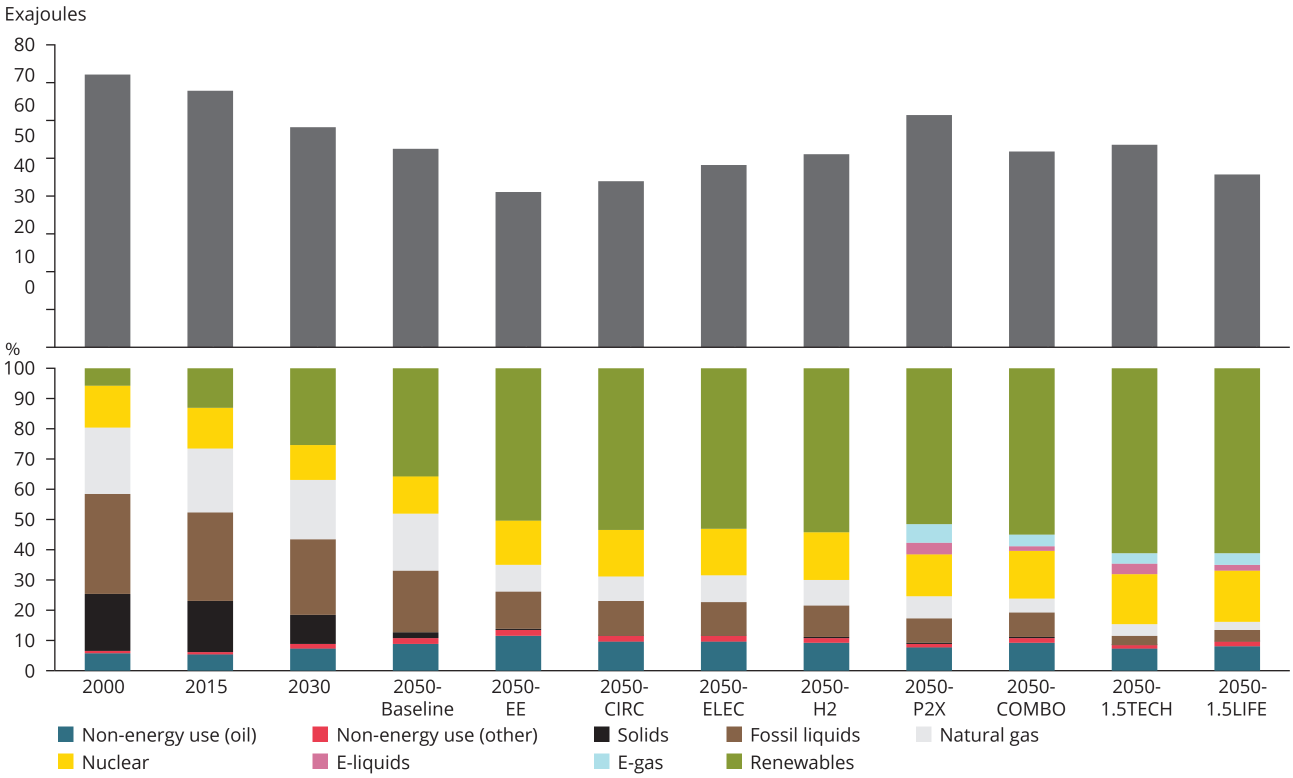
Shifts in primary energy sources and technologies

Rapid growth in RES is a central element in all decarbonisation scenarios. RES growth has been fastest in the power sector, and this trend is expected to continue. Electricity production will increasingly depend on time-variable RES, in particular wind and solar power, which are directly dependent on weather conditions. Achieving long-term climate targets also requires substantial growth in RES in other sectors and uses, in particular transport and heating. Regional strategies for RES expansion need to consider the energy-water-land nexus (see Section 2.1.5) and assess the viability of specific RES under changing climate conditions.

Hydropower will continue to play an important role in the European RES mix, both as an energy source and for energy storage. Hydropower facilities are likely to see technological modifications in the future based on the development and expansion of hydropower pumped storage, which will increase energy system resilience. Expansion opportunities are constrained by wider sustainability concerns, in particular conflicts with nature protection. The greatest remaining potential for new hydropower developments is in eastern Europe, especially in the Western Balkan region, where the EU has taken a strong interest in developing the region's energy sectors (IHA, 2018). Hydropower is highly sensitive to climate conditions, with beneficial as well as adverse impacts of climate change expected in various European regions. Any expansion of hydropower should consider the viability of investments under changing climate conditions, in addition to other sustainability concerns.

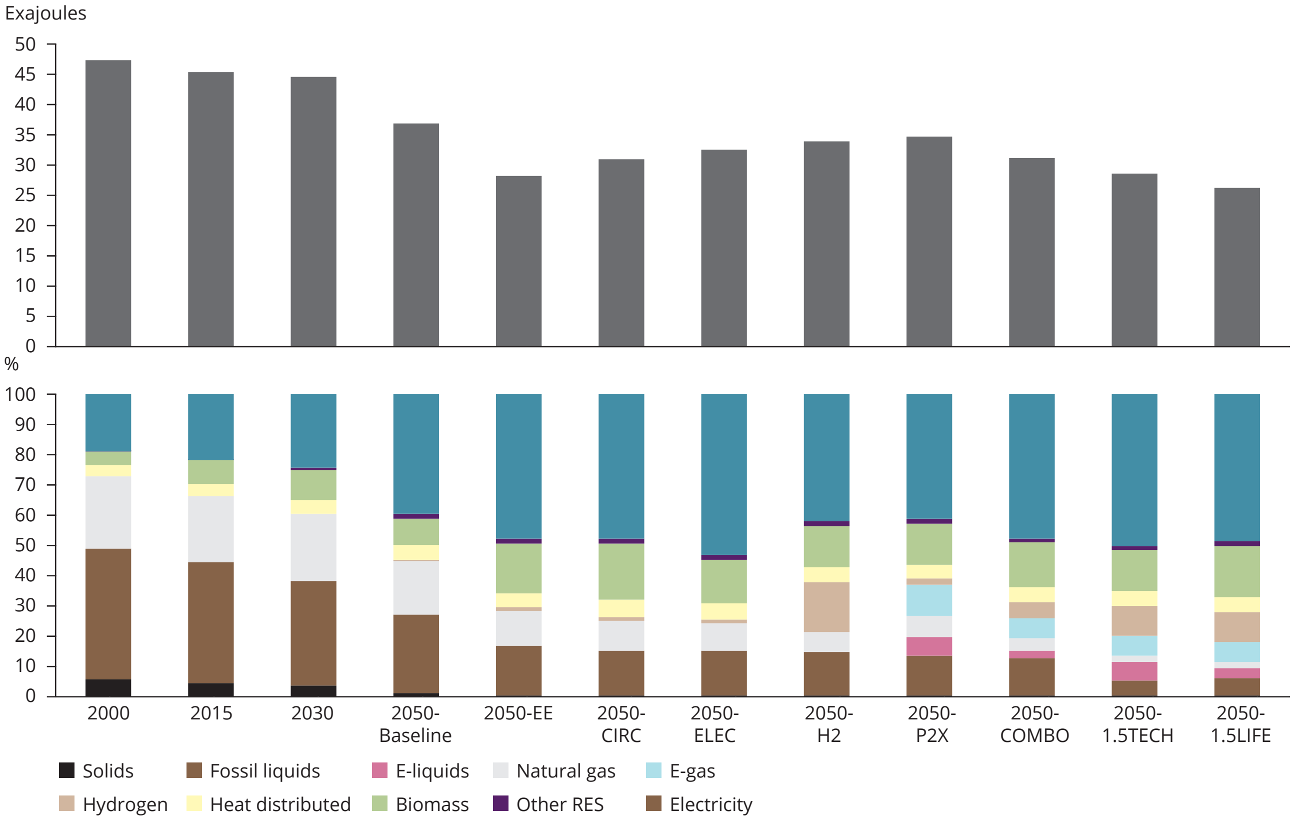
Natural gas (i.e. fossil methane) can be an important transition fuel. Natural gas is less carbon-intensive than coal if fugitive emissions are well controlled. It is more readily available than RES in the short term and already has well-established infrastructure. For these reasons, natural gas is seen in many scenarios as providing an important option for a move away from coal and towards (future) low-carbon energy sources. It can also serve as a backup for time-variable RES. Natural gas may be increasingly replaced by low-carbon gases (biogas, biomethane, synthetic methane and green hydrogen) from renewable sources. There are considerable differences between scenarios regarding the overall role of gas in the future

Figure 2.7. **Share of energy sources (bottom) in gross inland consumption of primary energy (top)**



Source: Adapted from EC (2018q).

Figure 2.8 **Share of energy carriers (bottom) in final energy consumption (top)**



Source: Adapted from EC (2018q).

as well as the share of low-carbon gas (EC, 2018q). Most gas infrastructure is resilient to a wide range of climate conditions. Adaptation challenges can arise for offshore infrastructure, coastal infrastructure (e.g. LNG terminals) and infrastructure in permafrost regions at risk of thawing.

Shifts in final energy carriers

Fossil fuels for transport and heating need to be replaced by low-carbon energy carriers. For transport, these include electricity (for electric and hybrid vehicles), hydrogen (for fuel cell vehicles) and biofuels or e-fuels (for vehicles with internal combustion engines). Supporting infrastructure, such as charging infrastructure for electric vehicles, needs to be designed to be operational in a wide range of climate conditions. Options for decarbonising heating include electric heat pumps, biomass district heating systems and the use of waste heat. No particular adaptation challenges are foreseen for these technologies.

Hydrogen could play an important role in a future energy system. There are ambitious plans for a green hydrogen economy (including power-to-hydrogen), for example in the Netherlands (Noordelijke Innovation Board, 2018). Scenarios for hydrogen development are associated with considerable uncertainty, because most technologies are still in an early stage of commercial development. It is not currently possible to identify particular adaptation challenges.

Changes in transmission and storage infrastructure

RES may be located far away from the main energy consumers, and their availability over time does not necessarily match the demand curve. Therefore, an energy system with a stronger role of variable RES, and of electricity as an energy carrier, requires substantial expansions of transmission and storage infrastructure.

The expansion and strengthening of electricity grids are important for the integration of increasing shares of intermittent renewables in the European energy system and for limiting the requirements for costly backup capacity, such as gas-fired power plants. This includes expanding cross-border connections and developing 'smart grids' (Schaber et al., 2012; Becker et al., 2014). European electricity network interconnection has improved in recent years, but additional strengthening of grid networks is needed and expected. The vulnerability of the network to climate extremes, such as heat waves, storms, and snow and ice accumulation, is a relevant cause of concern (see Section 3.4 and the case studies in Sections 4.5.5 and 4.5.6). An increased level of monitoring and control can significantly reduce service interruptions and improve the resilience of the low- and medium-voltage grids.

Increasing energy storage is essential for managing the variability of renewables. Increasing storage capacity is a priority for the Commission, which has proposed a market design initiative to introduce elements that facilitate investments in energy storage (EC, 2017a). Pumped hydropower is currently the most important technology for large-scale energy storage, but it is sensitive to water availability. Rapid advances in battery technologies, and associated cost reductions and increased uptake at both industrial and household levels, can have significant benefits for energy system resilience. Closer links between the electricity and gas sectors through power-to-gas may also be part of the solution.

The gas infrastructure may expand, for the reasons discussed above. Adaptation challenges are related mostly to offshore and coastal infrastructure and to infrastructure in permafrost regions.

CCS could be an important element in a decarbonising energy system. However, the feasibility of large-scale CCS deployment is uncertain because of the limited evidence gathered so far. Furthermore, CCS decreases the efficiency of power plants, which in turn increases their fuel and water use. Therefore, the introduction of CCS can increase adaptation challenges related to the energy-water nexus (Chandel et al., 2011; Byers et al., 2016). Under the assumption that additional biomass resources are available for energy provision, the use of bioenergy combined with CCS could lead to negative carbon emissions. However, this approach is as yet unproven and could further increase challenges related to the energy-water-land nexus (EASAC, 2019).

Changes in energy demand and societal changes

The deep decarbonisation pathways in the EU long-term strategy 'A Clean Planet for All' place a strong focus on decreasing overall energy demand. This will be achieved through energy efficiency improvements in buildings and electrical devices, and, potentially, changes in consumer behaviour.

Climate change can also induce changes in total and peak energy demand for heating and cooling (see Sections 3.2.2 and 3.2.3). Changes in energy demand affect the overall level of the mitigation and adaptation challenge.

The pervasiveness of activities and services that depend on a continuous electricity supply has increased the social and economic costs of blackouts. Studies from several European countries have estimated that the societal costs of a power cut can be 10-100 times higher than the direct costs to the energy company (see Box 4.1 for further information). Stronger societal expectations regarding a stable electricity supply are an important driver for a more resilient energy system, which includes climate resilience as a central component.

New low-carbon technology developments may also lead to structural changes, in particular growth in decentralised energy solutions. These can create adaptation challenges if decisions affecting the management of complex infrastructure are taken by a decentralised group of new market actors rather than centrally by more experienced actors. At the same time, decentralised actors can be more flexible and are more knowledgeable about the local situation, including specific adaptation needs and options.

3 Climate change impacts on the European energy system

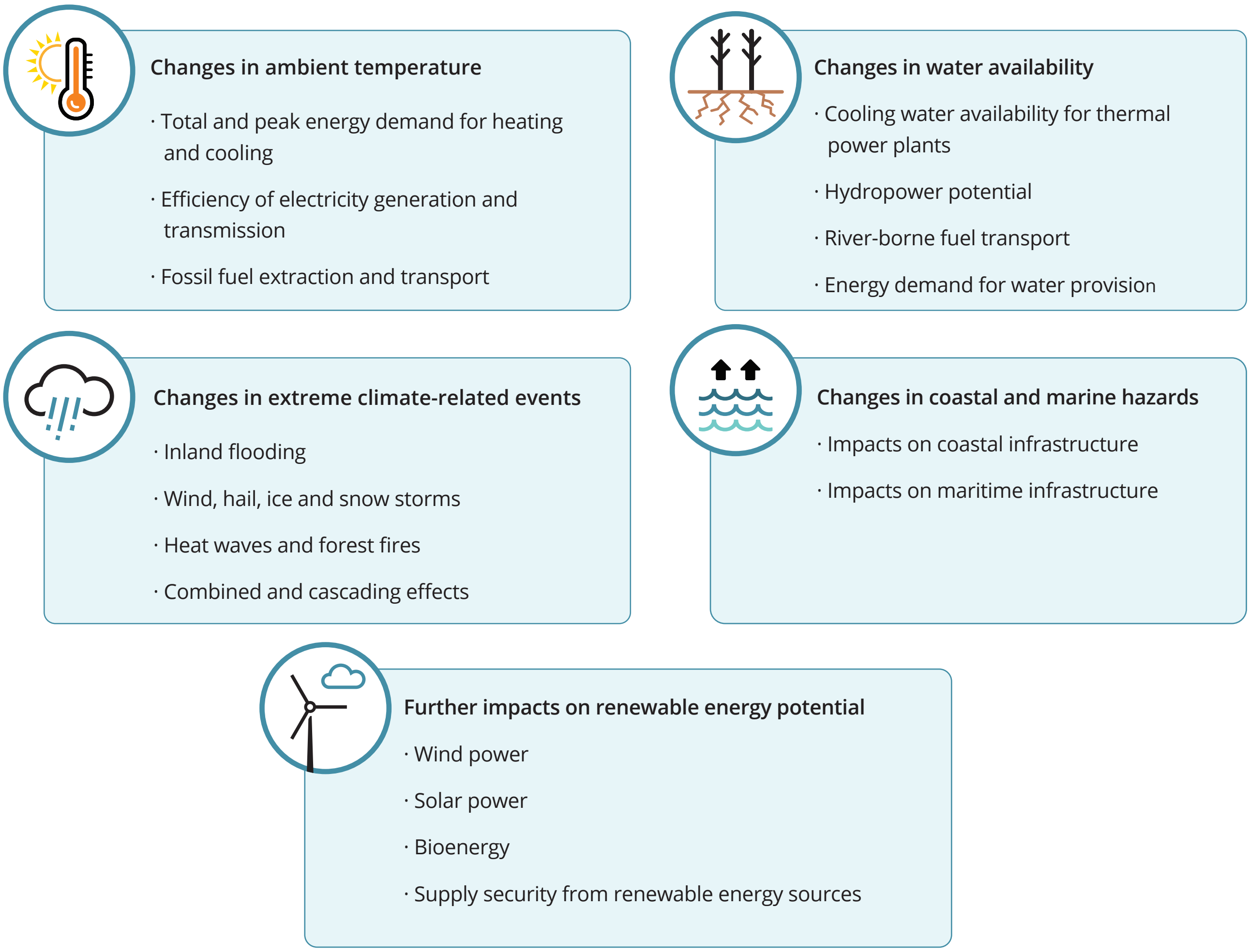
Key messages

- Anthropogenic climate change has already significantly affected the European climate, and further change is inevitable. The most important changes for the energy system include increases in mean and extreme air and water temperatures, and changes in annual and seasonal water availability, extreme climate-related events, and coastal and marine hazards.
- Warming temperatures decrease energy demand for heating, but increase energy demand for cooling. They can also affect electricity generation and transmission as well as fossil fuel extraction and transport.
- Water availability is generally projected to increase in northern Europe and to decrease in southern Europe, but with marked seasonal differences. These changes can affect cooling water availability for thermal power plants, hydropower and bioenergy potential, river-borne fuel transport and energy demand for water provision.
- Climate change can also affect the potential for wind and solar power, but available projections are associated with significant uncertainty.
- Many extreme weather events, including heat waves, heavy precipitation events, storms and extreme sea levels, are projected to increase in frequency and/or magnitude as a result of climate change. Without appropriate adaptation measures, direct economic losses to the European energy system could amount to billions of euros per year by the end of the century, with much larger indirect costs.
- Climatic risks to the energy system can be further aggravated by the combination of different climatic hazards or by extreme events that affect several components of the energy system simultaneously.
- Climate change impacts and related adaptation needs differ widely across Europe, depending on climatic and environmental conditions as well as the structure of the regional energy system. Northern Europe experiences both beneficial and adverse impacts on its energy system, whereas southern European regions experience overwhelmingly adverse impacts.
- Most adaptation challenges to the energy system can be addressed by technical and/or management options, but many of these options are associated with additional economic costs and/or environmental impacts.

The evidence for the anthropogenic influence on the global climate system is unequivocal. **Anthropogenic climate change has already led to substantial changes in the averages and extremes of many climate variables.** Further climate change is inevitable, but the magnitude and pace depends on the success of global climate mitigation policies. **Past and future changes in climate are affecting many aspects of human societies, including the energy system** (IPCC, 2013, 2014).

This chapter gives an overview of climate change impacts on the European energy system and related adaptation needs. Section 3.1 gives an overview of important changes in the climate system for which projections are available across Europe. The following sections look at the main impacts on the energy system and associated adaptation options caused by key changes in the climate system (see Figure 3.1), namely increasing temperature (Section 3.2), changing water availability (Section 3.3), changes in extreme climate-related events (Section 3.4) and changes in coastal and marine hazards (Section 3.5). Section 3.6 addresses further climate change impacts on renewable energy sources that do not fit easily in any of the previous sections. Section 3.7 reviews cross-cutting assessments of climate change impacts on the European energy system that complement the information presented in the previous sections. The concluding Section 3.8 presents a summary of adaptation needs, opportunities and options for the European energy system.

Figure 3.1 Important climatic changes and their impacts on the energy system



Changes in ambient temperature

- Total and peak energy demand for heating and cooling
- Efficiency of electricity generation and transmission
- Fossil fuel extraction and transport

Changes in water availability

- Cooling water availability for thermal power plants
- Hydropower potential
- River-borne fuel transport
- Energy demand for water provision

Changes in extreme climate-related events

- Inland flooding
- Wind, hail, ice and snow storms
- Heat waves and forest fires
- Combined and cascading effects

Changes in coastal and marine hazards

- Impacts on coastal infrastructure
- Impacts on maritime infrastructure

Further impacts on renewable energy potential

- Wind power
- Solar power
- Bioenergy
- Supply security from renewable energy sources

Source: EEA.

The high import dependence of the European energy system leaves it vulnerable to supply disruptions in countries from which Europe imports large shares of fuels (see Section 2.1.1). However, the effects of climate change impacts on the production and transport of energy carriers outside Europe on the European energy system are outside the scope of this report.

3.1 Overview of climate change projections for Europe

Table 3.1 gives an overview of the projected changes in several climate and climate-related variables that are particularly relevant from the perspective of the energy system, for each of the European regions identified in Section 1.2. The focus of this table is on the direction of the projected changes (i.e. increase or decrease) rather than their magnitude. Table 3.2 presents the specific information sources underlying Table 3.1. Most of the information is drawn from the EEA report *Climate change, impacts and vulnerability in Europe — an indicator-based report* (EEA, 2017b) and the underlying indicators. Where available, the climate change projections are based on a high emissions or forcing scenario (³) (e.g. representative concentration pathway (RCP) 8.5) for the late 21st century. This choice has been made for technical reasons, because high forcing scenarios typically generate a clearer anthropogenic climate change signal than natural climate variability; it does not imply that such a scenario is considered likely. In some cases,

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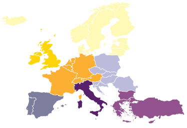
(³) An 'emissions scenario' describes the potential evolution of several GHGs and other radiatively active emissions, whereas a 'forcing scenario' describes the radiative forcing to the climate system resulting from these emissions. The 'representative concentration pathways' (RCPs) adopted by the IPCC Fifth Assessment Report are forcing scenarios rather than emissions scenarios. Although the two terms are not identical, they are closely related. In particular, a high (low) emissions scenario is associated with a high (low) forcing scenario. This report sometimes uses the more intuitive term 'emissions scenario' in connection with RCPs even though the term 'forcing scenario' would be more exact.

projections are based on a different scenario or time horizon depending on data availability. The use of different scenarios prevents a direct comparison of the magnitude of change across climate variables. However, the direction of the projected changes (i.e. significant increase or decrease) shown in Table 3.1 is considered robust to the choice of the particular emissions scenarios and data source. Further information on the magnitude, regional and/or seasonal pattern of changes in the climate variables shown in Table 3.1 and on the underlying projections is available in the respective EEA indicators and the other information sources cited in Table 3.2.

More detailed information on past and projected climate change in Europe is available from the **Climate Data Store (CDS) of the Copernicus Climate Change Service (C3S)** (⁴) and from the **IMPACT2C web atlas** (⁵). Climate information with particular relevance for the energy sector is available in the **CLIM4ENERGY visualisation tool** (⁶) (see also Section 4.2.4).

Table 3.1 **Projected changes in climatic conditions across Europe**



		Northern Europe	British Isles	Central western Europe	Central eastern Europe	Iberian Peninsula	Apennine Peninsula	South-eastern Europe
Ambient temperature	Air temperature	⇧	⇧	⇧	⇧	⇧	⇧	⇧
	River temperature	⇧	⇧	⇧	⇧	⇧	⇧	⇧
Water availability	Annual precipitation	⇧	⇧	⬀	⬀	⇩	⬂	⬂
	Annual river flow	⇧	⇧	⬀	⬀	⇩	⬂	⬂
	Low river flow*	⬀	⇩	⬂	⇔	⇩	⇩	⇩
	Summer soil moisture**	⬀	⬂	⬂	⇔	⇩	⇩	⇩
Extreme climate-related events	Heat waves	⇧	⇧	⇧	⇧	⇧	⇧	⇧
	Inland floods	⇔	⇧	⇧	⇧	⇔	⬀	⬀
	Wind storms	⬀	⬀	⬀	⬀	⬂	⬂	⬂
	Forest fire danger	⇔	⇧	⬀	⇔	⇧	⇧	⇧
Coastal and marine hazards	Relative sea level	⇔	⇧	⇧	⇧	⇧	⇧	⇧
	Storm surges and wave length	⬀	⬀	⬀	⬀	⇔	⇔	⇔

⇧ Increase throughout the region

⇩ Decrease throughout the region

⇔ Inconsistent or limited changes

⬀ Increase in most of the region

⬂ Decrease in most of the region

* A downward arrow indicates a lower streamflow during low flow events, i.e. more severe river flow droughts.

** A downward arrow indicates lower soil moisture (in summer), i.e. more soil water stress.

Source: The data sources are specified in Table 3.2.

(⁴) https://climate.copernicus.eu and https://climate.copernicus.eu/climate-data-store
(⁵) https://www.atlas.impact2c.eu/en
(⁶) http://c4e-visu.ipsl.upmc.fr

Table 3.2 Information sources for Table 3.1

Climate category	Climate indicator	Sources	Notes
Ambient temperature	Air temperature	Jacob et al., 2013; EEA, 2017b, Map 3.4	Based on projected changes in annual air temperature by the late 21st century under the RCP8.5 scenario from EURO-CORDEX simulations.
	River temperature	van Vliet et al., 2013a; EEA, 2017b, section 4.3.5	Available projections for river temperature do not distinguish between European regions, but river temperature generally follows air temperature (Mohseni and Stefan, 1999).
Water availability	Annual precipitation	Jacob et al., 2013; EEA, 2017b, Map 3.8	Based on projected changes in annual precipitation by the late 21st century under the RCP8.5 scenario from EURO-CORDEX simulations. Reductions in precipitation during summer are projected even for some regions where annual water availability is projected to increase or remain constant.
	Annual river flow	Bisselink et al., 2018, Figure 20	Based on projected changes in average streamflow by the late 21st century under the RCP8.5 scenario as calculated by the Lisflood model.
	Low river flow	EEA, 2017b, Map 4.12, updated based on personal communication with Luc Feyen (JRC)	Based on projected changes in the 10-year river water deficit by the late 21st century for the RCP8.5 scenario as calculated by the Lisflood model. The river water deficit is defined as the cumulative discharge below a certain threshold (in this case the fifth percentile of daily river flow in the baseline period).
	Summer soil moisture	Bisselink et al., 2018, Figure 41	Based on the projected change in root soil moisture stress in summer for a global warming of 2 °C as calculated by the Lisflood model. (This model simulation has not been performed for the RCP8.5 scenario.)
Extreme climate-related events	Heat waves	Russo et al., 2014; EEA, 2017b, Map 3.6	Based on projections of changes in 'very extreme' heat waves (see the reference for an exact definition) by the late 21st century under the RCP8.5 scenario from a CMIP5 ensemble of global climate models. Qualitatively consistent results were derived with regional climate models (Smid et al., 2019).
	Inland floods	Alfieri et al., 2015; EEA, 2017b, Map 4.8, updated based on personal communication with Luc Feyen (JRC)	Based on projected changes in peak 100-year river discharge by the late 21st century for the RCP8.5 scenario as calculated by the Lisflood model. Pan-European projections for flash floods are not currently available.
	Wind storms	Donat et al., 2011; EEA, 2017b, Map 3.11	Based on projections of changes in extreme wind speed by the late 21st century under the IPCC SRES A1B scenario from global and regional climate model ensembles, supplemented by other modelling studies. The level of uncertainty for this indicator is larger than that for other indicators.
	Forest fire danger	EEA, 2017b, Map 4.18; updated based on de Rigo et al., 2017, Figure 8	Based on the projected change in average forest fire danger (Canadian Fire Weather Index) by the late 21st century under the RCP8.5 scenario.
Coastal and marine hazards	Relative sea level	IPCC, 2013; EEA, 2017b, Map 4.5	Based on the projected change in relative sea level by the late 21st century for the RCP4.5 scenario based on an ensemble of CMIP5 climate models. Quantitative projections for the Black Sea are not available. The value for 'South-eastern Europe' is therefore based on projections for the eastern Mediterranean only.
	Storm surges and wave height	Vousdoukas et al., 2017, Figure 5; EEA, 2017b, Section 4.2.2	Based on projections of the combined effect of storm surges and waves to 100-year extreme sea levels by 2050 for RCP8.5.

Note: CMIP5, Coupled Model Intercomparison Project.
The term 'climate-related event' comprises extreme weather events (i.e. heat waves and wind storms) as well as hazards that are clearly linked to extreme climate conditions (i.e. inland floods and forest fire danger).

3.2 Impacts of increasing temperature

Increasing temperature can affect all components of the energy system. Arguably, changes in energy demand (i.e. heating and cooling demand) are more important than changes in energy production, conversion and transmission.

3.2.1 Changes in ambient temperature

Air temperature is rising both globally and in Europe. Globally, 17 of the 18 warmest years on record have occurred since 2000. European land temperatures in the most recent decade (2009-2018) were 1.6-1.7 °C above pre-industrial levels. Winter temperatures have increased most in northern Europe, and summer temperatures have increased most in southern Europe. This increasing trend is likely to continue in the future as a result of the emissions already released to the atmosphere; the magnitude of future warming depends on emissions in the coming decades (EEA, 2019c).

In parallel with air temperature, **lake and river temperatures in Europe have increased** by 1-3 °C over the past century. Inland surface waters are projected to continue to warm further, driven by changes in regional air temperature (Dokulil, 2013; EEA, 2016c).

3.2.2 Total energy demand for heating and cooling

Heating and cooling in residential buildings and businesses (excluding process heat in industry) use about one third of the EU's final energy (EC, 2016c). This part of the energy balance is directly sensitive to changes in temperature (and to a lesser degree, in humidity). Heating degree days (HDD) and cooling degree days (CDD) are proxies for the energy required to heat or cool, respectively, a home or a business. HDDs and CDDs are defined relative to a baseline outside temperature below or above which a building is assumed to need heating or cooling.

The EEA indicator on heating and cooling degree days is based on sub-daily temperature data and uses baseline temperatures for HDDs and CDDs of 15.5 °C and 22 °C, respectively (Spinoni et al., 2015; EEA, 2019d). According to this indicator, **the number of population-weighted HDDs in Europe decreased on average** by 6.5 HDDs per year over the period 1981-2017; this corresponds to 0.29 % per year, relative to the average over this period. **The number of population-weighted CDDs increased** by 0.9 CDDs per year over the same period, which corresponds to 1.0 % per year. In absolute terms, the decrease in HDDs is much larger than the increase in CDDs, whereas in relative terms, the increase in CDDs is much larger than the decrease in HDDs, because of lower absolute values (EEA, 2019d).

Map 3.1 shows projected trends for changes in HDDs and CDDs until 2100 for two different global forcing scenarios (RCP8.5 and RCP4.5). Model results for a scenario compatible with the temperature stabilisation target in the Paris Agreement were not available. The geographical patterns reflect the pace of regional warming in different seasons as well as regional heating and cooling demand. As a result, the largest decrease in HDDs is projected for northern Europe where heating demand is highest whereas the largest increase in CDDs is projected for southern Europe, where cooling demand is highest.

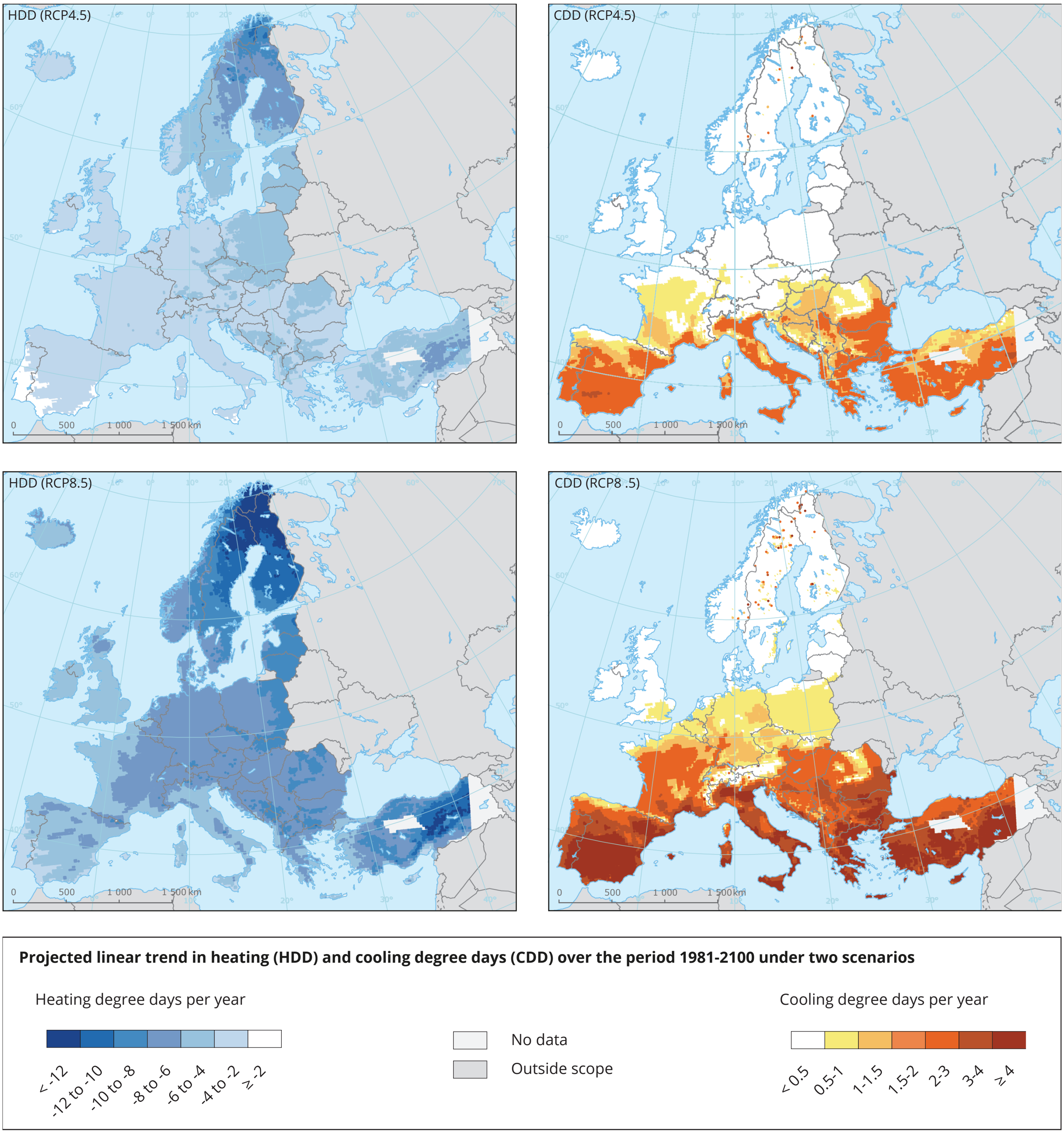
The actual energy demand for heating and cooling depends not only on the HDDs and CDDs at the specific location, but also on a variety of socio-economic and technological factors, such as living space per person, building design and insulation, availability and type of heating and cooling systems, energy prices and income levels, and behavioural aspects. Importantly, heating and cooling systems are often based on different technologies, with different primary energy needs and economic costs (Auffhammer and Mansur, 2014; Buceti, 2015).

Several model-based studies agree that the projected changes in temperature reduce the total energy demand in cold countries in Europe, whereas energy demand in warm countries increases. The studies also agree that increases or decreases in total energy or electricity demand at the national level as a result of climate change alone will be below 5 % by the middle of the century (Mima and Criqui, 2015; Damm et al., 2017; Wenz et al., 2017). Although these changes are rather minor, adaptation needs can arise from their combination with changes in socio-economic characteristics (e.g. increased availability of cooling systems) and from changes in peak energy demand (see Map 3.1).

3.2.3 Peak electricity demand for cooling

Climate change affects not only overall energy demand but also peak demand. **Peak electricity demand for cooling, which is almost exclusively provided by electricity, will increase throughout Europe.** The largest absolute increases in electricity peak demand for cooling have been projected for Italy, Spain and France (Damm et al., 2017). A different study, using wider country coverage and somewhat different assumptions, projects increases in average daily electricity peak load over the 21st century under a high emissions scenario of up to 8 % for some Western

Map 3.1 Projected change in heating and cooling degree days



Note: The maps show projected changes in HDDs (left column) and CDDs (right column) over the period 1981-2100 for two emission scenarios: RCP4.5 (medium emissions, top row) and RCP8.5 (high emissions, bottom row). The maps are based on the ensemble mean of 11 bias-adjusted EURO-CORDEX simulations. Changes are expressed as linear trends per year.

Sources: EEA (2019); Spinoni et al. (2018).

Balkan countries, with somewhat lower values for EEA member countries (Wenz et al., 2017).

The main adaptation challenge relates to the stability of electricity networks during heat waves when an increased peak electricity demand for cooling may coincide with limited cooling water supply for thermal power generation. In countries and regions where air conditioning is common, network stability during heat waves needs to be considered in the planning and management of electricity production and distribution infrastructure. The stability of the electricity supply during heat waves can be increased by strict efficiency standards for cooling equipment, which limit the demand peak; increased transmission capacity, including international linkages; sufficient backup capacity; and shifts to power sources with low water use, in particular solar photovoltaics (PV). Cooling needs can also be reduced through improved building design, such as insulation, orientation and sun protection for windows, and through cooling technologies that do not use electricity, such as heat-driven absorption cooling and the direct utilisation of cooling water where available. A recent review highlights assessments of the costs and benefits of adaptation options for cooling as a key knowledge gap (Tröltzsch et al., 2018).

3.2.4 Efficiency of electricity generation and transmission

Increasing temperatures, including extreme heat, are also affecting electricity generation and transmission. They lead to efficiency losses of thermal power plants (i.e. fossil fuel, biomass and nuclear power plants). The loss in power output is estimated to be around 0.5 % per degree (Cronin et al., 2018). These losses can be reduced by pre-cooling the air used in combustion, but this also consumes energy.

The rated capacity of power lines and transformers can be reduced during heat waves. Studies in the United States have estimated the reduction in transmission capacity of power lines at about 1.5 % per degree of summer warming (Sathaye et al., 2013). This decrease can threaten the security of the electricity supply in warm regions if it coincides with peaks in electricity demand for cooling during heat waves. Adaptation measures include installing conductors with hotter operating limits, the use of 'low-sag' conductor material in transmission lines or increasing the overall transmission capacity of power lines (see the case study in Section 4.5.5).

3.2.5 Fossil fuel extraction and transport

The largest impacts of a warming climate on fossil fuel extraction and transport in Europe are expected for the Arctic region. This region is already experiencing very high temperature increases, and this trend is expected to continue (Huang et al., 2017). As a result of this warming, previously inaccessible fossil energy resources may become accessible. If these resources are exploited, this may lead to positive impacts on the local economy. It could also increase energy security if these fuels replace fuels from geopolitically unstable regions. However, such developments can have significant negative impacts on the regional environment, which is characterised by fragile and already changing ecosystems. Furthermore, increased production and use of fossil fuel resources in the Arctic would counteract climate change mitigation efforts (EEA, 2017g). Currently, fossil fuel extraction in the (European and non-European) Arctic is limited. Several planned projects have been halted or cancelled because of excessive cost, unknown human and environmental risks, significant stakeholder opposition and regulatory challenges (Koch, 2015; Schaps, 2015).

Energy infrastructure in the (European and non-European) Arctic is affected by degrading permafrost. This could result in damage to existing gas and oil pipelines and subsequent disruptions to the energy supply (Forzieri et al., 2018; Hjort et al., 2018).

3.3 Impacts of changing water availability

Climate change is affecting water availability, and there are large variations across European regions. These changes, combined with increases in water temperature, can have substantial impacts on different forms of power production; they can also affect energy demand, for example through increased energy needs for desalination or irrigation.

3.3.1 Changes in water availability

Climate change is projected to intensify the hydrological cycle in general and to change precipitation patterns across Europe. The most relevant hydrological variables from the perspective of the energy system are annual river flow and river flow droughts (for thermal power plants and hydropower plants) and soil water availability (for bioenergy production). These variables are driven by the combined effect of changes in precipitation patterns, temperature and the physiological responses of plants to increasing atmospheric CO_2 concentrations.

Past and projected changes in precipitation show marked differences across Europe. Northern Europe has generally become wetter in recent decades (up to 70 mm per decade), **whereas southern Europe has generally become drier** (up to 90 mm per decade). This trend is projected to continue in the future but with marked seasonal differences. The strongest decrease is projected for southern Europe in the summer (EEA, 2017d).

Projected changes in annual river flow show a pattern similar to that for annual precipitation. Decreasing river flows are projected for southern European countries (particularly Cyprus, Greece, Italy, Malta, Portugal, Spain, and Turkey) and increasing flows for northern European countries (EEA, 2016a; Bisselink et al., 2018).

Droughts can be distinguished into meteorological, soil moisture (or agricultural), hydrological (including river flow) and socio-economic droughts. **The severity and frequency of meteorological and hydrological droughts has increased in parts of Europe, particularly south-western and central Europe.** Available studies project large increases in the frequency, duration and severity of meteorological and river flow droughts in most of Europe over the 21st century, except for northern European regions (EEA, 2019f; Bisselink et al., 2018).

Changes in summer soil moisture follow a pattern similar to that of changes in river flow droughts. **Decreases in summer soil moisture (i.e. increases in soil moisture stress) are projected for most European regions, except for northern and north-eastern Europe.** Summer soil moisture is projected to decrease in some regions where annual precipitation is projected to increase, such as north-western Europe (EEA, 2016b; Bisselink et al., 2018).

3.3.2 Cooling water availability for thermal power plants

Most thermal power plants (i.e. fossil fuel, biomass and nuclear power plants) are reliant on large quantities of water for cooling. Depending on the specific cooling technology, cooling water is either discharged to a water body at higher temperature or evaporated in cooling towers. Thermal power plants cooled with freshwater are vulnerable both to reductions in cooling water availability and to increases in its temperature. These hazards, individually or in combination, can lead to partial or complete shutdowns of power plants. Shutdowns can occur even if the amount of streamflow is still sufficient for cooling purposes, because the water temperature of the river into which the cooling water is discharged must not exceed a threshold temperature established to protect its ecosystems. For example, during the heat waves in 2003, 2006, 2009 and 2018, numerous nuclear reactors in France and other countries were temporarily shut down because of cooling water shortages and/or to prevent temperature exceedances in rivers (Paskal, 2009; Dubus, 2010; Rübbelke and Vögele, 2011; Reuters, 2018). Furthermore, increased water temperature causes efficiency losses in power production and associated output losses. The combined summer heat wave and drought of 2003 is estimated to have reduced thermoelectric power utilisation rates in Europe by about 5 % (van Vliet et al., 2016a).

Several studies have used coupled climate-energy-water models to assess the impacts of future climate change on electricity production in Europe. They have estimated that **climate change could decrease the usable water capacity of thermoelectric power plants in Europe by more than 15 %** in some cases by the middle of the century and would increase mean annual wholesale prices for electricity for most European countries (van Vliet et al., 2012, 2013b, 2016b). However, there are large differences depending on the region, the season and the specific cooling technology applied.

Adaptation options for thermal power plants in water-stressed regions include technological changes such as closed cooling and dry cooling systems. However, dry cooling is more costly and could result in efficiency losses in the order of 10 % (Murrant et al., 2015; van Vliet et al., 2016c). Alternatively, condensing power plants could be converted to combined heat and power plants that use the excess heat (e.g. in district heating systems). A more fundamental adaptation option is switching to alternative generation technologies with low water use (e.g. wind and solar PV). Carbon capture and storage (CCS) decreases the efficiency of thermal power plants and increases their cooling water requirements. Therefore, water scarcity may limit the feasibility of CCS as a decarbonisation strategy in regions with cooling water constraints.

A recent study assessed climate change impacts on more than 1 300 thermoelectric power plants and more than 800 water basins throughout Europe. The study found that climate change would increase the number of basins under water stress and that the majority of vulnerable basins in Europe are located in the Mediterranean region. It also considered four adaptation options to alleviate water stress caused by electricity generation: (1) seawater cooling, (2) dry air cooling, (3) early retirement, and (4) enhanced renewable energy generation. Additional seawater cooling of coastal units was seen as the most effective option for the Mediterranean region by 2030 (Behrens et al., 2017).

3.3.3 Hydropower potential

The dependence of hydropower plants on streamflow for power production makes them sensitive to changes in rainfall, snowfall, and snow and glacier melt (Majone et al., 2016; Bonjean Stanton et al., 2016). In locations where streamflow is expected to decline, this would undermine the productivity of hydropower installations and their cost effectiveness compared with other generation technologies. An increase in streamflow could increase hydropower production, but high river flows can also damage hydropower plants. Run-of-river plants have limited regulating capacity and are thus directly affected by changes in streamflow. Hydropower projects with substantial reservoir storage can be more resilient to short-term changes in river flows, and they can provide additional services, such as flood protection. However, they are affected by increasing temperatures, which increases evaporation from the reservoir. More than half of Europe's hydropower capacity is held in pumping-storage power plants, which buffer not only against fluctuating streamflow but also against fluctuating electricity demand (World Energy Council, 2019).

Hydropower generation in Europe is dominated by the Nordic countries (in particular Norway and Sweden) and the Alpine region. Increased annual or seasonal water availability is projected for most of these regions due to increasing precipitation and possibly increased glacier melt. However, hydropower is also an important energy source in southern European countries that face decreasing water availability, in particular in Turkey (which has considerable expansion plans), but also in Italy, Portugal and Spain.

Glacial retreat caused by rising temperatures can have different impacts on hydropower. In the short to medium term, glacial retreat can increase hydropower production by increasing streamflow (see the case study in Section 4.5.3 for an example). However, excessive water availability can challenge hydropower storage capacities, with the risk of power outages. Glacial retreat may also increase sediment transport, particularly in Alpine regions. This sediment can accumulate in reservoirs and reduce their storage capacity if not managed correctly. It can also flow into water intake channels, thereby reducing water flow, while also causing turbine deterioration (Gaudard and Romerio, 2014; International Hydropower Association, 2019). In the long term, glacial retreat decreases streamflow, in particular in the spring and summer melt season.

3.3.4 River-borne fuel transport

Climate change is projected to increase the risk of river flow droughts in most parts of Europe. **Low water levels in rivers during drought conditions can restrict inland navigation**, including the transport of coal and oil by barge. For example, the unprecedented drought that affected considerable parts of Europe in the spring and summer of 2018 resulted in shipping restrictions on the Rhine, Elbe and Danube rivers. Shallow waters required vessel operators to reduce loads, which led to increased shipping and storage costs and capacity limitations, with subsequent knock-on effects throughout the energy supply chain (Lehane, 2018).

3.3.5 Energy demand for water provision

Increasing temperatures are the main means by which climate change affects energy demand, but changes in water availability can also have an effect. **Decreasing precipitation, increasing evaporation due to increasing temperatures and salt-water intrusion due to rising sea levels, combined with socio-economic changes, could increase the energy demand to provide sufficient water** for agriculture, households and other uses. The EU currently has around 13 % of the global desalination capacity, most of it in Spain (IEA, 2016c). The demand for energy-intensive seawater desalination could increase in water-stressed regions in southern Europe, but quantitative projections are not available. Energy demand may also increase in other elements of the water supply chain.

3.4 Impacts of changes in extreme climate-related events

Extreme weather and climate-related events, such as coastal and inland flooding, storms, hail and lightning, heat waves, droughts and wildfire events, can affect the energy system in many ways (Schaeffer et al., 2012; EC, 2013a; Troccoli, 2018). This section focuses on the direct physical impacts on energy infrastructure. Selected impacts related to heat waves and droughts have already been presented in Sections 3.2 and 3.3.

Many extreme weather events are projected to increase in frequency and/or magnitude as a result of climate change. Without appropriate adaptation, direct economic losses to the European energy system could amount to billions of euros per year by the end of the century (Forzieri et al., 2016, 2018). Overall impacts on society could be much higher than the direct losses, because damage to critical energy infrastructure can result in failures and cascading effects on related and dependent infrastructures, with far-reaching economic and social consequences (Karagiannis et al., 2017; Varianou Mikellidou et al., 2017). An examination of about 40 major blackouts worldwide over the past 40 years found that extreme weather was the most important primary cause. Within this category, storm damage to the transmission system was the cause of half of the failures. Other notable weather effects were drought (loss of cooling water) and ice build-up on transmission lines (Boston, 2013).

3.4.1 *Changes in extreme climate-related events*

Climate change has resulted in changes to many extreme weather events both globally and in Europe (EEA, 2017b, 2017a). Further changes in the frequency, intensity and location of such events are projected throughout Europe (Forzieri et al., 2016). Extreme weather events relevant to the energy system include heat and cold waves, heavy precipitation events, droughts, and wind and hail storms. Such extreme events can cause or aggravate further climate-related hazards, such as pluvial and fluvial floods and forest fire danger.

The intensity of **heavy precipitation** events has generally increased since the 1950s in northern and north-eastern Europe, whereas changes have been more inconsistent in southern and south-western Europe. Heavy precipitation events are projected to become more frequent in most parts of Europe in the future (EEA, 2019e). As a result, **an increase in the occurrence and frequency of inland floods (i.e. pluvial and fluvial floods) is projected for most parts of Europe** (EEA, 2017f). Snow and ice can also affect energy infrastructure, in particular electricity transmission and distribution. However, reliable projections for changes in weather conditions that support snow and ice accumulation are not currently available.

Wind storms have not shown robust long-term trends so far, partly due to limited data availability. Climate change simulations show diverging projections on changes in the number of wind storms across Europe. Most studies agree that the risk of severe winter storms, and possibly of severe autumn storms, will increase for the North Atlantic and northern, north-western and central Europe over the 21st century (EEA, 2017h). Convective storms can be associated with hail and/or lightning, which can affect energy infrastructure. However, Europe-wide projections for changes in hail and/or lightning are not currently available (Yair, 2018).

Heat waves and extreme heat events have become much more frequent and intense in recent decades as a result of climate change. For example, 65 % of Europe has experienced all-time record high temperatures in the period 2003-2010 alone. Further temperature records in Europe were broken in subsequent years. **Extreme summer heat waves, such as those experienced in different parts of Europe in 2003, 2010 and 2018, will become much more common in the future.** For example, at the end of the 21st century, maximum temperatures in 90 % of the summers in southern, central and north-western Europe are projected to be warmer than in any summer in the period 1920-2014 for a high-emission scenario (EEA, 2019c).

The occurrence of **forest fires** is linked to seasonal meteorological conditions, forest management practices, vegetation coverage and various socio-economic factors. These complex interactions make it difficult to assess historical trends and to project future changes in forest fire risk. Fire danger indices such as the Canadian Fire Weather Index and seasonal severity ratings have been developed in order to rate the potential for fires caused by weather conditions. Available projections for these indices suggest that **the duration, severity and area at risk of forest fires will increase in the future in most European regions**, with the possible exception of northern and central eastern Europe (EEA, 2019a; de Rigo et al., 2017). However, projections of forest fire risk are sensitive to the particular index used. For example, although available European-level studies suggest inconsistent changes in forest fire risk in an average summer in northern Europe, national-level studies using different indices suggest an increased forest fire risk in Sweden (Sjökvist et al., 2013).

3.4.2 *Impacts of inland flooding*

Inland floods can have significant impacts on energy infrastructure, such as electric substations, and oil and gas pipelines (Varianou Mikellidou et al., 2017). For example, heavy and prolonged rainfall throughout Portugal in 2000 caused damage to levees and the overtopping of dams. The subsequent flooding threatened to damage a major gas pipeline in the area, leading to the evacuation of more than 100 people (Cruz and Krausmann, 2013). The river-based transport of fuels may also be affected.

Increasing heavy precipitation events are expected to increase river and flash floods in many parts of Europe. Country-level analysis shows that the largest increases in flood hazard, and by association the highest needs for adaptation, are projected for the United Kingdom, France, Italy, Romania, Hungary and Czechia (Rojas et al., 2013). Adaptation options include risk-based planning, changing the operational regimes of reservoirs, dyke construction, component-based flood barriers and relocation (Ebinger and Vergara, 2011).

3.4.3 *Impacts of storms*

Wind, hail, ice and snow storms can adversely affect energy transformation and transport, transmission, distribution and storage infrastructure, resulting in blackouts and costly

repairs (Rübbelke and Vögele, 2011). Power lines and wind turbines are particularly affected. For example, the series of wind storms that struck central western Europe in December 1999 (Storms Lothar and Martin) were estimated to have caused economic losses of EUR 15 billion overall, with associated blackouts affecting 3.4 million people (Groenemeijer, 2015).

Wind storms can affect overhead power lines either directly or indirectly, through vegetation coming into contact with or falling on to them. Ice and snow storms can also have important impacts on electricity transmission infrastructure, leading to costly damage and power outages. Ice can accumulate on power lines and vegetation when freezing rain or fog comes into contact with them at temperatures below freezing. Ice storms are most frequent in northern Europe. The accumulation of wet snow on power lines is promoted by conditions of surface temperatures close to freezing, high humidity and moderate winds, which are often observed over the Mediterranean area (Bonelli et al., 2011; Llasat et al., 2014). The meteorological conditions for snow and ice accretion are complex, and there are currently no reliable long-term projections for these hazards.

The structural enforcement of pylons and improved vegetation management are important elements in making power lines more resilient to storms, but they can be associated with significant costs. Underground cabling is being considered in several European countries as another measure to reduce storm damage, but it is also an expensive adaptation option (see the case study in Section 4.5.6).

Hail storms, which are most frequent in mountainous areas and pre-Alpine regions, can cause costly damage, in particular to solar panels (Ebinger and Vergara, 2011). A trend towards an increasing number of hail storms has been noted in Austria and southern France, and decreasing (but not statistically significant) trends have been noted in parts of eastern Europe. Future projections of hail events are subject to a large degree of uncertainty, but model-based studies show some agreement that hail storm frequency will increase in central Europe (EEA, 2017c).

3.4.4 Impacts of heat waves and forest fires

Heat waves can cause overheating in electric transformers, in particular large power transformers, through reduced structural integrity and chemical reactions. This overheating can result in short circuits, power outages and costly repairs (Gao et al., 2018). The risk of transformers overheating during heat waves is further increased by peaks in electricity demand in regions where air conditioning is common.

Heat waves combined with droughts can lead to further adverse impacts on the energy system. They can decrease water levels in storage hydropower plants, thereby reducing their generation and storage capacity. They can also increase the risk of forest fires. On the one hand, forest fires can damage energy infrastructure, in particular wooden power poles. On the other hand, electricity transmission infrastructure is an important ignition cause of forest fires (Camia et al., 2013). Box 3.1 presents a recent example from outside Europe with catastrophic human, social and economic consequences, including for a large electric utility.

3.4.5 Combined and cascading effects

The combination of different climatic hazards can aggravate the risks to the energy system. For example, both droughts and heat waves are projected to increase in southern Europe. The simultaneous occurrence of these hazards can limit the energy supply and transmission in hot, water-scarce regions while increasing peak electricity demand for cooling. In extreme cases, this combination of hazards may lead to blackouts, with knock-on effects on other sectors that depend on a stable electricity supply. Another dangerous combination of hazards is river flooding plus a storm surge, which can multiply flooding risks in coastal regions, including risks to the energy infrastructure.

Box 3.1 Energy infrastructure creating fatal risks to public safety

California suffered from unprecedented wildfires in 2017 and in 2018 due to extremely warm, dry and windy conditions. Many of the fires in 2017 were found to have been caused by electric power and distribution lines, conductors and power poles owned by Pacific Gas and Electric Company (PG&E), which sparked fires as a result of coming into contact with vegetation, sagging or other failures (CAL Fire, 2018a, 2018b). It is suspected that the 2018 Camp Fire, the deadliest and most destructive wildfire in California's history, was also caused by a faulty PG&E transmission tower (Gafni, 2018). Facing USD 7 billion in claims arising from the Camp Fire, PG&E, the largest energy utility company in the United States, had to file for bankruptcy in January 2019 (Tsang, 2019).

Box 3.2 Examples of widespread power outages resulting from damage to transmission and distribution networks

A large power outage took place in **Italy and Switzerland in September 2003**. The primary cause was a tree flashover that led to the tripping of an electricity transmission line connecting Switzerland and Italy, which was exacerbated by inadequate responses in the immediate aftermath of the event. The load rescheduling led to flashovers and the subsequent tripping of other highly loaded lines connecting Switzerland and Italy. The resulting decrease in tension and frequency caused an almost immediate chain-reaction of power plant shutdowns and cascading failures along the Italian transmission network, which also affected the interconnections with Slovenia and Austria. Power failures lasted from 90 minutes in north-west Italy to 19 hours in Sicily. They affected about 56 million people in Switzerland and Italy, to whom about 180 GWh of electricity failed to be delivered. The economic costs of this blackout have been estimated at EUR 1.2 billion (Walker et al., 2014).

The triggering event for this systemic failure could have been avoided by proper maintenance of transmission lines and control of the foliage surrounding transmission lines in Switzerland. Further analysis of the events highlighted that the network operator in Italy did not act fast enough to reduce the grid capacity being used for pumped storage, which could have eased the burden on transmission lines from increased electricity imports from France. This case highlights that assessing the risks and vulnerabilities of a system, and following through on necessary maintenance measures, is integral to preserving its function in times of stress. By taking stock of potential vulnerabilities to the energy system, the damage costs of EUR 1.2 billion could have potentially been avoided (Johnson, 2008; Böttcher, 2016).

Storm Gudrun caused significant destruction in parts of **northern Europe in January 2005**. In Sweden, 30 000 km of distribution lines were damaged, leading to long-lasting power disruptions for around 730 000 customers. In urban areas with underground cabling, power was restored within a few hours, whereas rural areas experienced outages lasting up to 20 days. The Swedish network operators reported losses of around EUR 250 million, but the overall costs of the power interruptions to society were estimated at EUR 3 billion (Gündüz et al., 2017).

Extreme events can also affect two or more components of the energy system simultaneously. The risk of cascading impacts and system failure is particularly high in the case of power outages, because electric power is central to many other components of the energy system as well as to society at large. Box 3.2 provides two examples of cascading impacts from damage to transmission lines.

3.5 Impacts of changes in coastal and marine hazards

3.5.1 Changes in coastal and marine hazards

Changes in mean and extreme sea levels, storm surges and wave heights affect coastal hazards, such as inundation, flooding and erosion, as well as marine hazards. This is of relevance for coastal and offshore infrastructure.

Global and European **sea levels** have risen significantly since 1900. Global sea level rise has accelerated from earlier rates of 1.2-1.7 mm per year over the 20th century to at least 3 mm per year in recent decades. **Most coastal regions in Europe have experienced an increase in absolute and relative sea levels, which increases the risk of coastal flooding.** Geographic variations occur as a result of local land subsidence or rise, coastal morphology, changes in wind and wave regimes, and other factors. The model simulations used in the IPCC AR5 projected a rise in global sea level over the 21st century that is likely in the range of 28-98 cm (depending on the emissions scenario), but substantially higher values of sea level rise were not ruled out. This range will be revised in the IPCC Special Report *The Ocean and Cryosphere in a Changing Climate*, which is due for publication in September 2019. Several recent model-based studies, expert assessments and national assessments have suggested an upper bound for 21st century global mean sea level rise in the range of 1.5-2.5 m. (EEA, 2019b; Vousdoukas et al., 2017).

Trends towards increased **wave heights** in winter have been recorded in the North Atlantic and are affecting coastlines in western Europe (Castelle et al., 2018). Projections of the **future contribution of climate extremes (storm surges and wave heights) to extreme sea levels** suggest an increase along the North Sea, British and Baltic Sea coasts, mixed changes in the Mediterranean and decreases along the Norwegian coast and the Atlantic coast of the Iberian Peninsula (Vousdoukas et al., 2017).

3.5.2 Impacts on coastal infrastructure

Many types of energy infrastructure, such as oil and gas terminals, refineries, nuclear and fossil fuel power plants, are often placed in close proximity to coastlines or estuaries where they are exposed to various coastal hazards (Cruz and Krausmann, 2013).

A comprehensive assessment of climate change risks to key coastal energy infrastructure was conducted in the ClimateCost project (Brown et al., 2014).

Coastal erosion, which is facilitated by sea level rise, results in the loss of natural barriers to rising waters. Subsequent damage to coastal infrastructure may occur via direct wave impact, loss of infrastructure stability through land loss, or subsequent flooding events (Azevedo de Almeida and Mostafavi, 2016). Adaptation measures to coastal flooding and erosion are closely connected and often involve physical protection measures. As an example, beach profiling, beach feeding and shingle recycling were used to reduce coastal erosion and associated flooding at the Dungeness nuclear power station in the United Kingdom (DECC, 2010).

Storm surges refer to abnormal rises in water levels that are generated by a storm. They are exacerbated by sea level rise and can combine with high-tide events to create extreme sea levels. Coastal energy infrastructure, including ports and refineries related to offshore oil, gas and wind energy production activities, and coastal power plants, are particularly vulnerable to storm surge impacts (Azevedo de Almeida and Mostafavi, 2016). Due to changing water levels and sediment supply, storm surges can also temporarily disrupt the flow of cooling water at coastal power plants.

Tidal dynamics may also be affected as a consequence of sea level rise and storm surges, thereby impacting specific renewable energy sources such as tidal and wave power (Lewis et al., 2017; Pickering et al., 2017).

Adaptation measures against storm surges depend on the specific type of infrastructure. Forecasting and planning around such events is essential to protect vital infrastructure. Physical infrastructure, ecosystem-based solutions for coastal protection and management measures can also increase resilience (see the case study in Section 4.5.4).

3.5.3 Impacts on maritime infrastructure

Maritime storms are a major hazard for offshore energy infrastructure. The increase in wind speeds and wave heights during storm events, which may be exacerbated by sea level rise, makes the operation and maintenance of oil and gas platforms and of wind farms more dangerous and they may require temporary shutdowns (Bell et al., 2017).

Responding to the increasing importance of offshore renewable energy production, the EU has funded several research projects with regard to multi-use offshore platforms (Quevedo et al., 2013; Zanuttigh et al., 2016). There are also innovative efforts under way for offshore system integration that reuse existing sea-based infrastructure (North Sea Energy, 2019).

3.6 Further impacts on renewable energy potential

This section summarises further impacts of climate change on renewable energy sources (RES) that do not fit easily in any of the previous sections.

3.6.1 Wind power potential

Wind power generation is directly dependent on the availability of wind. If the wind speed is below the cut-in speed (around 3 m/s) or above the cut-out speed (around 20-25 m/s), wind turbines are switched off. Between those values, higher wind speeds allow for higher power production. Wind patterns are affected by large-scale circulation changes due to global warming. Past records of wind patterns have shown varied trends throughout European regions.

Many recent studies have assessed changes in future wind energy potential in Europe under climate change (Tobin et al., 2014, 2016; Reyers et al., 2016; Carvalho et al., 2017; Davy et al., 2018; Moemken et al., 2018; Scott Hosking et al., 2018). These studies have used different emissions scenarios, combinations of global and regional climate models, dynamic and statistical downscaling techniques, bias correction methods and wind turbine characteristics. The studies agree that **climate change will have a small effect on the overall wind energy potential in Europe**, with changes at the European level in the range of ±5 % during the 21st century. Several studies suggest an increased potential at the European level in winter, but a decrease in summer and autumn. Local and regional changes in annual wind energy potential can be up to ±15 %, with changes up to ±30 % possible for individual seasons. **Most studies project an increase in the Baltic Sea region and a decrease in southern Europe whereas both increases and decreases have been projected for other regions.**

While there is considerable uncertainty around specific changes in regional wind power potential, the overall magnitude of changes is limited. Therefore, the impacts of climate change should neither undermine nor favour wind energy development in Europe. However, accounting for climate change effects in particular regions may help to optimise wind power development and energy mix plans

(Tobin et al., 2014). For example, the Baltic Sea region might become more attractive for wind power development, in particular offshore wind power. In contrast, a renewable electricity strategy for southern European countries or regions may wish to combine wind power with solar power, and possibly other RES, to improve the stability of the electricity supply throughout the year. Climate services can inform siting decisions by providing more detailed information on current and future wind resources.

3.6.2 Solar power potential

Solar irradiance, which is affected by changes in cloud coverage and atmospheric water vapour content, is the most important determinant of solar energy potential. Available studies have found **both small increases and decreases in solar irradiance and solar PV potential in Europe as a result of climate change** (Jerez et al., 2015; Wild et al., 2015). A recent study has found that global and regional climate models do not agree on the direction of future changes in cloud coverage and insolation in Europe (Bartók et al., 2017). Hence, current projections for changes in solar irradiance in Europe cannot be considered robust. The efficiency of PV cells decreases by about 0.4 percentage points per degree of increase above 25 °C of cell temperature (Kaldellis et al., 2014). Therefore, solar PV is slightly affected by ambient temperature and wind speed, as both can have an impact on cell temperature. In summary, the impacts of climate change should neither undermine nor favour the development of solar PV in Europe.

Concentrated solar power (CSP) is more suitable for delivering baseload electricity than solar PV, because the medium heated by the concentrated rays of the sun can store heat for several hours. In contrast to solar PV, CSP benefits from increasing temperatures. The only available study at the European level **projects significant increases in solar CSP potential in Europe, with increases in the range of 10-20 % for various European countries** by the middle of the century (Wild et al., 2017). However, current CSP technologies require substantial amounts of freshwater for the steam turbines (INEA, 2018). Currently, Spain is the only European country where CSP is deployed commercially. **CSP has commercial potential in several Mediterranean countries, but expansion may be constrained by insufficient water availability.** Adaptation options that reduce water consumption include alternative cooling technologies, such as dry cooling and hybrid cooling (Frisvold and Marquez, 2014).

3.6.3 Bioenergy potential

Climate change can affect bioenergy through changes in the growing season, suitable growing area and productivity of trees and energy crops. However, there is still a great deal of uncertainty about the compound effects of climate change and increasing atmospheric CO_2 conditions on various crops under field conditions. Generally, **climate change allows warm-adapted tree species and warm-season crops to expand northwards in Europe, whereas southern Europe is projected to experience a decline in its suitability for forest growth and decreasing crop yields as a result of increasing heat and water stress** (EEA, 2017b, Sections 4.4 and 5.3). Biomass availability from forestry can be negatively affected by increasing forest fire risk, particularly in southern Europe (de Rigo et al., 2017).

The two available European-level studies assessing climate change impacts on bioenergy crops found a similar geographic pattern. The first study predicted that the potential distribution of temperate oilseeds, cereals, starch crops and solid biofuels will increase in northern Europe due to increasing temperatures and decrease in southern Europe due to increased drought. Bioenergy crop production in Spain is identified as being particularly vulnerable to climate change. Mediterranean oilseeds and solid biofuel crops (e.g. sorghum, Miscanthus), currently restricted to southern Europe, are predicted to extend further north as a result of higher summer temperatures (Tuck et al., 2006). The second study found similar regional results, but it stressed the potential role of technological developments to mitigate the adverse effects of climate change (Cosentino et al., 2012).

Plans for expanding bioenergy production in water-scarce regions, in particular in southern Europe, need to consider the energy-water-land nexus in order to minimise conflicts with other users (see also Section 2.1.5). Some European power producers use biomass imported from outside Europe (see the case study in Section 4.5.4). This approach can be regarded as a measure for increasing the stability of supply. However, it raises important sustainability questions relating to direct and indirect land use changes potentially triggered by bioenergy production and, to a lesser degree, to emissions from long-range transport. Replacing monocultures with mixed forests and reducing clear-cut areas can contribute to climate-resilient forestry.

3.6.4 Supply security from renewable energy sources

One of the main concerns for an energy system based largely on renewable energies is the so-called *dunkelflaute* (i.e. an extended period of time with very low production of wind and solar energy). In regions where electricity use for heating is widespread, this problem is aggravated by demand peaks during cold winter periods (cold *dunkelflaute*). **Reliable projections of changes in the occurrence of a (cold) *dunkelflaute* in Europe are not available.** The dominant driver behind wind power variability in central Europe is the North Atlantic Oscillation (NAO). A negative phase of NAO is linked to the inflow of Arctic air, which can cause extended periods of low wind power generation combined with increased heating needs. One recent study found that the impacts of NAO variability on the wind and solar power generation in Europe are much larger than the mean impacts of climate change up to 2050. This finding suggests that, if the power system is able to cope with weather variability, it can also cope with climate change impacts (Ravestein et al., 2018).

A study on Germany suggests that a reliable and sustainable electricity supply based on RES that can cope with a cold *dunkelflaute* requires a combination of international interconnections and various flexibility options, including pumped storage hydroelectricity, battery storage (e.g. from electric cars), power-to-gas, and flexible gas and biomass power plants (Huneke et al., 2017). A recent International Renewable Energy Agency (IRENA) report provides a wider perspective on solutions for the integration of variable RES into the power system, which comprises innovative technologies, business models, market design and system operation (IRENA, 2019).

3.7 Cross-cutting impact assessments of the European energy system

This section reviews selected relevant assessments of climate change impacts, vulnerabilities and adaptation needs. The focus is on cross-cutting assessments of the European energy system as a whole or of the electricity system. The main purposes are to give an overview of the knowledge base and to guide the interested reader to relevant literature with further details. Selected reports from international organisations and national governments are presented in Chapter 4.

3.7.1 Model-based assessments of climate change impacts on the energy system

Several studies have conducted economic assessments of climate change impacts and adaptation needs in the energy system. The best assessed topics are changes in overall and peak energy demand relating to heating and cooling (see Sections 3.2.2 and 3.2.3).

One of the first comprehensive assessments of the economic impact of climate change on the EU power sector was a study carried out for the Directorate-General for Energy of the European Commission (Rademaekers et al., 2011). This study was used as an input for a Commission staff working document accompanying the EU strategy on adaptation to climate change (EC, 2013a). An updated summary was later published as a journal paper (Lise and van der Laan, 2015). The study used a combination of literature review, stakeholder interviews and quantitative modelling to estimate the investment needs for adaptation in the EU power sector for various technologies, regions and time horizons for two scenarios. Among other things, the study includes assessments of the benefits and costs of a wide range of adaptation measures. The results suggest that the most severe impacts for most power technologies would result from flooding, that sea level rise could have a severe impact on offshore wind and that increasing air temperatures and storms could have a severe impact on grids. The study also found that further investment would be needed in climate change adaptation for hydropower in southern Europe to account for lower average precipitation. The quantitative results rely on wide-ranging assumptions, which are not always traceable. Some key results, such as that overall investment needs are dominated by climate-proofing offshore wind power against the impacts of sea level rise, are not supported by other studies.

Two studies from the **ClimateCost project** used a modified version of the POLES energy model to analyse the impact of climate change on the European energy system (Dowling, 2013; Mima and Criqui, 2015). On the demand side, this study considered changes in heating and cooling demand; on the supply side, it considered changes in the efficiency of thermal power plants and changes in hydropower, wind power and solar PV electricity output. According to these studies, demand-side impacts are larger than supply-side impacts. However, this study considered neither possible change in extreme weather events nor decarbonisation scenarios.

The recently concluded **PESETA III project** of the Joint Research Centre (JRC) assessed the economic impacts of climate change on several European sectors, including energy (Ciscar et al., 2018; Despres and Kitous, 2018). **The overall effect of the projected changes in heating and cooling energy demand on welfare in Europe was**

assessed as beneficial, but there were considerable regional variations.

Another recent JRC study conducted within the **ENHANCE project** combined model-based projections of changes in multiple climatic hazards with sensitivity assessments of different types of critical infrastructure in Europe (EU-28 plus Iceland, Norway and Switzerland) based on an expert survey (Forzieri et al., 2018). The study projects a **sharp rise in the expected annual damage (EAD) from climate extremes on critical infrastructure in Europe, including 10 types of energy infrastructure,** as a result of climate change. The multi-hazard damage for infrastructure in the energy sector is projected to rise up to 15-fold, from a baseline EAD of EUR 0.5 billion per year to one of EUR 1.8 billion (uncertainty range: EUR 1.1-2.8 billion) in the 2020s, EUR 4.2 billion (EUR 3.0-6.7 billion) in the 2050s and EUR 8.2 billion (EUR 5.0-10.7 billion) per year in the 2080s, respectively. These damages, and the resulting adaptation needs, are dominated by the impacts of droughts and heat waves, in particular in southern Europe, whereas the overall role of floods is projected to decrease. The wider societal and economic impacts of potential blackouts triggered by floods and storms were not considered in this study.

A study conducted within the **IMPACT2C project** used a consistent modelling approach to assess the impacts of three levels of global warming (1.5 °C, 2 °C and 3 °C) on wind, solar PV, hydropower and thermoelectric power generation potential in Europe (Tobin et al., 2018). The results suggest that **climate change has adverse impacts on electricity production in most European countries and for most technologies.** Hydropower and thermoelectric generation may decrease by up to 20 %, whereas impacts on solar PV and wind power potential are more limited (and more uncertain). In agreement with other studies, **more severe impacts were generally found in southern Europe than in northern Europe.** For most countries, greater integration of renewables could reduce the vulnerability of power generation to climate change.

3.7.2 Global and European literature reviews

The global and sectoral part of the **Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5)** includes a section on energy, which covers energy demand, energy supply, transport and transmission of energy, and macroeconomic impacts (Arent et al., 2014, Section 10.2). The regional chapter for Europe includes two short subsections: one on energy production, transmission and use and one on bioenergy production (Kovats et al., 2014, Sections 23.3.4 and 23.4.5). This review highlights changes in hydropower potential and in bioenergy production potential, a decrease in the usable capacity of thermal power plants in summer, a decrease in heating energy needs and a large increase in cooling energy needs. All changes show substantial regional disparities, with beneficial impacts dominating in northern Europe and adverse impacts dominating in southern Europe.

A systematic literature review of 50 peer-reviewed publications on the impacts of climate variability and change on electricity supply in Europe was conducted within the **BASE project** (Bonjean Stanton et al., 2016). This review study points to robust negative impacts of climate change on thermal electricity generation throughout Europe. Impacts on renewable electricity generation show strong regional variation, and the available evidence is considered patchier.

A recent review study has critically reviewed the global academic literature on the impacts of climate change on the energy system, with a focus on supply-side impacts (Cronin et al., 2018). Almost half of the reviewed studies had a focus on Europe. Of these 57 studies, 17 addressed wind energy, 12 thermoelectric power plants, 10 hydropower, 8 bioenergy, 6 solar power, 3 wave energy and 1 transmission and pipelines. The study also reviewed how the impacts of climate change on the energy system are reflected in current integrated assessment models of climate change, and it identified research gaps. Two earlier reviews of the global literature had a more balanced coverage of energy supply and demand (Schaeffer et al., 2012; Chandramowli and Felder, 2014).

The **EEA report *Climate change, impacts and vulnerability in Europe*** included a dedicated section on energy (EEA, 2017b, Section 5.4). This section includes an indicator on HDDs and CDDs and a review of studies on changes in future energy demand, on changes in electricity production and on impacts on energy infrastructure. The EEA report presents a more recent and more comprehensive review of the relevant literature for Europe compared with the IPCC AR5, but the overall findings are consistent.

Another recent literature review was conducted within the **EU-CIRCLE project**, with a focus on climate change impacts on critical infrastructure in the energy sector (Varianou Mikellidou et al., 2017). Out of the 82 reviewed studies, 39 (47 %) focus on the impacts of climate change, 25 (30 %) discuss adaptation and resilience measures, and only 18 (23 %) discuss interdependencies with other sectors. The study also suggests an integrated risk management framework, which comprises three stages: (1) risk assessment; (2) assessment of interdependencies with other sectors; and (3) assessment of adaptation and resilience options.

Table 3.3 **State of knowledge and key gaps for climate change impacts on energy**

Impact/topic	Quantity and quality of information	Key gaps
Supply side		
Hydropower	Good	• Assessment of adaptation options • Relationship between water availability and actual power generation • Effects on overall energy systems
Wind power	Moderate	• Few Europe-wide studies, focus mainly on energy resources and not on energy system impacts
Solar power production	Moderate	• Few Europe-wide studies, focus mainly on energy resources and not on energy system impacts
Thermoelectric power	Good	• Effect on individual plants has been studied, but not yet impact on energy system
Demand side		
Cooling and heating demand	Good	• Limited research on the interaction between extensive (e.g. expansion in air conditioners, change in building characteristics) and intensive margin (e.g. use of electricity conditional on the demand for appliances) • Most analyses focus on the residential sector, with limited research in other sectors (e.g. industry, commercial, agriculture) • Most analyses focus on degree days, limited assessment of other climate indicators including extreme weather events
Policy challenges		
Decarbonising the European economy	Good	• Existing studies have a relatively strong focus on electricity supply, with less detail on industry, heating and demand
Increasing energy security	Moderate	• In terms of the impacts of climate change on energy security of supply, relatively little research on adaptation options
Increasing energy efficiency	Moderate	• Previous model studies have a relatively simple representation of energy efficiency improvements; only recently have model studies focused on the effect of behavioural change • How to support behavioural change is under-researched

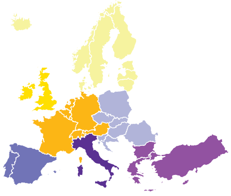
Source: Adapted from Tröltzsch et al. (2018).

A brief review of the recent literature on climate change impacts on the European energy system was conducted for the **EU long-term strategic vision A Clean Planet for All** (EC, 2018q, Section 5.9). The **COACCH project** has reviewed the state of knowledge regarding climate change impacts and adaptation for key economic sectors (Watkiss et al., 2018; Tröltzsch et al., 2018). A summary of its findings is presented in Table 3.3.

3.8 Summary of adaptation needs, opportunities and option

Figure. 3.2 provides an overview of selected climate change impacts for each European region and each energy system component (see Section 1.2 for details). Symbols are used to classify impacts according to the energy source affected (renewable, fossil and other) and their desirability from a societal perspective, considering economic as well as environmental factors (beneficial, adverse and mixed). Similar impacts for 'neighbouring' regions are combined. There are large differences between regions and between system components. **Northern Europe experiences both beneficial and adverse impacts from climate change, whereas southern European regions experience only adverse impacts. The energy transformation component faces only adverse impacts,** whereas all other components are projected to experience beneficial as well as adverse impacts, sometimes

Figure 3.2 Selected climate change impacts on the energy system across Europe



	Primary energy production	Energy transformation	Transportation, transmission, distribution and storage	Energy demand
Northern Europe	+ ◍ **Hydropower:** Increasing potential due to increased streamflow + ◍ **Offshore wind power:** Increasing potential due to increasing wind speeds + ◍ **Biomass energy:** Increasing productivity as growing area moves north ▣ ◐ **Oil and gas extraction:** Increased accessibility of resources in the Arctic − ◍ ◐ **Offshore energy production infrastructure (wind, oil, gas):** Increasing risks from sea level rise, storm surges and coastal erosion	− ◉ ◐ **Coastal energy infrastructure (power plants and refineries):** Increasing risks from sea level rise, storm surges and erosion	▣ ◐ **Oil and gas transport:** New route opportunities for sea transportation in Arctic areas due to melting sea ice − ◐ **Oil and gas transport:** Increasing risks to pipelines in Arctic areas due to degrading permafrost − ◉ **Transmission and distribution grids:** Increasing risk from storms	+ ◉ **Heating and cooling demand:** Reduced net energy demand due to increasing ambient temperature.
British Isles	− ◍ ◐ **Offshore energy production infrastructure (wind, oil, gas):** Increasing risks from sea level rise, storm surges and coastal erosion		− ◉ **Transmission and distribution grids:** Increasing risks from storms and inland floods − ◉ **Electrical susbtations:** Increasing risk from inland floods	
Central western Europe		− ◐ ◉ ◍ **Thermal power plants (fossil, nuclear and biomass):** Reduced output or forced shutdown due to reduced cooling water availability		
Central eastern Europe	Mixed impacts			
Iberian Peninsula	− ◍ **Hydropower:** Decreasing potential due to decreasing streamflow		− ◉ **Transmission and distribution grids:** Reduced capacity due to increasing heatwaves − ◉ **Pumped hydro storage:** Reduced potential due to decreasing water availability and increasing evaporation	− ◉ **Peak electricity demand:** Increasing demand for cooling due to increasing heatwaves − ◉ **Energy demand for desalination:** Increasing demand due to decreasing freshwater availability
Apennine Peninsula	− ◍ **Concentrated solar power:** Constraints for expansion due to water scarcity			
South-eastern Europe	− ◍ **Biomass energy:** Decreasing productivity due to increasing water scarcity			

\+ Predominantly beneficial impacts

− Predominantly adverse impacts

▣ Impacts not classifiable as beneficial nor adverse due to complex economic and environmental effects

◍ Renewable energy sources

◐ Fossil energy sources

◉ Other energy sources and carriers (nuclear, electricity, heating and cooling)

Source: EEA.

in the same region. It should be kept in mind that Figure 3.2 presents only a small selection of climate change impacts on the energy system. Furthermore, the various impacts included are of different magnitude and societal relevance. Therefore, care should be taken when interpreting or comparing impacts affecting different regions or system components.

Table 3.4 complements Figure 3.2 by presenting adaptation options for the key climate change risks identified but without regional differentiation. The table shows that there are technical and/or management options to address most challenges that climate change poses to the energy system. However, many adaptation options are associated with additional economic costs and/or environmental impacts. Given that the appropriateness of a particular adaptation option can vary significantly by the specific item being affected and its location, depending on environmental, technological, regulatory and other factors, there is no 'one-size-fits-all' adaptation solution. More detailed information on adaptation options for the power sector is available in a World Business Council for Sustainable Development report (WBCSD, 2014, Tables 5 to 10).

Table 3.4 Adaptation options for key climate change risks to the energy system

Energy system component	Key climate change risk	Adaptation option
Primary energy production	Challenge of growing energy crops in some regions due to temperature increase and/or reduced water availability	• Adapted agricultural practices (improved irrigation, more drought- and/or pest-resistant crops) • Relocation to different region • Shift to other (renewable) energy source
	Damage to offshore infrastructure (oil, gas, wind) from increased coastal and marine hazards and storms	• Climate proofing of infrastructure • Adapted maintenance and damage response mechanisms • Decommissioning of older offshore oil and gas infrastructures, for which adaptation is not cost-efficient
	Reduced hydropower production from lower streamflow and/or reservoir levels	• Adjusted hydropower management plans • Shift to other (renewable) energy source
	Increased risk of damage to hydropower stations and downstream risks from river flooding	• Adjusted hydropower management plans • Retrofitting of hydropower plants (see the case study in Section 4.5.2)
	Water shortages for CSP technologies	• More water efficient operations (see Box 2.2) • Dry and hybrid cooling technologies • Incorporation of on-site energy storage facilities could compensate for sporadic energy production • Investment in additional personnel for cleaning of mirror components could lead to more efficient water use
	Increased risk of damage to various infrastructures from coastal and inland flooding	• Climate proofing of infrastructure (e.g. siting on higher ground, protective barriers, hardening, covers) (see the case study in Section 4.5.4) • Adapted maintenance and damage response mechanisms • Improved forecasting and planning • Beach profiling and ecosystem-based approaches to reduce coastal erosion and associated flooding • Dyke construction, nature-based solutions (e.g. 'giving room to the river') and component-based flood barriers • Identifying relocation options
	Changes in wind resources	• Placement of new wind farms, supported by climate services

Table 3.4 Adaptation options for key climate change risks to the energy system (cont.)

Energy system component	Key climate change risk	Adaptation option
Energy transformation	Efficiency losses of thermal power plants due to higher temperatures	• Pre-cooling of air used in combustion
	Capacity and/or efficiency decreases in thermal power plants due to reduction of and/or warmer cooling water	• More efficient water cooling systems • Dry cooling technologies • Output losses can be compensated for through less water-intensive (renewable) power generation
	Increased risk of damage from sea level rise, storm surges, flooding and wind storms	• Climate proofing of infrastructure (e.g. siting on higher ground, protective barriers, hardening, covers) (see the case study in Section 4.5.4) • Adapted maintenance and damage response mechanisms • Improved forecasting and planning • Beach profiling to reduce coastal erosion and associated flooding • Dyke construction and component-based flood barriers • Identifying relocation options
Transport, transmission, storage and distribution	Reduced efficiency of transmission and distribution lines (overhead and underground)	• Adjust thermal rating of equipment (see the case study in Section 4.5.5) • Changes to standards of operational assets (see the case study in Section 4.5.5) • Equipment designed for higher temperatures, including high-temperature transformers, high-temperature low-sag conductors and gas insulated lines or substations
	Damage to pipelines and other infrastructure in Arctic and mountain regions from melting ice and permafrost	• Climate proofing of infrastructure (e.g. reinforced foundations, hardening) • Adapted maintenance and damage response mechanisms
	Increased/reduced production potential from pumped storage	• Adjusted hydropower management plans • Adjusted storage
	Increased risk of damages to infrastructure from sea level rise, storm surges, flooding, snow/ice and wind storms	• Climate proofing of infrastructure (e.g. moving cables underground, siting on higher ground, protective barriers, hardening, covers) (see case studies in Section 4.5) • Adapted maintenance and damage response mechanisms (e.g. improved preventive maintenance of vegetation near overhead lines)
Energy demand	Increased peak cooling demand	• Greater use of demand management technologies • Modified building design for improved cooling • Efficiency standards for cooling devices • Early warning systems to alter consumer behaviour
	Higher energy demand in water-scarce regions (for desalination) and low-lying regions (pumping)	• Increased energy generation capacity, favouring low water demand technologies (e.g. solar, wind) • Adapting existing flood control infrastructure to enable energy generation

Source: EEA, based primarily on IEA (2016b) and Ecofys (2017).

4 Building a climate-resilient energy system

Key messages

- There are both synergies and trade-offs between climate change adaptation, mitigation and wider sustainability objectives. The important connections between energy policy and other policy areas call for a comprehensive policy approach that considers multiple societal and policy objectives jointly.
- Businesses are key actors in the design and implementation of resilience-building measures in the energy system. Governments can facilitate such actions through a variety of measures, including policies and regulation, information and services, resilience of state-owned assets, and mobilising financial resources.
- Market actors in the energy system face a number of barriers that may impede the implementation of effective adaptation policies. Well-designed European and national policies can play a key role in overcoming these barriers.
- Key EU climate and energy policies and strategies promote the mainstreaming of climate change adaptation into energy policies. The recent evaluation concluded that the EU Strategy for adaptation to climate change has triggered adaptation actions in many areas. The development of the Energy Union provides an important opportunity for further integrating climate change adaptation in European and national energy planning. The EU also supports building climate resilience in the energy system by requiring climate-proofing of major new energy infrastructure, funding relevant research and innovation projects, and developing climate services for the energy sector as part of the Copernicus services.
- Almost all European countries have concluded a national climate change impact, vulnerability or risk assessment that covers the energy sector. Most countries also include energy as a relevant sector in their national adaptation strategies and/or plans. However, available government documents provide only limited evidence for the implementation of adaptation actions in the energy sector.
- Individual countries are facilitating adaptation in the energy system by providing guidelines for vulnerability assessment and resilience planning, through support for the development of weather and climate services, and through reporting obligations for infrastructure providers.
- Many energy utilities and network providers are already adapting their activities to observed and projected impacts of climate change. Case studies in this chapter include improved flood risk and water management by hydropower producers, strengthening the biomass supply chain, and increasing the climate resilience of power lines. Some of these activities have been triggered or facilitated by government policies and regulation.
- Various international governmental and sectoral organisations are supporting climate change adaptation by providing guidance, developing information sharing platforms, facilitating communities of practice and acting as catalysts for the development of relevant services.

Many different actors and actions are needed to ensure that the European energy system is adapted to changing climatic conditions and resilient to climatic hazards, now and in the future. This chapter discusses key adaptation types and actors, analyses barriers to action as well as approaches to overcome them, reviews the relevant EU policy context, and presents the relevant activities of European institutions and organisations, countries and other relevant actors.

4.1 Adaptation types, actors and barriers

4.1.1 Types of adaptation actions

The typology of adaptation actions used in this report combines elements of adaptation typologies developed by international organisations (see Table 4.1). Adaptation actions are first grouped into **building adaptive capacity** and **delivering adaptation actions.** The first category is further divided into **information and knowledge**, and **policies and framework** actions, and the second category into **management** and **physical** actions. Physical adaptation actions comprise both 'grey' and 'green' actions, as distinguished in a generic EEA typology (see Table 4.1 for a description). 'Green' options can play an important role in reducing risks from climate-related hazards while achieving various co-benefits (EEA, 2017a; OECD, 2018). However, two recent reviews of adaptation options in EU energy policy have identified hardly any 'green' options, which suggests that they have a limited role in strengthening the resilience of the energy system (Capriolo, 2016, section 3.2.5; Ecofys, 2017).

4.1.2 Adaptation actors

Many different stakeholders can potentially play a role for climate change adaptation in the European energy system. **Figure 4.1 provides a mapping of key stakeholders across the four components of the energy system** (see Section 1.2), distinguishing 'key influencers' and 'key actors'. The specific roles of these stakeholders, including the division between public and private actors, differs across European countries reflecting different national energy models (Dallamaggiore et al., 2016; IEA, 2016b; Russel et al., 2018).

Key actors are accountable for one or several activities in the energy system, depending on the regulatory framework and the level of vertical integration in the energy sector. The key actors and their roles are:

- **Primary energy extractors** extract fossil or nuclear fuels.
- **Producers and generators** produce the power, refined fuels, heat and cold for final use. This may include producers that also operate energy storage facilities, such as pumped hydro plants;
- **Transmission system operators (TSOs)** and **distribution system operators (DSOs)** operate the national, regional and local grids, pipelines and networks for distributing power, fuel

Table 4.1 Typologies of climate change adaptation actions

Source	Category	Sub-category	Description
EEA (this report)	Building adaptive capacity	Information and knowledge	Collecting and monitoring data, providing climate services, risk assessments, producing guidelines and other measures that facilitate targeted adaptation
		Policies and frameworks	Actions taken by public actors, such as legislation, regulation and standards, which provide obligations, incentives or funding for adaptation actions by organisations or the wider public
	Delivering adaptation actions	Management	Modifying management procedures of relevant public and private actors (such as infrastructure providers)
		Physical	Technological or engineering solutions such as siting, building or strengthening of assets; ecosystem-based approaches (where relevant) are also included
World Bank (Ebinger and Vergara, 2011)	Building adaptive capacity		Collecting and monitoring data, research and awareness raising in order to facilitate the improvement of knowledge systems, improving the capacities of local institutions, forming of partnerships, and supporting public governance
	Delivering adaptation actions		Preventing or reducing risks, sharing responsibility for losses or risks, or creating opportunities
IEA (IEA, 2016b)	Technological and structural measures		Enhancing asset resilience through implementing technological measures to mitigate damage/ reduce losses, or by taking out structural reinforcements or adjustments
	Management and siting measures		Modifying management procedures, placing structures in areas deemed less prone to climate change risks
EEA (EEA, 2013)	Grey actions		Technological or engineering solutions such as building or strengthening of assets
	Green actions		Ecosystem-based approaches that use the services of nature to improve resilience
	Soft actions		Managerial, legal and policy approaches to alter behaviour and governance

and/or heat to consumers. They can also be involved in energy storage. TSOs and DSOs (whether public or private) have a key role in implementing physical adaptation actions.

- **Consumers** influence overall energy demand through their consumption patterns, including those resulting from climate change. Consumers can also have a role in the market, which is important when costs of adaptation measures taken by the energy sector are passed on;

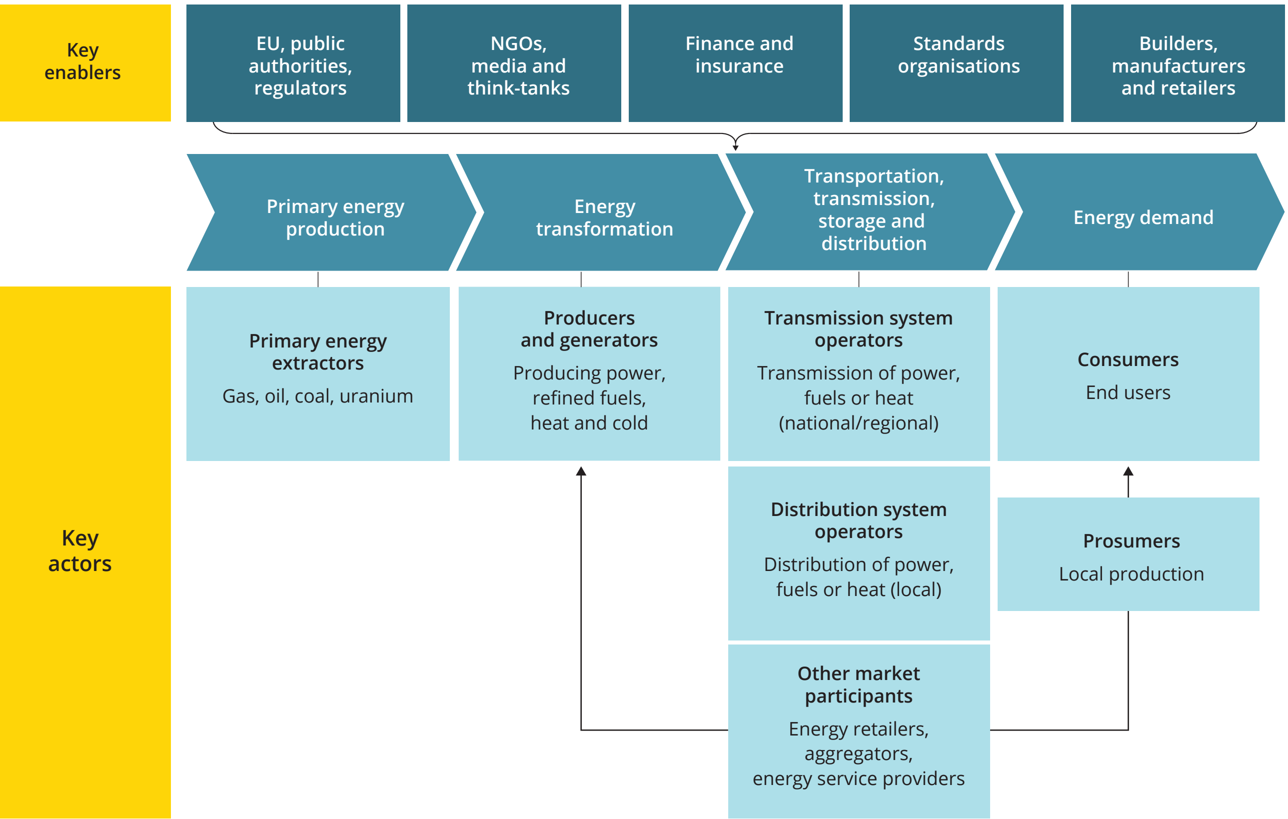
- **Prosumers** are actors that both produce and consume electricity (e.g. a home fitted with PV panels that supplies power to the grid during the day and consumes power from the grid in the evening). Prosumers represent an increasingly important role in achieving the energy transition, but an efficient integration into the European energy system as a whole is lacking (Sajn, 2016; EC, 2017d).

- **Other market participants**, such as retailers and aggregators, play an important role in the energy system by bridging between producers, TSOs and DSOs, and consumers and prosumers.

Key enablers are stakeholders outside the 'classical' energy sector who influence the operation of the energy system in different ways. The key influencers and their roles are as follows:

- **EU, public authorities (national, regional and local government) and regulators** are responsible for setting the policy and market frameworks for the European energy system. Among others, regulators can also have the crucial role of determining who pays for resilience building. The public sector also takes a role in fostering innovation in the energy sector, for example through making funding available for research, development and innovation.

Figure 4.1 Energy system stakeholders



Sources: EEA, based on Dallamaggiore et al. (2016) and other sources.

- **Research and knowledge institutions** can influence (adaptation in) the energy system through the provision of relevant knowledge, information and ideas. They include academic research institutions, climate service providers and other knowledge providers.

- **Non-governmental organisations (NGOs), media and think-tanks** can influence the energy system through their support of certain narratives, movements and policy positions.

- **Finance and insurance** covers all public and private institutions involved in investing in or insuring the energy sector. They can influence adaptation in the energy system by requiring particular standards or reporting requirements for financing or insuring energy infrastructure.

- **Standards organizations** develop technical standards, including for energy infrastructure. Standards can be voluntary or binding, when they have been adopted by a regulator. Even voluntary standards can have a large influence if they are widely adopted by industry or by finance and insurance institutions.

- **Builders, manufacturers and retailers** have a strong influence on the energy demand of buildings and energy consuming goods. The products and technologies they offer can influence the pace of adoption of new technologies.

4.1.3 Role of governments

Building climate resilience in the energy system inevitably raises the question who is responsible for delivering adaptation actions. The question on the role of the EU, national and subnational governments, and other public authorities is particularly for the energy system relevant where a critical infrastructure is owned by a wide range of organisations, including private actors, public-private partnerships and local utilities. The debate on the role of governments has been interpreted somewhat differently within Europe. For example, the German adaptation strategy states that 'adaptation to climate change in the energy sector is essentially a task for the energy industry itself', entailing that 'federal and Länder authorities may be able to provide assistance, contribute knowledge and set new regulatory trends' (Government of Germany, 2008, p. 33). Other countries (e.g. Denmark and the United Kingdom) assign a stronger role to public authorities for fostering, facilitating and monitoring adaptation by private actors (Russel et al., 2018, Section 6.3).

As a starting point, infrastructure providers have a self-interest in protecting their infrastructure and in providing secure services to their customers. However, some unique characteristics of the energy system need to be considered here. First, essential components of the energy system, such as electricity transmission and distributions networks, are (quasi) monopolistic, i.e. there are no competitive markets. Second, the functioning of the energy system in general, and the electricity system in particular, requires the efficient cooperation of many different infrastructure providers across borders. Hence, an individual actor does not necessarily have the information, or incentives, to manage its infrastructure in a way that ensures the stability of the whole system. Finally, a stable energy supply is essential for almost all aspects of modern life, and supply interruptions can lead to very large costs to society (see Box 4.1 for further information). Considering these factors, academic studies as well as reports by international organisations have concluded that **governments and public authorities have a strong role in ensuring a secure (as well as affordable and sustainable) energy supply.** This includes building climate resilience in the current and future energy system (Schneider, 2014; Cortekar and Groth, 2015; Russel et al., 2018, section 6.3).

Businesses are key actors in the design and implementation of resilience-building measures in the energy sector. Governments can and should facilitate such actions through a variety of measures, including policies, information and services, the resilience of state-owned assets, and mobilising financial resources (see Figure 4.2) (IEA, 2015, 2016b). The influence of public policies on critical infrastructure providers can be distinguished between regulatory policies, which are most suitable for incremental adaptation, and developmental or enabling policies, which foster the experimentation required for transformational adaptation (Russel et al., 2018, Section 6.3). Regulatory approaches can range from facilitating voluntary self-regulation through enforced self-regulation, negotiation and delegation to an agency to command and control (Schneider, 2014). Careful consideration of synergies between existing energy policies and regulations and required adaptation measures can help public authorities to find the most efficient policy approach for mainstreaming adaptation action in key sectoral policies (Capriolo, 2016, Section 3.2.5).

Box 4.1 The societal costs of blackouts

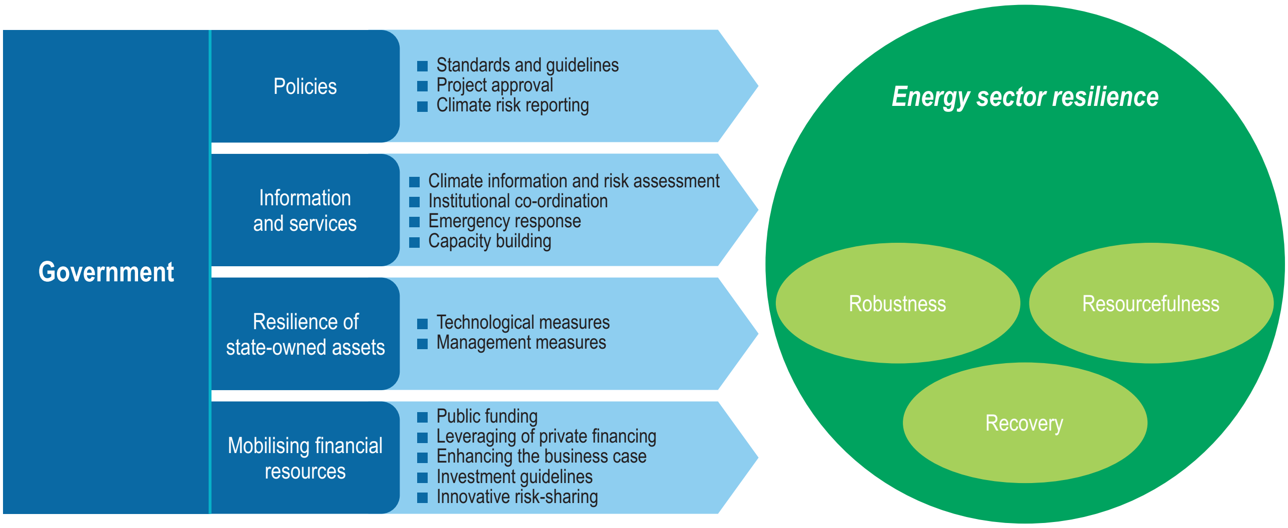
The key argument for the strong role of governments in ensuring a secure energy supply is that the costs of a supply interruption to society are much higher than the costs to the energy sector itself. The societal costs of large-scale blackouts in Europe can easily reach billions of euros (see Box 3.2 for details) (Walker et al., 2014; Küfeoğlu, 2015; Growitsch et al., 2015; Gündüz et al., 2017).

The cost to society of the interruption in the provision of electrical power is commonly measured in terms of value of lost load (VoLL), which can be understood as an economic indicator for the value of electricity security. VoLL estimates are highly sensitive to the characteristics of the outage, in particular the timing and duration, the location, sector/and or social grouping affected, and whether it is planned or unexpected.

A recent literature review of VoLL estimates to households in Europe revealed a wide range, from EUR 0.82 to 66/kWh. Most of these estimates were based on surveys, which used either a willingness-to-pay or willingness-to-accept approach. The same study also applied a production-function approach to develop more consistent VoLL estimates for households. This method led to country estimates of between EUR 3 and 16/kWh, with an EU average of EUR 9/kWh (Shivakumar et al., 2017). Notably, the national VoLL estimates based on the production-function approach are between 25 and 100 times higher than the electricity prices for household consumers, with an EU average of EUR 40/kWh (Eurostat, 2019a).

A study for the British Government used both economic modelling and international case studies to estimate the economic and social costs of electricity shortfalls in the United Kingdom. This study also found very high levels of uncertainty within existing estimates of VoLL in the United Kingdom, and it stressed that VoLL should be regarded as a range rather than a single value (Walker et al., 2014). The study did not conclude with a particular range (nor a central value) for VoLL, but the figures cited within the study are compatible with the range of the EU-wide study cited above.

Figure 4.2 Role of governments in enhancing energy sector resilience



Sources: Reproduced with permission from IEA (2016b). © OECD/IEA Energy, Climate Change and Environment: 2016 Insights, IEA Publishing. Licence: www.iea.org/t&c

Box 4.2 Avoiding maladaptation in the energy system

Avoiding 'maladaptation' is increasingly discussed in the academic literature and in policy discourses around adaptation. However, maladaptation is a complex concept, and many competing definitions exist (Barnett and O'Neill, 2010; Magnan et al., 2016). In a broad sense, maladaptation refers to adaptation strategies or actions with adverse negative effects that are more serious than the climate impacts being avoided, in other words, to 'solutions that are worse than the problem' (Scheraga and Grambsch, 1998). Negative side effects can refer to disproportionate environmental, economic and/or social costs of an action. These side effects may occur further in the future (i.e. actions that reduce short-term climate impacts at the cost of increasing long-term vulnerability); they may also affect other people and locations (e.g. flood protection measures at a river that increase flooding risks downstream) or other sectors and policy objectives (e.g. adaptation measures that vastly increase greenhouse gas emissions).

The IPCC Fifth Assessment Report has devoted a whole section to maladaptation, which includes examples of actions that may be considered maladaptation and discusses causes of as well as experiences with maladaptation (Noble et al., 2014, Section 14.6). Assessments of (mal)adaptation are unavoidably subjective. Hence, the question of whether a particular 'solution is worse than the problem' cannot always be answered unequivocally.

In the context of this report, maladaptation in the energy sector refers to strategies and actions that give excessive priority to an energy adaptation goal over concurring policy goals. An important approach for avoiding maladaptation is to develop clean energy strategies that address climate change mitigation and adaptation perspectives jointly in the context of wider sustainability concerns, considering the interactions of the energy system with water and land systems.

4.1.4 Links between climate change adaptation, mitigation and wider sustainability objectives

From an environmental policy perspective, climate change mitigation is driving the transformation of the European energy system, but this transformation needs to be flanked by adaptation and resilience-building measures. **Climate change adaptation in the energy system aims to ensure that the main goals of the EU Energy Union, namely a secure, sustainable and affordable energy supply, can be achieved in a changing climate.** Furthermore, the energy system may compete for water and (arable) land with other sectors and systems, such as agriculture, forestry and natural ecosystems (for a more detailed discussion of the energy-water-land nexus, see Section 2.1.5).

The important connections between energy and other sectors, systems and policy areas call for a comprehensive policy approach that considers multiple societal and policy objectives jointly. For example, a mitigation strategy that does not consider adaptation needs (e.g. resulting from decreasing water availability) may result in a more expensive or less secure energy supply in the future. At the same time, an adaptation strategy developed in isolation can make it more difficult or costly to achieve mitigation and other policy objectives. Such adaptation measures are often termed 'maladaptation' (see Box 4.2).

There are both synergies and trade-offs between climate change adaptation, mitigation and wider sustainability objectives, as expressed in sectoral EU policies or the 17 Sustainable Development Goals of the 2030 UN Agenda for Sustainable Development (UN, 2015). For example, measures to improve energy efficiency typically have mitigation as well as adaptation benefits, because reduced energy demand reduces not only greenhouse gas (GHG) emissions but also the overall demand for adaptation measures in the energy system. In contrast, end-of-pipe mitigation technologies, such as carbon capture and storage, typically achieve mitigation objectives while increasing adaptation and wider sustainability challenges, because they increase primary energy demand and potential conflicts around scarce water and land resources. Finally, some adaptation policies in the energy sector can increase the mitigation challenge. For example, dry cooling can reduce the water need of a fossil fuel power plant by more than 90 % compared with wet cooling (Macknick et al., 2012), but it decreases its thermal efficiency, thereby leading to higher costs, higher GHG emissions and sustainability challenges in the upstream fuel chain. **Table 4.2 shows selected mitigation measures with co-benefits or potential trade-offs with adaptation.**

Trade-offs between different policy objectives, such as climate change mitigation and adaptation, cannot be avoided. However, **policymakers and planners need to consider such trade-offs carefully in order to develop a mix of measures that achieves various policy objectives simultaneously**, without undue adverse side effects. The choice of particular energy technologies needs to reflect the local climatic, environmental and other conditions. For example, a renewable energy source with high water requirements can be appropriate in a region with abundant water, but it could make adaptation excessively difficult in a water-constrained region where further decreases in water availability are projected. The **International Resource Panel** has

Table 4.2 Synergies and trade-offs between mitigation and adaptation in the energy system

Mitigation measures with co-benefits for adaptation	Mitigation measures with potential trade-off with adaptation
Wind and solar PV: lower water use than thermal generation	Inappropriate expansion of biofuels: could exacerbate competition for land and water with agriculture and biodiversity conservation
Thermal insulation of buildings: reduces energy demand and improves thermal comfort	Hydropower expansion: could increase the complexity of managing water resources
Distributed renewable power generation supported by good interconnectivity: reduces disruption of outages	Carbon capture and sequestration: increases cooling water consumption
Energy storage: supports intermittent renewable energy sources and provides back-up during demand peaks	Nuclear power: risk of outages during heat waves and droughts

Source: Adapted from EC (2018q).

recently published two thorough reviews of the wider environmental and resource implications of low-carbon energy technologies and of demand-side technologies for reducing energy demand (UNEP, 2016, 2017). These reports provide valuable information for developing low-carbon strategies in a wider sustainability context.

Recent EU policies place a strong focus on the mainstreaming of climate change mitigation and adaption in EU and national planning and reporting processes (see Section 4.2). It is important that European countries follow up when developing their national energy strategies and plans. The brief analysis of national activities in this report (see Section 4.3) suggests that many European countries are still in an early phase of addressing the adaptation needs of their rapidly evolving energy systems.

4.1.5 Adaptation barriers — and ways to overcome them

Planning and implementing climate change adaptation policies and measures faces a number of barriers (Moser and Ekstrom, 2010; OECD, 2015). These barriers may impede the implementation of effective and efficient adaptation policies unless targeted efforts are undertaken to overcome them. Some barriers are generic for most adaptation actions (e.g. uncertainty about some aspects of future climate change), whereas others are specific to the energy system or to specific actors in it (e.g. regulatory context). The energy sector remains highly scrutinised by policymakers and regulators given the strategic importance of energy for modern societies. The policy framework, through its strategic, legal and regulatory mechanisms, can help or hinder action on climate change adaptation. **Well-designed policies play a key role in addressing adaptation barriers, as they provide the framework for action by other key actors.**

This section gives a brief overview of important barriers to adaptation in the energy system and presents some generic ideas for addressing these barriers, in particular through public policies. This overview is by no means comprehensive; it is intended primarily to give an indication of how public policies can address some commonly cited challenges for adaptation. Non-state actors such as financing and insurance institutions can also play an important role in facilitating adaptation in the energy system, but their role is not discussed in detail in this report. Many examples of how public and private actors at different levels are successfully building climate resilience in the energy system are presented in the following sections of this chapter.

Awareness of the (potential) need for adaptation

Adaptation requires that a (potential) adaptation actor is aware that past and/or future climate change necessitates doing certain things differently from how they would be done in a stationary climate. Hence, awareness of a potential problem (or opportunity) is a crucial first step in the adaptation policy cycle. Such awareness can come from, among other things, past experiences with managing climate or weather extremes, peer learning, stakeholder and expert meetings, government-led or other climate change impact, vulnerability and risk (CCIV) assessments reports, or a combination thereof.

Governments can help raise awareness of climate change impacts and related adaptation needs among (potential) adaptation actors through targeted CCIV assessment reports, stakeholder events, mandatory climate risk screening in infrastructure planning and approval, reporting requirements for critical infrastructure providers, and other activities.

Understanding the specific climate change impacts and adaptation challenges

Understanding the current and/or future impacts of climate change on a particular strategy, asset, service or activity is another key requirement for targeted and effective adaptation action. Important progress has been made in recent years in understanding past climate change, in projecting future change and in understanding its impacts on ecosystems, economic sectors (including the energy sector) and society as a whole, through substantial efforts by many actors at the international, European, national and subnational levels. As a result, many projections of climate change and its impacts in European regions have become more robust. However, information about local-scale changes in climate characteristics relevant for stakeholders in the energy system is still not readily available.

Many actions mentioned above under 'raising awareness', such as CCIV assessments targeted at the energy system, are also relevant for improving understanding of specific climate change impacts. **The development of user-friendly climate services is an important strategy for closing the gap between information needs and availability** (see Sections 4.2.4 and 4.3.3 for further information). Such climate services should provide quality-controlled downscaled climate projections, preferably translated into variables directly relevant to energy stakeholders. Establishing communities of practice that bring energy system stakeholders together with climate experts are further ways in which governments can address the information challenge.

Decision-making under conditions of uncertainty

All climate change projections are subject to uncertainty. The level of uncertainty depends, among other things, on the climate variable, the spatial resolution and temporal aspects of the specific projection of interest (see Section 3.1). Furthermore, climate change adaptation in the energy system occurs in a dynamic environment that is characterised by rapid, and sometimes unpredictable, changes in the political, regulatory, economic, social and technological context (see Sections 2.2 and 4.2). Although some uncertainties can be reduced by developing and sharing better information (e.g. through targeted climate services), **adaptation actors unavoidably need to take decisions in a context of multiple uncertainties.**

There are many approaches for (adaptation) decision-making under uncertainty, including robust decision-making, real option analysis and the adaptation pathways approach (Haasnoot et al., 2013; Capela Lourenço et al., 2014; Watkiss et al., 2014; OECD, 2015). Their suitability in a specific context depends on various factors, such as the availability of quantitative information, the type and magnitude of uncertainties, the importance of climate change compared with other factors, the potential costs and risks of acting (too) early versus acting (too) late, and the reversibility of specific adaptation actions.

Most stakeholders in the energy system have experience in decision-making under conditions of uncertainty as part of their everyday business. Governments can facilitate the appreciation of the 'novel' uncertainties related to long-term climate change by developing probabilistic climate projections, adaptation platforms (including decision-making tools) and targeted guidance material, possibly in collaboration with sector associations. Communities of practice can help make this knowledge actionable through mutual learning.

Identification and assessment of adaptation options

Targeted adaptation requires adaptation actors to be aware of potential adaptation options and to have some understanding of their costs and benefits (in a broad sense). Adaptation options differ widely depending on the adaptation actor and the challenge they are facing (see Chapter 3). Some of them can be addressed by minor changes in established management practices, others involve technological changes associated with increased costs, and still others require fundamental changes in how and where things are done.

An assessment of adaptation options requires detailed knowledge of the specific decision context, which is often available only to the adaptation actors themselves. Governments can facilitate this assessment through some of the abovementioned measures, including targeted adaptation platforms and communities of practice. Reporting requirements and other ways of information sharing can help actors to learn from each other. Furthermore, targeted research and innovation funding can help develop new adaptation options and services or reduce their costs for individual actors.

Creating a 'business case' for adaptation

Most adaptation actions in the energy system will be implemented by market actors. **Many adaptation options make a 'business case' for individual actors** (i.e. the net present value of their expected benefits outweighs the costs) because they reduce damages or other financial losses, improve revenues, avoid reputation loss or provide other tangible benefits. Hence, a well-informed actor will implement such actions without the need for policy interference. However, some adaptation actions do not make a business case under 'pure' market conditions, because their costs and benefits are unevenly distributed across actors and/or time. One reason is market externalities. For example, the costs of a power blackout to a modern society are much higher than the immediate revenue losses to the power producers or network operators (co-) responsible for it (see Box 4.1). Another reason is system complexity. For example, the stability of the electricity supply in most European countries depends on the cooperation of many actors from different countries. Hence, ensuring or increasing network stability under changing climatic conditions may require coordination among many actors in order to be effective. The importance of efficient coordination has increased as a consequence of the liberalisation of energy markets in Europe, which may mean that energy companies are no longer vertically integrated. Finally, the market discount rates commonly applied in investment decisions may not be compatible with the long asset lifespan of energy infrastructure and the long-term horizon of climate change impacts and adaptation benefits.

Governments and EU institutions play an important role in facilitating adaptation actions that are beneficial from a whole-society perspective in situations in which markets provide insufficient incentives to individual actors to achieve socially desirable levels of adaptation. They can do this through additional market incentives, design standards, regulations at national and/or European level, public-private partnerships and other measures. The design, implementation and control of such policy interventions requires considerable expertise in order to avoid inefficiencies and undesired side effects. For example, regulators with price setting or advisory powers significantly influence investments by energy utilities and the way in which investment costs are passed on to consumers. If the criteria used by regulators to assess the permissible investments and cost transfer do not take climate change adaptation into consideration, any extra costs associated with increasingly resilient investments may not be transferred to consumers, generating a further barrier to such investments (Government of the UK, 2012). Box 4.3 provides additional information on barriers to adaptation, as reported by stakeholders from the United Kingdom. Information asymmetry between

Box 4.3 Barriers to adaptation as reported by British energy stakeholders

Critical infrastructure and service providers in the United Kingdom, including energy regulators, utilities and network operators, have an obligation to report on their climate change risks, adaptation actions and plans, including the barriers encountered (see Section 4.3.3). These reports have allowed for an analysis of barriers to adaptation as perceived by these stakeholders (Government of the UK, 2012, 2017; Street et al., 2016, 2017).

Four barriers to effective adaptation were identified within the current institutional framework in the United Kingdom:

1. the lack of quantified objectives, or clear adaptation policy goals and targets at a national or local level;
2. the 'lack of coordination and unclear goals' due to complex governance arrangements, involving multiple partners, along with a lack of definition of risk ownership, which can lead to 'fragmented, limited or non-existent adaptation actions';
3. the vulnerability of the adaptation delivery mechanism due to the financial fragility of the network of organisations supporting the government and the relevant administrations in delivering adaptation; and
4. the lack of a proper assessment of the 'resources and capacity needed to deliver adaptation at the local level'; in many instances, the 'responsibility for delivering adaptation is increasingly devolved to the local level', but local decision-makers often lack adequate skills and knowledge to tackle the challenges brought about by adaptation to climate change.

The reports on the energy sector converged on a few classes of barriers, which appear to be of general relevance beyond the United Kingdom:

- the limited suitability of the available knowledge base in climate change to provide reliable information at the fine level of geographical resolution required to carry out adaptation actions in practice;
- the interdependence with adaption needs in other sectors, particularly in the case of prevention of flooding; and
- the constraints brought about by economic considerations, such as the impacts of the costs of adaptation options on the economic viability of the companies affected, and the uncertainty surrounding the actual magnitude of such costs and hence the actual availability of funds needed to cover them.

private actors in the energy sector and policymakers developing the adaptation policy framework can be a challenge for efficient and effective market regulation.

4.2 European Union policies and actions

European energy policy and climate change adaptation policy have largely been developed separately. Recently, **considerable efforts have taken place to mainstream climate change adaptation into EU sectoral policies, including energy policy** (Capriolo, 2016; EC, 2018i, Annex XI). This section gives an overview of EU policies and actions that are relevant to adaptation in the energy system. Euratom policies, including guidelines on the safety of nuclear power plants, are not considered here, because they fall outside the scope of this report (see Section 1.2).

4.2.1 European Union adaptation strategy and related activities

European adaptation policy is driven by a mix of EU and national policy and strategies. The EU strategy on adaptation to climate change, adopted in 2013, forms the backbone of adaptation activity in the EU (EC, 2013b). It has three objectives and eight key actions, which are shown in Table 4.3. The EU adaptation strategy includes several supporting documents. Among them, the Commission staff working document on adapting infrastructure to climate change (EC, 2013a) includes a section with a specific focus on the energy transmission and distribution grid.

The EU adaptation strategy has been evaluated recently against the five 'better regulation' criteria by measuring progress for each of its eight actions (EC, 2018v, 2018h, 2018i). This evaluation may lead to a revision of the strategy in the future. The overview below summarises selected findings from the evaluation of the EU adaptation strategy that are relevant for the energy system. For further information, see EC (2018i, Sections 4 and 7).

Action 1 of the EU adaptation strategy concerns the adoption of comprehensive adaptation strategies by all Member States. The Commission has provided guidelines to support Member States in formulating their adaptation strategies. The Commission has also developed an 'adaptation preparedness scoreboard' with key indicators measuring Member States' readiness levels, which was applied in the evaluation of the EU adaptation strategy (EC, 2018h, 2018i, Annex IX). **According to this scoreboard, only nine Member States are actively promoting adaptation in the energy sector.** Further information on national adaptation action is provided in Section 4.3.

Action 2 has triggered substantial funding for climate change adaptation through LIFE projects. However, none of these projects addresses the energy sector, which is outside the scope of the LIFE programme.

Table 4.3 Objectives and actions of the EU Adaptation Strategy

Objectives	Actions
1. **Promoting action by Member States**	1: Encourage all Member States to adopt comprehensive adaptation strategies 2: Provide LIFE programme funding to support capacity building and step up adaptation action in Europe 3: Introduce adaptation in the Covenant of Mayors framework
2. **Promoting better informed decision-making**	4: Bridge the knowledge gap 5: Further develop Climate-ADAPT as the 'one-stop shop' for adaptation information in Europe
3. **Promoting adaptation in key vulnerable sectors**	6: Facilitate the climate proofing of the common agricultural policy, the cohesion policy and the common fisheries policy 7: Ensure more resilient infrastructure 8: Promote insurance and other financial products for resilient investment and business decisions.

Note: Climate-ADAPT, the European Climate Adaptation Platform.

Source: Adapted from EC (2018q).

Action 3 addresses the Covenant of Mayors for Climate and Energy. By April 2018, 1 076 Covenant signatories from 25 EU Member States, covering around 60 million inhabitants, had committed to conducting vulnerability and risk assessments and to developing, implementing and reporting on adaptation plans (Covenant of Mayors Office, 2015). Across the EU, around 40 % of cities with more than 150 000 inhabitants are estimated to have adopted adaptation plans to protect citizens from climate impacts (EC, 2018v; Reckien et al., 2018). However, there is no systematic information available on the extent to which cities are addressing energy in their adaptation plans.

Action 4 addresses EU research funding and how this is targeted. It has sought to better identify the adaptation knowledge gaps and then to adjust the programming of EU research funding, especially Horizon 2020, to address these gaps. It has also promoted EU-wide vulnerability assessments through the Joint Research Centre. Ultimately, this action is expected to improve adaptation actions, including in the energy system. **The Commission has recently published a policy booklet presenting a selection of its research, science and innovation projects on climate change adaptation** (EC, 2018e). Further details on this topic with a focus on the energy system are provided in Section 4.2.4; selected results are presented in Section 3.7.

Action 5 focuses on the development of the European Climate Adaptation Platform, Climate-ADAPT ([7]), a knowledge platform for sharing key adaptation-relevant information and best practice examples (EEA/EC, 2019). Climate-ADAPT was relaunched in March 2019 with new functionalities and additional information. Information on Climate-ADAPT is relevant for the energy sector as well. **The case studies presented in Section 4.5 of this report are all published in more detail on Climate-ADAPT.**

Action 6 includes the major structural funds in the EU, the European Regional Development Fund (ERDF) and the Cohesion Fund (CF). Mainstreaming of climate change considerations can have relevant impacts on these projects, including those linked to the energy sector. Within such funding, major projects must integrate climate change adaptation considerations throughout the preparatory and implementation stages. The guidelines for the individual programmes focus on the methodological approach to vulnerability and risk assessment for major projects, something that is also relevant for energy sector infrastructure. **A report on climate change and major projects outlines climate change-related requirements and guidance for major projects in the 2014-2020 programming period with relevance for the energy sector** (EC, 2016a).

Action 7 is based on the development of technical standards, strategic guidelines, mandatory climate risk assessments and climate services targeted to the energy, transport and buildings sectors. Appropriate technical standards can assist infrastructure providers in alleviating the adverse impacts of climate change on the operational, financial, environmental and social performance of their infrastructure. This can be achieved by ensuring that infrastructure is climate resilient and has sufficient safety margins. Standards related to climate-sensitive infrastructure should be periodically revised in order to trace the development of climate change. **The European standardisation organisation, CEN, and the European electrotechnical standardisation organisation, CENELEC, have an EU mandate to review existing infrastructure standards with adaptation relevance, including in the energy sector** (see Box 4.4 for further information). According to current Commission proposals, a wider range of EU-funded infrastructure investments needs to be climate proof during the 2021-2027 EU budget period (EC, 2018v, footnote 51).

Action 8 has seen some progress in the insurance and broader financial sector. Institutional investors, including insurers, may finance investments in the energy sector. They typically focus on re-financing, acquisitions and secondary market activities, essentially taking on established projects from project developers (IRENA, 2018a). They have an important interest in ensuring that the investments they acquire are climate resilient. Action 8 resulted in setting up a high-level expert group on sustainable finance (with EEA participation), the findings of which are at the heart of a **Commission action plan on sustainable finance** (EC, 2017e, 2018p). These activities aim to redirect private sector investment towards climate change mitigation and adaptation, and resilience (EC, 2018v, footnotes 62 and 63). Further information on this topic is available in Section 4.2.3.

Box 4.4 CEN and CENELEC adapting European standards to climate change

CEN and **CENELEC** are responsible for numerous product and service standards in the EU. They have taken up a mandate under Action 7 of the EU adaptation strategy to integrate climate change adaptation in technical standards (CEN-CENELEC, 2018). This work is coordinated by the CEN-CENELEC Adaptation to Climate Change Co-ordination Group.

CEN-CENELEC have published a guide for addressing climate change adaptation in standards (CEN-CENELEC, 2016). This guide provides a checklist and decision tree to ensure that standards develop and enhance climate resilience. CEN-CENELEC are also reviewing and revising infrastructure-related standards. In the first phase of the work, the European standards were screened for potential adaptation relevance. The preliminary work programme includes a list of 14 priority standards, 13 of which already exist but need to be revised and one of which is new and needs to be developed. Within the energy sector, three standards relating to gas infrastructure (EN 16348, EN 15399) and to installation and equipment for liquefied natural gas (EN 1473) were identified for revision. In the current second phase (2018-2022), Technical Committees are revising these standards to 'represent best practice in adaptation and resilience building' (CEN-CENELEC, 2018). A tailored guidance document is under development to support further consideration of adaptation to climate change in the future revision of existing standards, as well as development of new ones. A key challenge for the revision of standards is the availability of relevant and reliable climate information, both for the recent past and the future. The Copernicus Climate Change Service (see Section 4.2.4) is seen as a key resource in this respect.

CEN and CENELEC are also in charge of developing and revising standards for electric appliances under the Ecodesign Directive and the Energy Labelling Regulation, which mandate minimum energy efficiency standards and energy performance labels for appliances (EU, 2009, 2017). Of particular relevance in the context of this report are efficiency standards for air conditioners, the use of which is projected to grow rapidly as a result of climate change and socio-economic developments. These standards have been adapted recently by CEN (EU, 2012; EC, 2018g).

4.2.2 EU energy policy and related activities

EU energy policy aims to achieve three key goals (or 'pillars'): secure energy supplies (security of supply pillar), affordable prices (competitiveness pillar), and sustainable energy production and use (environment pillar) (EC, 2018n). Climate policies have played an increasingly important role in European energy policy-making since the 1992 Rio Earth Summit (EC, 2015a). The 2020 climate and energy package adopted in 2009 placed climate change mitigation at the centre of EU energy policy. With the European Union firmly committed to the goals of the 2015 Paris Agreement, climate change will remain an important policy focus. **Adaptation considerations are increasingly mainstreamed in EU energy policy.**

The Energy Union

The **European Energy Union Strategy** launched in 2015 is a comprehensive European energy policy package that addresses the three pillars of EU energy policy by focussing on five dimensions (EC, 2018c):

1. **Security, solidarity and trust** (security of supply pillar): diversifying Europe's sources of energy and ensuring energy security through solidarity and cooperation between EU countries.

2. **A fully integrated internal energy market** (competitiveness pillar): enabling energy to flow freely through the EU, through adequate infrastructure and without technical or regulatory barriers.

3. **Energy efficiency and moderation of demand** (environment/security of supply pillar): improved energy efficiency will reduce dependence on energy imports, lower emissions, and drive jobs and growth.

4. **Decarbonising the economy** (environment pillar): the EU is committed to the Paris Agreement and to retaining its leadership in the area of renewable energy.

5. **Research, innovation and competitiveness** (competitiveness pillar): supporting breakthroughs in low-carbon and clean energy technologies by prioritising research and innovation to drive the energy transition and improve competitiveness.

The Energy Union Strategy includes quantitative mitigation targets for 2030, building on the climate and energy package targets for 2030 (see Section 2.2.1 for details) (EC, 2016f).

The development of the Energy Union is supported by several pieces of legislation, some of which are described below.

The Regulation on the governance of the Energy Union and climate action (EU, 2018d), adopted in December 2018, includes several requirements for

EU Member States that are relevant in the context of this report. First, Member States need to develop integrated **national energy and climate plans (NECPs)** with a 10-year perspective that are aligned with the five dimensions of the Energy Union (Article 3). Climate adaptation and resilience is addressed in two dimensions therein: horizontal 'adaptation goals' are required under the 'Decarbonisation' dimension, whereas objectives relating to 'resilience of regional and national energy systems' need to be included under the 'Energy Security' dimension.

The NECPs will be implemented in the 2021-2030 period, with an update to be provided in 2024 and subsequent plans to be developed every 10 years. Member States were requested to submit their draft plans to the Commission by 31 December 2018. The Commission will provide recommendations by 30 June 2019 (EU, 2018d). In the light of these recommendations, Member States are to submit final plans by 31 December 2019. Starting in March 2023, Member States are required to provide **progress reports** on the implementation of the NECPs every 2 years (Article 17). All Member States had submitted their draft NECPs by late February 2019 (EC, 2019c). The timing of this EEA report did not enable the analysis of the coverage of adaptation and climate resilience in the draft NECPS, most of which are available only in the relevant national languages.

Member States are also required to develop **long-term strategies** (LTSs) with a perspective of at least 30 years, which shall include 'adaptation policies and measures' (Article 15). The first LTSs need to be submitted by 1 January 2020, and subsequent LTSs by 1 January 2029 and every 10 years thereafter (with updates every 5 years if necessary). Finally, Member States need to **report on national adaptation actions** every 2 years, starting in March 2021 (Article 19).

An **Energy Union Committee** (related to the integrated national energy and climate progress reports) and a **Climate Change Committee** (related to the report on national adaptation actions) assist the Commission in implementing this regulation by defining the structure and format of the respective reporting templates. Further assistance will be provided by the EEA in relation to all reporting streams.

Another relevant piece of legislation is a (revised) **Regulation on risk-preparedness in the electricity sector**, which is close to adoption (EU, 2018c). The forthcoming Regulation includes four sets of measures:

1. common rules on how to prevent and prepare for electricity crises to ensure cross-border cooperation;

2. common rules for managing crisis situations;

3. common methods to assess risks relating to the security of supply;

4. a common framework for the better evaluation and monitoring security of the electricity supply.

In particular, this Regulation will require the **European Network of Transmission System Operators for Electricity (ENTSO-E)** to develop regional crisis scenarios for each region. These scenarios inform the development of national risk-preparedness plans that need to be developed by all Member States. The Regulation also includes an assistance mechanism between Member States. The agreed text repeatedly highlights 'extreme weather' or 'severe weather' as the trigger for electricity crisis situations. Interestingly, it does not explicitly refer to 'climate change', even though the impact assessment for this Regulation mentions climate change as a driver for increasing crisis situations (EC, 2016i). It is recommended that the development of crisis scenarios under this Regulation also considers unprecedented extreme weather events that may occur in a changing climate, such as extreme heat waves and droughts, possibly in combination.

The European Union energy strategies for 2020 and 2030 and the long-term strategy

The EU has developed various strategies to meet the EU Energy Union targets for 2020, 2030 and 2050 (see Section 2.2.2 for details). **The 2020 energy strategy** established five priorities (EC, 2010a):

1. Improve energy efficiency by accelerating investment into efficient buildings, products and transport.

2. Build a pan-European energy market via infrastructural development to integrate all EU countries to the internal market.

3. Protect consumer rights and achieve high safety standards in the energy sector.

4. Implement the Strategic Energy Technology Plan to accelerate low-carbon technology development and deployment.

5. Safeguard external supplies of energy.

The 2020 climate and energy package set the targets of reducing GHG emissions by 20 % compared with 1990, ensuring a share of 20 % renewable energy sources in energy consumption and achieving a 20 % reduction in total primary energy consumption by 2020 (compared with a business-as-usual baseline).

For the period after 2020, **the 2030 climate and energy framework** (EC, 2018a) puts forward new indicators for the competitiveness and security of the energy system, a new governance system based on national plans, and a new framework committed to the quantitative targets (see Section 2.2.2).

The Commission's proposal for a long-term EU GHG emission reduction strategy, 'A Clean Planet for All' (EC, 2018j), puts forward a vision to steer the EU economy and society towards a (largely) CO_2 emissions-free future in 2050. It also emphasises the importance of adaptation and climate resilience.

Other European Union policies with adaptation relevance for the energy system

In 2013, the Commission adopted the first list of **projects of common interest** on trans-European energy infrastructure (EC, 2010b, 2018m). Infrastructure priorities focus on strategic planning, establishing a comprehensive infrastructure development scenario, smart grids, defining clear and transparent priority project criteria, ensuring fast and transparent permit-granting procedures and improving EU financial instruments. The Innovation and Networks Executive Agency was established in 2014 to implement the Trans-European Transport Network (TEN-T) programme, while also implementing the Connecting Europe Facility (EC, 2018d, 2018n).

The Trans-European Networks for Energy (TEN-E) (EC, 2018w) strategy is focused on improving the links between the energy infrastructure of the EU across Member States. The mandatory TEN-E guidelines adopted in 2013 (EU, 2013b) place a stronger emphasis on climate mitigation than adaptation. However, they prescribe that Member States should give due consideration in infrastructure planning to improving resilience and preventing technical failures induced by climate change (EC, 2018i, footnote 83).

The **Commission proposal for a regulation on the internal market for electricity** is currently proceeding through the legislative process as part of the implementation of the Clean Energy package (EC, 2016j; European Parliament, 2018). Its key objectives include the redesign of the electricity market to enable greater consumer empowerment to manage their own energy consumption, participate on an equal footing to other market participants and support demand-side solutions, storage and the integration of digitisation and innovative technologies. These last flexibilities could potentially help to achieve important benefits in terms of energy system resilience.

The **Directive on the protection of critical infrastructure** (EU, 2008a) has established the European Programme for Critical Infrastructure Protection (EPCIP). One of the pillars of the EPCIP is the Critical Infrastructure Warning Information Network, which offers accredited members of the EU's critical infrastructure protection community the opportunity to exchange and discuss information related to a range of hazards and to share good practices across multiple sectors, particularly in the case of transboundary networks. This Directive is currently being evaluated (EC, 2018o).

The **Offshore Safety Directive** (EU, 2013a) requires that risk assessments concerning offshore oil and gas activities must consider environmental hazards, including the impacts of climate change. Similarly, the **Directive on maritime spatial planning** (EU, 2014a) requires that the development of energy sectors at sea improves resilience to climate change impacts.

Activities of European energy regulators

The **Agency for the Cooperation of Energy Regulators** (ACER), an EU agency, was created in 2011 to further complete the internal energy market for both electricity and natural gas. As an independent European structure that fosters cooperation among European energy regulators, ACER ensures that market integration and the harmonisation of regulatory frameworks are achieved within the framework of the EU's energy policy objectives (see Section 4.2.2). With the adoption of the Clean Energy package, ACER will have an enhanced role in the energy market and in the area of security of supply. ACER's roles will be adapted to the new challenges the electricity sector is facing, for example in the context of increased regional cooperation.

The **Council of European Union Energy Regulators** (CEER) is the voice of Europe's national energy regulatory authorities. It gives regulators a platform to share their experiences and develop regulatory capacities and best practices through workshops, events and training. Recent workshops organised by CEER have addressed, among other things, the security of supply, the integration of renewable energy into the energy system, digitisation and battery storage. Climate change has been an important topic in previous annual reports, albeit from a mitigation rather than adaptation perspective (CEER, 2012). CEER works very closely with, supports and complements the work of ACER.

The European Nuclear Safety Regulators Group (ENSREG) is an independent expert advisory group comprising senior officials from nuclear safety, radioactive waste safety and radiation protection regulatory authorities. ENSREG aims to provide improvements to nuclear safety and radioactive waste management through cooperation with Member States and improving transparency on nuclear waste and safety issues and by providing advice to the Commission. ENSREG also assists in the development of safety margins for nuclear power plants and the review of the response of nuclear facilities to extreme situations (including climate change-related events such as flooding) through the 'EU stress test' (ENSREG, 2012). Through the development of guidelines, measures to increase the robustness of plants have been implemented. These include the deployment of climate information services, the hardening of equipment, the improvement of severe accident management processes, and specific training measures.

Activities of European network operators

ENTSO-E represents electricity transmission system operators throughout Europe. It publishes annual mid-term adequacy forecasts (ENTSO-E, 2017) as well as 10-year network development plans (TYNDPs) (ENTSO-E, 2018). Resource adequacy reports seek to analyse the balance between available energy generation and load levels through modelling tools. ENTSO-E modelling now explicitly incorporates current and projected climate data, enabling an examination of climate change impacts on the adequacy of the EU electricity transmission system. TYNDPs offer a series of possible energy futures through which to deliver European energy targets, while incorporating projected climate change impacts on energy systems within their modelling. More information on these scenarios is presented in Section 2.2.2. ENTSO-E will have additional responsibilities following the adoption of the (revised) Regulation on risk-preparedness in the electricity sector (EU, 2018c) (see Section 4.2.2).

The European Network of Transmission System Operators – Gas (ENTSO-G) follows very similar processes to ENTSO-E, with which it works closely. ENTSO-G analyses disruption scenarios to the European gas supply and the resilience of the system to such events. The results are taken into account in the TYNDP for natural gas.

4.2.3 Adaptation finance

The EU does not have a specific fund for climate change adaptation. Instead, the Commission provides funding opportunities for climate change adaptation through existing structures. Furthermore, the Commission supports the reorientation of private capital flows towards sustainable investment, including climate change adaptation.

Mainstreaming adaptation in European Union funding programmes

Substantial mainstreaming of climate change adaptation in funding programmes has taken place in recent years. The EU has agreed that at least 20 % of its budget for 2014-2020 should be spent on climate-related action (EC, 2011a; European Council, 2013). The Commission proposal for the EU budget for 2021-2027 suggests that the share of climate-related spending be increased from 20 % to 25 % across all EU programmes, the equivalent of EUR 320 billion (EC, 2018b).

The key funding structures for climate action in the 2014-2020 EU budget include the LIFE programme (with about EUR 800 million spent on climate projects), Horizon 2020 (with 35 % of its EUR 70 billion budget devoted to climate-related projects), the EU Solidarity Fund (for natural disasters), as well as the five European structural and investment funds (ESIFs) (EC, 2016h):

1. the ERDF;
2. the European Social Fund (ESF);
3. the CF;
4. the European Agricultural Fund for Rural Development;
5. the European Maritime and Fisheries Fund.

The ERDF and the CF have provided funding for energy-related major projects, which are required to incorporate adaptation considerations (see Section 4.2.1). The ESF provides funding predominantly for investing in human capital to improve job prospects. The ESF can contribute to climate change adaptation through training high-, medium- and low-skilled workers, particularly for the refurbishment and retrofitting of buildings for climate resilience (EC, 2015b). The overall allocation of ESIFs towards supporting climate change adaptation is 15 % (and 25.6 % towards climate action in total). Nevertheless, certain measures, such as the protection of energy infrastructure from flooding, have not received sufficient attention (COWI, 2016, 2017).

Climate-related spending is tracked through 'EU climate markers', which are adapted from the 'Rio markers' developed by the Organisation for Economic Co-operation and Development (OECD). Analyses by the Commission indicate that the EU is broadly on track for the 20 % target, but further efforts are needed (EC, 2016d). A report by the European Court of Auditors acknowledged that ambitious work was under way and that the target has led to more, and better focused, climate action in the ERDF and the CF. At the same time, the report stressed the serious risk that the 20 % target will not be met, and that no significant shift towards climate action had yet occurred in some areas. The report also emphasised the methodological weaknesses of the current tracking method, including the failure of tracking mitigation and adaptation spending separately (ECA, 2016). Broadly similar conclusions, and various suggestions for improved climate mainstreaming in the next EU Multiannual Framework (2021-2027), have been reached in a recent study for the Directorate-General (DG) for Climate Action (Forster et al., 2017).

Action plan on sustainable finance

In March 2018, the Commission adopted an action plan on sustainable finance (EC, 2018k). This action plan intends to reorient capital flows towards sustainable investment, in order to achieve sustainable and inclusive growth; manage financial risks stemming from climate change, environmental degradation and social issues; and foster transparency and long-termism in financial and economic activity. Some of the proposed actions are relevant in the context of this report.

The **Directive on disclosure of non-financial information** (EU, 2014b) requires most large companies (including energy companies) to include information on certain social and environmental policies in their annual reports from 2018 onwards. The Commission has published non-binding 'Guidelines on non-financial reporting' that countries may use to provide this information (EC, 2017c). In January 2019, the Technical Expert Group on Sustainable Finance published its Report on climate-related disclosures (EU TEGSF, 2019). This report recommended that climate-related impacts and risks on a company's business model be included in the non-financial reporting. Climate-related risks are distinguished into physical risks (i.e. risks related to the impacts of climate change) and transition risks (i.e. risks related to the transition to a decarbonised economy). Key performance indicators shall be linked to national and international climate-related policies, whereby the EU adaptation strategy is mentioned explicitly. The main target of these annual reports are investors, but this kind of information could also be useful for monitoring progress in addressing adaptation by energy companies. These EU activities are aligned with the global Task Force on Climate-related Financial Disclosures (8). France introduced similar disclosure obligations for financial asset managers and institutional investors under the Energy Transition Law in 2015 (PRI/UNEP FI/UN Global Compact, 2016).

An analysis of companies' responses to the (voluntary) 2017 **Carbon Disclosure Project** questionnaire found that only 5 % of the responding companies used scenario analysis to evaluate their climate-related risks and opportunities but that this percentage is more than 20 % for oil and gas companies and energy utilities (Vailles and Metivier, 2019).

The Commission has also proposed a **Regulation on the establishment of a framework to facilitate sustainable investment** (EC, 2018t). This Regulation would establish the conditions and the framework to gradually create a 'taxonomy' of what can be considered an environmentally sustainable economic activity, with the aim of channelling investments into such activities. 'Climate change adaptation' is one of the five environmental objectives of the proposed regulation (Article 5), and a delegated act establishing its criteria should be developed by December 2019 (Article 7).

Activities of European financing institutions

The **European Investment Bank** (EIB) makes available dedicated adaptation funding and has developed investor guidelines with a focus on climate resilience. Furthermore, the EIB includes requirements for climate change adaptation in its climate strategy, particularly for projects in which climate change vulnerabilities present a high risk (EIB, 2015).

The **European Bank for Reconstruction and Development** (EBRD) is an intergovernmental organisation with a strong representation of EU Member States. The EBRD provides support to several European Neighbourhood countries on a wide breadth of topics, with 'power and energy' being the second largest sector. Targeted investment support for climate change adaptation is provided as part of the sustainable energy initiative, which was recently merged into the green economy transition approach (EBRD, 2018). Climate change risk assessment is a key element of the EBRD investment cycle. EBRD collaborates with many other organisations in order

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(8) https://www.fsb-tcfd.org

to improve climate resilience building by private stakeholders, including by participating in the Working Group on Adaptation to Climate Change (EUFIWACC) (see Section 4.2.4) and collaborating with the International Hydropower Association (see Section 4.4.2).

4.2.4 Developing the knowledge base for adaptation

Research and development projects

Many research and development projects and other programmes are improving the knowledge base for adaptation and resilience building in Europe. The energy sector is regularly included as one of the key sectors in projects related to climate change vulnerability assessment, adaptation planning and resilience building. Selected EU-funded research projects include (see Section 3.7 for some results):

- EU-CIRCLE (9) (a pan-European framework for strengthening critical infrastructure resilience to climate change);
- PESETA III (10) (Projections of economic impacts of climate change in sectors of the EU based on bottom-up analysis);
- RESIN (11) (Climate-resilient cities and infrastructure);
- ToPDAd (12) (Tool-supported policy development for regional adaptation);
- WATERFLEX (13) (Water-related modelling in electric power systems).

An overview of additional EU-funded projects that focus on strengthening the resilience of critical infrastructure in Europe (including, but not limited to, climate resilience) is available on the EU-CIRCLE website (14).

Various EU-funded projects focus on the development of innovative climate-resilient solutions for the renewable energy sector. Examples for concentrated solar power include MinWaterCSP (15) (Minimized water consumption in CSP plants) and WASCOP (16) (Water Saving for Concentrated Solar Power).

Climate change adaptation needs in the energy sector have also been the subject of studies commissioned by the Commission. A study for DG Energy assessed the costs of adaptation to the electricity sector (Rademaekers et al., 2011) (see Section 3.7.1 for further information). A study for DG Climate Action assessed adaptation knowledge in Europe for three infrastructure sectors, including energy (Ecofys, 2017).

Weather and climate services

Weather and climate services can help different actors in the energy system to improve operational and strategic decisions by considering relevant information about climate variability and change over various time scales.

The Copernicus Climate Change Service (C3S) (17) is an important new service and source of relevant climate information for various sectors. C3S aggregates satellite and in situ data to provide services to a wide range of actors in Europe, such as public institutions, private enterprises, scientific organisations and citizens. The data can be utilised to improve the decision-making and planning of climate adaptation measures. C3S provides climate change indicators and visualisation tools tailored for the energy sector through the Sectoral Information System, building on two demonstrator projects: CLIM4ENERGY (18) and European Climatic Energy Mixes (19). Other products offered include the Climate Data Platform, which provides historical climate data, trends, and seasonal and long-term forecasts. These products and services can, for example, support the planning of hydroelectric reservoir placement, assist solar generators to plan for adverse conditions, provide predictive models to assess conditions for grid upgrades, and help predict the potential yield of wind and solar generation sites. C3S is one of the few EU-wide information platforms with specific content and tools relating to the energy system or sector. The most recent Copernicus market report provides many examples of how C3S and other Copernicus services have been used for planning, developing and operating renewable energy technologies (EC, 2019a).

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(9) http://www.eu-circle.eu

(10) https://ec.europa.eu/jrc/en/peseta-iii

(11) http://www.resin-cities.eu

(12) http://www.topdad.eu

(13) https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/water-related-modelling-electric-power-systems-waterflex-exploratory-research-project

(14) http://www.eu-circle.eu/eu-funded-projects

(15) https://www.minwatercsp.eu

(16) http://wascop.eu

(17) https://climate.copernicus.eu

(18) http://clim4energy.climate.copernicus.eu

(19) http://ecem.climate.copernicus.eu

The Commission also supports the development of climate services through co-funding the European Research Area for Climate Services (ERA4CS ([20])) under the Joint Programming Initiative Climate ([21]). ERA4CS is funding many projects related to the development of climate services (for an overview, see JPI Climate, 2017).

EU-funded projects that address the development of weather and climate services with relevance for (parts of) the energy system include:

- CLARA ([22]) (Climate forecast enabled knowledge services);
- CLIM2POWER ([23]) (Translating climate data into power plant operational guidance);
- IMPREX ([24]) (Improving predictions and management of hydrological extremes);
- MARCO ([25]) (Market research for a climate services observatory);
- PUCS ([26]) (Pan-European urban climate services);
- S2S4E ([27]) (Sub-seasonal to seasonal climate forecasting for energy);
- SECLI-FIRM ([28]) (Added value of seasonal climate forecasting for integrated risk assessment);
- WINDSURFER ([29]) (Wind and wave scenarios, uncertainty and climate risk assessments for forestry, energy and reinsurance).

Several of these projects include case studies that demonstrate the value of weather and climate services for various stakeholders from the energy sector.

The recently formed World Energy and Meteorology Council ([30]) aims to facilitate progress in understanding the link between climate, weather and energy, and using relevant information (Troccoli et al., 2014, 2018; Troccoli, 2018). Further information on the development of climate services for the energy sector at the national/subnational level and the global level is available in Sections 4.3.3 and 4.4.1, respectively.

Guidelines for risk assessment, adaptation and resilience

Early consideration of climate change requirements in project development cycles facilitates the cost-efficient integration of resilience measures. **Various European institutions and organisations have produced guidelines to facilitate the inclusion of resilience measures in projects seeking EU funding.**

In 2011, the Commission developed guidelines for investors, including for the development of energy projects, with a focus on 'making vulnerable investments climate resilient' (EC, 2011b). Later, the Commission published guidelines for actors seeking funding for major projects (i.e. projects with costs exceeding EUR 50 million) (EC, 2016a). These guidelines give an indication of activities that should be carried out in the development of major projects. Adaptation-relevant activities include implementing vulnerability and risk assessments, considering environment and climate change aspects, factoring in technical aspects during design, implementing adaptation measures and monitoring critical climate hazards. The guidance document explains how to conduct vulnerability and risk assessments by providing a sample method for project managers for making infrastructure climate resilient. The method places particular emphasis on selecting scenarios that incorporate realistic global temperature rises, selecting a timescale for the vulnerability and risk assessment that corresponds to the intended lifespan of the investment, and taking into account significant changes in weather events that could hamper the project.

Eight European financing institutions, including the Commission, the EIB and the EBRD, have created a **working group on adaptation to climate change (EUFIWACC)**. EUFIWACC has developed practical guidance for project managers to incorporate appropriate climate-resilient measures within project development. The guidance gives a list of important points to consider during the scoping, planning and design, analysis of costs and benefits, and the evaluation and monitoring periods of projects. It is intended to be applicable to a diverse array of actors, including those in the energy system (EUFIWACC, 2016).

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(20) http://www.jpi-climate.eu/ERA4CS
(21) http://www.jpi-climate.eu
(22) http://www.clara-project.eu
(23) https://clim2power.com
(24) http://imprex.eu
(25) http://marco-h2020.eu
(26) http://climate-fit.city
(27) https://www.s2s4e.eu
(28) http://www.secli-firm.eu
(29) https://sites.google.com/view/windsurfer
(30) http://www.wemcouncil.org

The Commission published or updated several other EU guidance documents for planning infrastructure projects to include consideration of climate risk in the planning phase, including a cost-benefit analysis (EC, 2018i, footnote 86). The Commission has also supported the development of guidelines for adaptation in the energy system in developing countries through the EU Energy Initiative Partnership Dialogue Facility (Stuart, 2017).

Various EU-funded research and development projects have addressed climate change vulnerability and risk assessment for critical infrastructure, including in the energy system. The RAIN project (31) has assessed the complex interactions between extreme weather events and land-based infrastructure systems, including energy-related infrastructure. The INTACT project (32) has focused on assessing the resilience of European critical infrastructure to extreme weather conditions, on raising awareness among operators of critical infrastructure, and on identifying potential measures to increase resilience. Key project results are available through the INTACT Wiki (33). The STREST project (34) has developed and tested a harmonised approach to stress tests for critical non-nuclear infrastructure against natural hazards, including geophysical events and floods.

Adaptation platforms

Adaptation platforms are web-based portals that provide information relevant for adaptation policymaking and planning to a range of stakeholders. The leading European adaptation platform is **Climate-ADAPT** (35), co-managed by the EEA and the Commission. Many countries have also developed national adaptation platforms (EEA, 2015, 2018i).

4.3 Activities by European countries

National governments play an important role in influencing the development of the energy system and in facilitating adaptation. Among other things, they identify climate-related vulnerabilities and risks, develop national adaptation strategies and plans, provide supporting information and guidance, and establish appropriate policies and frameworks to stimulate practical action. In some cases, they also fund or implement adaptation measures directly. For a more detailed discussion of the role of governments in building climate resilience in the energy system, see Section 4.1.3.

4.3.1 Overview

Table 4.4 gives an overview of the engagement of national governments with respect to climate change adaptation in the energy system, based on a number of published documents. It is important to note that this overview is necessarily incomplete and that a comparison across countries is hampered by differing national circumstances, such as the role of national versus subnational authorities. Despite those caveats, the tabular overview provides some indication of the level of engagement across Europe.

The data sources and assessment approach for each of the columns in Table 4.4 is described below. Further information on the reasoning behind the 'colour coding' for each country is provided in Annex 1. **Updated information on countries' adaptation activities is available in the country profiles on Climate-ADAPT** (36).

1. Availability of national CCIV assessment

CCIV assessments are key components of adaptation policy development. They facilitate the development of national and/or sectoral adaptation strategies and plans by identifying focal areas for action. The assessment here is based on a recent EEA report, which provides an overview of multi-sectoral CCIV assessments in EEA member countries based on a desk review and a country survey (EEA, 2018f) (updated in the case of Poland).

2. Coverage of the energy sector in national CCIV assessments

The assessment here is based primarily on the coverage of the energy sector in multi-sectoral CCIV assessments, in particular those reviewed by the EEA in its report *National climate change vulnerability and risk assessments in Europe*, 2018 (EEA, 2018f) (37). Sectoral CCIV assessments, national communications to the United Nations Framework Convention on Climate Change (UNFCCC) and other documents were also considered where available and relevant.

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(31) http://rain-project.eu
(32) http://intact-project.eu
(33) http://scm.ulster.ac.uk/~scmresearch/intactnew/index.php/INTACT_Wiki
(34) http://www.strest-eu.org
(35) https://climate-adapt.eea.europa.eu
(36) https://climate-adapt.eea.europa.eu/countries-regions/countries
(37) All assessments are available here: https://projects.eionet.europa.eu/2018-eea-report-national-cciv-assessments/library/national-documents

3. National adaptation strategies and/or national adaptation plans adopted

National adaptation strategies (NASs) and national adaptation plans (NAPs) are government documents that help to integrate climate change adaptation considerations into the national decision-making processes. A NAS builds on an on different sectors, policy domains and/or regions. A NAP aims to implement practical measures in order to achieve the objectives established in a NAS. However, the distinction is not always clear-cut given different national circumstances. Information on the status of NASs and NAPs is based on country reporting to the EEA (EEA, 2018g; updated based on Eionet, 2019). For EU Member States, monitoring is obligatory under the Greenhouse gas Monitoring Mechanism Regulation (EU, 2013c) whereas monitoring is voluntary for other EEA member countries. In Table 4.4, green indicates that both a NAS and a NAP are in place; yellow indicates that only a NAS is in place; red indicates that neither a NAS nor a NAP is in place.

4. Coverage of the energy sector in NASs and/or NAPs

The assessment here is based on a brief analysis of the NAP and/or the NAS (see previous column). A NAS or NAP under development was also considered (where applicable). The colour scheme reflects both the type of policy document and the depth of coverage of the energy system. Specifically, green shading requires that significant parts of the energy system are addressed in an adopted NAP (not just a NAS).

5. Adaptation measures implemented in the energy sector

The assessment in these two columns is based on two different documents, which are explained below. In both cases, the colour coding takes into account several factors, including the specificity of a measure (e.g. generic activity versus activity targeted at the energy system), the proximity to implementation (e.g. preparatory activities such as studies and capacity building versus concrete actions such as legal and regulatory requirements or physical measures), the degree of initiative (e.g. participating in a transnational cooperation versus initiating action), and the scope of the activity (e.g. small pilot project versus comprehensive sectoral strategy). The final assessment unavoidably includes some subjective elements.

Adaptation preparedness scoreboard **country fiches** have been developed by the Commission, in consultation with Member States, in order to assess the adaptation preparedness of all EU Member States based on a number of indicators. They have been published together with the evaluation of the EU adaptation strategy (see Section 4.2.1). The assessment here is based on a brief analysis of the country fiches (EC, 2018h). Literature cited in the country fiches was also considered where relevant.

The **UNFCCC** requires parties included in its Annex I to submit national communications (NCs) every 4 years. All EEA member countries are included in Annex I of the UNFCCC, and, therefore, they had to submit their seventh NC by 1 January 2018. Within these communications, parties must show the activities they have undertaken by reporting on GHG emissions, measures taken to mitigate GHG emissions, and measures to counteract adverse effects of climate change. The assessment here was based on a brief analysis of the seventh NCs to the UNFCCC (38).

Table 4.4 shows that all EU Member States and three other EEA member countries have conducted a multi-sectoral national CCIV assessment. **Almost all CCIV assessments have included the energy sector to some degree.** Some countries have conducted specific assessments for the energy sector. Most EEA member countries have adopted a NAS, and about half of them have also adopted a NAP. **Most, but not all, NASs and NAPs include energy as a relevant sector for adaptation.** Only a few countries mention adaptation actions in the energy sector in their country fiches or NCs. The majority of actions reported are preparatory actions, such as capacity building (see Annex 1 for details). Note that adaptation in the energy system may also have been implemented in countries that have not reported such activities.

The evaluation of the EU strategy on adaptation to climate change gives some additional insights into the adaptation needs of the energy sector. The stakeholders involved in the consultation process identified climate proofing of energy infrastructures as the priority area of intervention for adaptation in the energy sector. They have also pointed out that energy is one of the areas in which knowledge gaps persist (EC, 2018i).

A comprehensive review of all NASs and NAPs, many of which are available only in the national language(s), is beyond the scope of this report. However, the following subsections present some examples of how national governments have facilitated adaptation planning and implementation in the electricity system.

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(38) https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/national-communications-and-biennial-reports-annex-i-parties/seventh-national-communications-annex-i

Table 4.4 Coverage of the energy system in key national adaptation documents

Country	Document				
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/or NAP	Adaptation measures implemented in the energy sector	
Austria	🟩	🟩	🟩	🟩	🟨	🟥
Belgium	🟩	🟩	🟩	🟩	🟩	🟩
Bulgaria	🟩	🟨	🟥	🟨	🟥	🟥
Croatia	🟩	🟩	🟥	🟨	🟥	🟥
Cyprus	🟩	🟩	🟩	🟩	🟥	🟥
Czechia	🟩	🟩	🟩	🟩	🟥	🟥
Denmark	🟩	🟩	🟩	🟨	🟥	🟥
Estonia	🟩	🟩	🟩	🟩	🟥	🟥
Finland	🟩	🟩	🟩	🟨	🟨	🟩
France	🟩	🟩	🟩	🟩	🟥	🟥
Germany	🟩	🟩	🟩	🟩	🟩	🟨
Greece	🟩	🟩	🟨	🟨	🟥	🟥
Hungary	🟩	🟩	🟨	🟨	🟥	🟥
Iceland	🟥	🟥	🟥	⬜	⬜	🟥
Ireland	🟩	🟩	🟨	🟨	🟥	🟥
Italy	🟩	🟩	🟨	🟨	🟥	🟥
Latvia	🟩	🟩	🟥	🟥	🟥	🟥
Liechtenstein	🟥	🟨	🟨	🟨	⬜	🟩
Lithuania	🟩	🟩	🟩	🟩	🟥	🟥
Luxembourg	🟩	🟩	🟩	🟩	🟨	🟥
Malta	🟩	🟥	🟨	🟥	🟥	🟥
Netherlands	🟩	🟩	🟩	🟩	🟩	🟩
Norway	🟩	🟩	🟨	🟨	⬜	🟩
Poland	🟩	🟩	🟨	🟨	🟥	🟥
Portugal	🟩	🟩	🟨	🟨	🟨	🟥
Romania	🟩	🟩	🟩	🟩	🟥	🟥
Slovakia	🟩	🟩	🟨	🟨	🟥	🟥
Slovenia	🟩	🟥	🟨	🟥	🟨	🟥
Spain	🟩	🟩	🟩	🟩	🟩	🟥
Sweden	🟩	🟩	🟩	🟨	🟨	🟥
Switzerland	🟩	🟩	🟩	🟩	⬜	🟩
Turkey	🟩	🟨	🟩	🟨	⬜	🟥
United Kingdom	🟩	🟩	🟩	🟩	🟩	🟩

Note: Green, in place/identified; yellow, in progress/partially in place; red, not in place/limited or no action; grey, not applicable.

Source: EEA, based on data from EEA (2018d, 2018c); EEA/EC (2018); UNFCCC (2017); EC (2018h). Further information is available in the main text and in Annex 1.

4.3.2 *Selected climate change risk assessments and adaptation plans*

CCIV assessments are an important element of preparing countries for future climate change; they are also a key input to the development of NASs and NAPs. Such assessments can be initiated and conducted by various actors, including ministries, government agencies, research institutions and others (EEA, 2018f). CCIV assessments covering the energy sector have been prepared by almost all EEA member countries (see Section 4.3.1). This section presents the key features of a few CCIV assessments addressing the energy system, either separately or as part of a multi-sectoral assessment. These examples cannot be representative of all European countries, but they provide an insight into some of the approaches that can be taken and the outcomes of these processes.

Sectoral CCIV assessment for energy in the Netherlands

The Ministry of Infrastructure and Water Management has been appointed to act as the responsible ministry to oversee the development and implementation of the NAS in the Netherlands. The Ministry engages with multiple stakeholders from private, public and semi-public domains in order to implement CCIV studies and identify adaptation strategies. Through this stakeholder engagement, the Dutch Organisation for Applied Scientific Research (TNO) published a report on the risks and opportunities resulting from climate change for Dutch energy infrastructure (Vogel et al., 2014). This study compares the situation (and the progress made) in 2007 (when the first Dutch NAS was published) with the situation in 2014. TNO worked closely with other organisations, such as the Royal Netherlands Meteorological Institute, Knowledge for Climate and the Netherlands Environmental Assessment Agency (PBL). The report identified several climate vulnerabilities that should be addressed, including the negative impacts of extreme heat and droughts on the functioning of power stations due to effects on cooling water; sea level rise and flooding damage to various components of the energy system; limited public awareness of the negative impacts of climate change; and opportunities to design and export adaptation-based products and services. Further work by PBL constructed an energy vulnerability matrix. The matrix highlighted that the highest risks posed by a changing climate were in renewable energy, transmission lines, substations, cooling water and computer systems. The report also discussed cascading impacts of power outages, which are expected to become more significant in the future due to a higher reliance on digitised systems.

Sectoral CCIV assessment for energy in Spain

The Spanish Office of Climate Change (OECC), belonging to the Ministry for the Ecological Transition, is responsible for the planning and implementation of the NAS. In 2015, OECC commissioned a comprehensive assessment of climate change impacts on the Spanish energy sector, which was developed by the Institute for Research in Technology of Comillas University of Madrid (Girardi et al., 2015). On the one hand, the assessment process included the analysis of major climate change trends using the results from regional climate change projections. On the other hand, the assessment quantified the expected impacts of climate change on the Spanish energy system in three main areas: energy sources, energy demand and energy supply. Water is specifically considered, as it is a key resource for energy production and because it strongly affects many parts of the energy system in Spain. The assessment included a section on adaptation options and recommendations, bringing together the results from a literature review at global level and an expert consultation at national level.

Multi-sectoral CCIV assessment covering energy in the United Kingdom

The Department for Environment, Food and Rural Affairs publishes a United Kingdom-wide climate change risk assessment every 5 years under the Climate Change Act 2008. Other governmental organisations must also establish climate change vulnerability assessments and adaptation plans. This assessment yields a set of 'urgency scores' to prioritise adaptation actions and identify research priorities. Energy-relevant research priorities include the implications of projected changes in river flows on nearby pipelines; the risks to energy from high winds, lightning, storms and high waves; and the impacts of low or high river flows on electricity generation (Dawson et al., 2016).

Development of a sectoral adaptation plan for energy in Ireland

The Department of Communications, Climate Action and Environment has completed a climate change action plan for the electricity and gas networks sector in Ireland (Government of Ireland, 2018a). The report implemented a step-by-step approach to assess current and potential vulnerabilities, identifying and assessing adaptation options, and monitoring and reviewing adaptation plans. The approach included stakeholder engagement through public consultations during the drafting of the adaptation plan, which were used to inform the finalisation of the plan. Electricity and gas network stakeholder groups were also established to assist in developing the scope and content of the adaptation plan. This approach allowed climate events that affected energy infrastructure and services to be directly identified by stakeholders, in addition to adaptation options to address such vulnerabilities. The key climate impacts for the energy sector in Ireland were identified as flooding, temperature increases, sea level rise and changes in wind energy. The report also identified the key items of infrastructure within the energy sector that are vulnerable to these projected climate impacts. Based on the assessment of vulnerabilities, the study drafted an adaptation implementation plan to set out measures to be taken. The recommended actions predominantly focus on building adaptive capacity through the dissemination of adaptation information, while also delivering physical adaptation actions through 'building on measures already in place', although the nature of these measures is unclear.

4.3.3 Facilitating adaptation by energy system stakeholders

Guidance material for CCIV assessments and resilience planning

Guidelines for CCIV assessments and/or resilience planning can support the development of adaptation policies and actions by guiding readers through the key steps and most relevant issues in a structured manner and by pointing to relevant tools and resources. Several European countries have developed such guidelines that address sectoral departments and agencies, subnational governments and/or non-state actors (EEA, 2018f). Further guidelines have been developed by the Commission (see Section 4.2.4) and by international organisations (see Section 4.4.1).

Most guidance documents provided by national authorities are generic and intended to be applicable across a wide range of sectors. As an exception, a guidance document from the United Kingdom has developed a framework for climate risk assessments of national infrastructure from a systems perspective (Dawson et al., 2018). The framework proposes that infrastructure beyond physical assets is taken account of, incorporating resources that are conveyed by infrastructure (vehicles, data, water, etc.), processes that influence the infrastructure system (regulations, management, protocols, etc.), networks that join locations that demand resources/services (provided by individual physical assets to supply such resources/services) and services that benefit a range of users (heat, mobility, sanitation, etc.). Climate change can directly affect each of the components outlined above; therefore, adaptation measures may be implemented for any of these components. Prior to implementing measures on these components, a systems risk assessment of infrastructure must take place, which requires various steps. These are: (1) analyse climate variables; (2) characterise each infrastructure asset and understand its response to extreme events and changes in climate; (3) analyse the network-wide effects of impacts on components; (4) analyse interactions and interdependencies between infrastructure networks, in addition to cascading impacts; (5) assess the systemic risks that could occur as a result of infrastructure loss, including broader indirect impacts; and (6) implement adaptation measures.

Outside Europe, the United States Department of Energy has produced comprehensive guidelines for resilience planning in the electricity sector, which provide assistance to electricity utilities and other stakeholders in assessing vulnerabilities to climate change and extreme weather and in identifying an appropriate portfolio of resilience solutions. Among other things, these guidelines present a classification of adaptation measures in various parts of the energy system, and they outline a step-by-step approach for calculating the costs of adaptation measures along the energy value chain (US Department of Energy, 2016). The publication of these guidelines was complemented by networking and capacity-building efforts, such as the establishment of the Partnership for Energy Sector Climate Resilience (39) and the State and Regional Energy Risk Assessment Initiative (40).

Weather and climate services

Weather and climate services can provide crucial information for a wide range of stakeholders, including those from the energy sector, for managing short-term climate variability

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(39) https://www.energy.gov/policy/initiatives/partnership-energy-sector-climate-resilience

(40) https://www.energy.gov/ceser/state-and-regional-energy-risk-assessment-initiative

and long-term climate change (EC, 2018f). Several European countries are supporting the development of climate services with a view to facilitating adaptation to climate change. Some of these services specifically address stakeholders in the energy sector, including energy developers, producers, distributors and traders. They are supported in a wide range of activities, including site selection, planning maintenance and construction works, planning energy storage and production capacity, and providing targeted warning services. A comprehensive review of weather and climate services for the energy sector is beyond the scope of this report.

For relevant activities at the EU level, in particular the development of the C3S, see Section 4.2.4. The Global Framework for Climate Services is briefly described in Section 4.4.1.

Reporting obligations for infrastructure providers

In the United Kingdom, the Climate Change Act 2008 introduced reporting obligations on climate change risks. The 'Adaptation Reporting Power' (ARP) invites or requires selected infrastructure providers, including those in the energy sector, to report information on the risks and opportunities of climate change (Government of the UK, 2012; Jude et al., 2017). By doing so, the ARP aims to assist these organisations in taking the required action to adapt to the future impacts of climate change, in addition to raising awareness and building capacity. These reports are then used by public authorities to inform the United Kingdom climate change risk assessment (see Section 4.3.2) and to update the NAP, and by industry stakeholders to further develop their activities.

Under the first round of ARP reporting, the 103 reporting organisations were clustered into nine sectors, four of which were part of the energy system: electricity distributors, electricity generators, electricity transmitters and gas transporters (Government of the UK, 2012). The reporting itself did not follow a specific format, although the affected organisations were obliged to follow the requirements set out in the ARP and the statutory guidance document to ensure that all relevant steps were followed and that there was consistency across responses.

The reporting process of the ARP was found to affect organisations in various ways. For example, organisations gave greater consideration to the impacts of climate change on their business, with the reporting process ensuring greater visibility of climate change risks at the organisational and board level. The climate change risks identified within the ARP reporting process also stimulated some organisations to develop and enhance their climate risk management activities. Several actors were found to have developed their own quantitative risk assessment and monitoring tools, somewhat incentivised by the ARP process (Jude et al., 2017). Further analysis of the value of the ARP to organisations concluded that the process used should reflect differing organisational capacities, provide for a learning environment and give effective and comprehensive feedback (Street et al., 2017).

The ARP reports relating to the energy system suggest that most electricity generating companies had made progress in completing actions, with most actions addressing on-site flooding and drought impacts on water availability (Energy UK, 2015). Transmission system operators (TSOs) and distribution system operators (DSOs) are also adapting their networks to climate change, with a focus on reducing the risks from floods and storms (see Box 4.5 for details).

4.4 Activities by international organisations

4.4.1 International governmental organisations

International governmental organisations can support climate change adaptation by providing guidance, serving as information sharing platforms, facilitating communities of practice and acting as catalysts for the development of relevant services. Some of them may also co-fund the assessment, planning and implementation of adaptation measures. This section discusses selected international organisations with relevance for adaptation in the European energy system and their most relevant activities.

The **World Bank** was the first international organisation to address climate change adaptation specifically in the energy sector through its Energy Sector Management Assistance Program. In 2011, the World Bank published a comprehensive report on climate impacts and adaptation in the energy system, which was based on an expert workshop in 2009 (Ebinger and Vergara, 2011). This report addressed policymakers, energy planners and practitioners primarily in developing countries, but many of its findings are relevant also in industrialised countries. The background for this report was the recognition that developing countries were making considerable

Box 4.5 Adapting the United Kingdom's power network to climate change

Following the reporting requirements under the Climate Change Act 2008, United Kingdom energy network providers have released climate change adaptation reports, which include measures implemented to improve network resilience.

For example, the report by **Scottish and Southern Energy Power Distribution** presents the climate change risks posed to its network and establishes actions to mitigate these risks over timescales corresponding to the priority of the required action (SSEPD, 2015). Actions on the transmission and distribution systems include:

1. improving flood resilience through the building of flood walls;
2. sealing cables and raising substations;
3. initiating discussions on revising standards for overhead lines;
4. monitoring climate change impacts and updating projections;
5. updating the process for the management of trees; and
6. conducting research into tree-resilient overhead line designs.

National Grid, the United Kingdom transport system operator, has also undertaken climate change adaptation assessment and reporting. River floods, storm surges and sea level rise are expected to increase in substantial parts of the British Isles, presenting various threats to the electricity sector. These threats include material damage to substations, potentially resulting in power outages, fire, loss of temperature control and/or communication failures. To address such threats, National Grid is undertaking substation resilience improvements through a prioritised investment programme, using targeted risk assessments and including adaptation activities in its long-term business planning.

A site-based risk assessment using data from the United Kingdom's Environment Agency on river- and tidal-flood risk identified 47 substations as having the potential to be affected by a once-in-a-century flood, of which 13 were further prioritised based on site surveys and cost-benefit analyses. Such sites underwent various adaptation measures, ranging from rebuilding and elevating parts of these substations to drainage diversions. National Grid has invested GBP 17 million (≈EUR 19 million) at the highest risk sites. Other sites received GBP 136 million (≈EUR 153 million), with completion targeted by 2021. Permanent protection is the main target, but GBP 3 million (≈EUR 3.39 million) was set aside for mobile flood protection equipment. Distribution network companies have expressed appreciation of the benefits of early adaptation responses in order to mitigate future costs (National Grid, 2016).

One example of the success of the programme is provided by the Walham substation. Flooding of this substation in 2007 nearly caused the loss of power to 250 000 people. The site remained operational only due to the installation of a temporary barrier. This temporary barrier was replaced by a concrete flood wall and pumping station in 2012, which prevented any further damage to the substation when flooding of the area occurred again in 2013.

investments into energy infrastructure, with a focus on improving energy access and lowering GHG emissions, but that the energy sector was under-represented in the adaptation literature and activities. The report provides an overview of the knowledge on potential climate change impacts on energy systems, including its links with other sectors; it presents emerging practice and tools, and provides recommendations for integrating adaptation considerations into energy planning and operational practices. Some of the key messages and recommendations are that energy resources, infrastructure, services and demand are affected by climate change now and in the future; that adaptation is essential, in relation to both existing and new infrastructure; that integrated planning approaches for the energy sector should address climate change mitigation and adaptation jointly; and that the energy-water nexus needs to be considered. These findings are still relevant today. The report also identified obstacles for adaptation and priority actions.

The **International Energy Agency (IEA)** has addressed climate resilience in the energy system in several of its reports and through the Nexus forum since 2012. These activities target governments, businesses and organisations involved in the energy system. The chapter entitled 'Managing climate risks to the energy sector' in a 2013 IEA report covered both sudden and gradual impacts of climate change on energy demand and supply; it stressed the need to address climate change mitigation and adaptation jointly, and it made recommendations for measures enhancing climate resilience (IEA, 2013). This work was expanded in 2015 and 2016 by two reports that focused on climate risks in relation to extreme weather and water stress (IEA, 2015, 2016b). These reports provided further insights into the synergies and trade-offs between different decarbonisation pathways and climate resilience. They also provided specific recommendations as regards the role of governments in building climate resilience into the energy system, through policies, information and services, the resilience of state-owned assets, and mobilising financial resources. The development of these reports has been supported by the Nexus forum, a series of workshops focusing on the climate-energy-security nexus. This series included workshops on the water and energy nexus and on policies and practices to enhance energy sector resilience (IEA, 2014, 2016a, 2016c). Issues relevant to climate change adaptation are also addressed in other IEA reports, such as The future of cooling (IEA, 2018a).

The **OECD** has a programme of work that aims to integrate climate change into infrastructure decisions. It has recently published a policy paper on climate-resilient infrastructure (CRI), including energy infrastructure, which builds on relevant experience from OECD and G20 countries (OECD, 2018). This publication provides a framework for planning and designing CRI, strengthening the enabling environment for CRI and mobilising investment in CRI. Among other things, it encourages governments to ensure that international, national and local approaches to policies, standards and regulations are aligned to facilitate adaptation within the private sector.

The **OECD**, the **World Bank** and **UN Environment** have jointly developed the report Financing climate futures (OECD/World Bank/UN Environment, 2018). This report identifies six transformational areas that are required to ensure that infrastructure is aligned to the aims of the Paris Agreement.

The **International Renewable Energy Agency (**IRENA) supports countries in their transition to a sustainable energy future. In 2015, IRENA published a report on the energy-water-food nexus (see Section 2.1.5) (IRENA, 2015). This report explores integrated solutions for jointly meeting policy goals for these strongly linked sectors under climate change, with a particular focus on the role of renewable energy technologies. It also sets out criteria for analysing the energy-water-food nexus, which help to guide policymakers away from the 'silo-approach' to integrated resource planning.

The **World Meteorological Organization** has initiated the **Global Framework for Climate Services** (GFCS). The GFCS 'Energy Exemplar' aims to develop user-tailored weather-water-climate services in close cooperation with the energy industry. The first Energy Exemplar report provides, among other things, a detailed analysis of the potential of climate services for five different focus areas: (1) Identification and resource assessment; (2) Impact assessment; (3) Site selection and financing; (4) Operation and maintenance; and (5) Energy integration. It also describes in detail seven specific examples of climate products and services for the energy sector (WMO/GFCS, 2017).

4.4.2 International sector associations

Several international sector associations have developed relevant guidance material on climate change adaptation and strengthening resilience in the energy system.

The **International Hydropower Association** is preparing a climate resilience guide for the hydropower sector with the joint support of the World Bank and the EBRD (Climate Resilience Secretariat, 2018). This guide aims to assist hydropower companies in considering climate change risks in project design and operation, while also addressing the needs of the wider financial, policy and local communities. The preparation of a beta version of the guide is built on a stakeholder engagement phase. The release of the final version is expected in 2019.

The **World Energy Council** (WEC) published a report on managing the financing of energy sector infrastructure resilient to extreme weather risks as part of their 'Road to Resilience' series (World Energy Council, 2015). The report highlights the need for a strong regulatory framework that provides clear guidance on and definitions of what resilience is in the context of the energy system, what degree of resilience is sufficient, and how this may be financed. The WEC has also published reports on managing risks as part of the energy-water-food nexus (World Energy Council, 2015, 2016). The WEC encourages stakeholder cooperation to overcome current climate change information deficits among project developers and investors in order to ensure the correct pricing of investment risk under changing climates. By developing the necessary tools to compare the costs with the benefits of investing in resilience, private sector investment in the energy sector can be secured to ensure that energy assets receive adequate and stable returns throughout their lifetime.

The **World Business Council for Sustainable Development** (WBCSD) is an organisation of 200 forward-thinking companies from across the globe. It published a comprehensive report that analyses climate impacts and adaptation strategies for the power sector (WBCSD, 2014). The report distinguishes clearly between long-term climate impacts, long-term adaptation and long-term planning on the one hand and extreme weather events, climate resilience and crisis planning on the other. It presents multiple adaptation options to various climate change impacts along the energy system value chain. The report closes with specific recommendations for industry stakeholders, policymakers and public-private collaborations.

4.5 Adaptation case studies from energy utilities and network providers

4.5.1 Overview

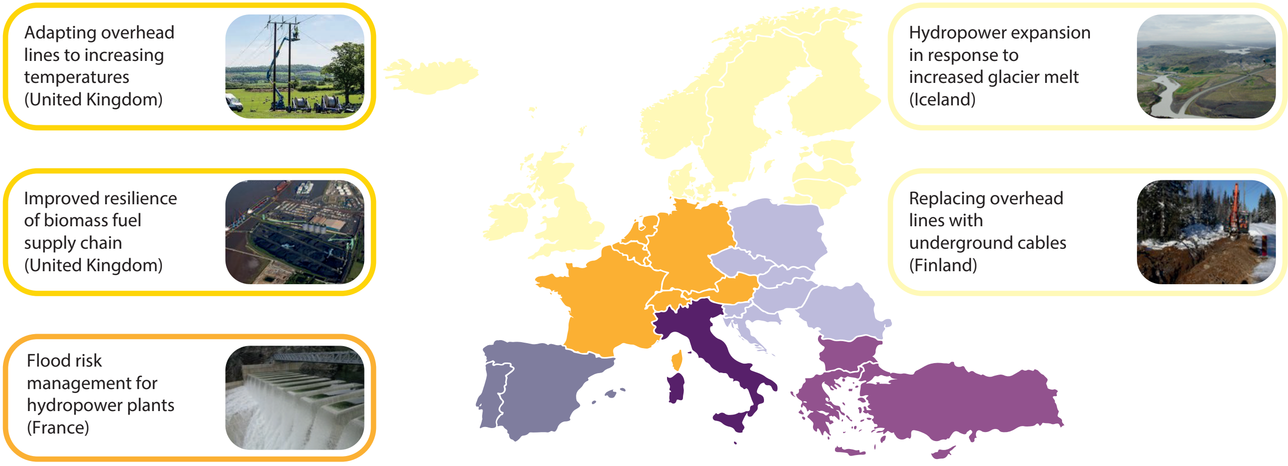
Public and private energy producers and other infrastructure providers are already adapting to climate change. A report for Natural Resources Canada based on an analysis of 200 projects globally found that climate change adaptation activities are becoming more mainstream in the energy sector (Braun and Fournier, 2016). The subsector that is most often represented in adaptation activities is energy generation, in particular related to hydropower. Ouranos has developed an online database on climate change adaptation in the energy sector with dozens of case studies (Ouranos and Natural Resources Canada, 2018). The geographical focus is North America, but several European case studies are also included. Other relevant case studies (termed 'business cases') for adaptation in the energy system, including several case studies from Europe, are provided in a WBCSD report (WBCSD, 2014).

This section presents a summary of five case studies on adaptation actions implemented by energy producers and network operators in Europe (see Figure 4.3). These case studies were selected from several sources based on the following criteria: relevance of long-term climate change, implementation of measures, importance in a decarbonised energy system, relevance of public policies, availability of information on success and limiting factors and on (expected) costs and benefits, and transferability of results. The geographical distribution of the case studies and their balance across energy system components was also considered. **Each of the five case studies is presented in considerably more detail on Climate-ADAPT** ([41]) (see the specific references below), which contains further case studies and is continuously expanded.

The five case studies are rather different, as they have intentionally been selected to showcase the diversity of potential adaptation actions by infrastructure operators in the energy sector. However, all of them relate to renewable sources of electricity production or to electricity transmission and distribution. This choice reflects the relevance of these technologies and infrastructure components in a decarbonised energy system as well as the availability of information on implemented adaptation actions.

The first two case studies are related to hydropower. The largest power producer in France has undertaken a systematic climate change risk assessment for its infrastructure and activities (see Box 4.6). This company has developed a cost-effective technology to reduce flood risks following heavy precipitation events. The

Figure 4.3 Overview of five adaptation case studies



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[41] https://climate-adapt.eea.europa.eu/knowledge/tools/case-studies-climate-adapt

technology has not been licensed, and it has already been applied in numerous locations in different countries. The other case study is from the national power producer in Iceland, which has adapted its hydropower infrastructure and practices in order to exploit increased water availability due to (temporary) increases in glacial melt water. Sophisticated climate projections and economic analysis are central to this case study, as is international cooperation. Both hydropower case studies were implemented without specific policy triggers. The adaptation measures were regarded as cost-effective from the viewpoints of the companies.

The third case study is related to power production from biomass. A large power company in the United Kingdom has diversified its supply chains for overseas biomass supply in order to increase import capacity and to build redundancy in the case of extreme weather events. These measures required close collaboration with the owner and operator of the sea ports where biomass terminals were upgraded or newly built. This measure was facilitated by national legislation relating to both climate change mitigation (which requires power companies to increase the share of renewable energy sources) and adaptation (which requires power companies and other infrastructure providers to report on climate-related risks and adaptation measures).

The last two case studies relate to increasing the climate resilience of power lines (see also EC, 2018i, Annex XIV, Case Study 4). A large electric utility company in the United Kingdom is adapting design standards to modify its distribution network to increasing temperatures. A key cost-effectiveness measure is to increase the design height for wood poles by 0.5 m in order to stay within legal safety limits for overhead lines despite increased sagging during heat waves. The second largest DSO in Finland is substantially investing in replacing most of its overhead power lines with underground cables, which are protected against storms, snow and ice accumulation. The substantial costs of doing so are reduced by partnering with telecommunication companies, which can use the same excavations for their own communication cables. These measures were adopted in response to a recently introduced legal requirement to limit electricity outages related to extreme weather, in particular storms and heavy snow.

An additional adaptation example is presented in Box 4.6.

4.5.2 Flood risk management for hydropower plants

***Electricité de France* (EDF), the largest electricity producer in France, has developed the piano key weir (PKW) system to improve flood discharge from hydropower dams during heavy precipitation events.** The PKW system provides an additional spillway to manage increased water flow without changing the maximum reservoir level. This is particularly relevant in the narrow gorges present in some of the Alpine regions where PKWs have been installed. The primary benefit of this technology is to protect hydropower assets from damage while also reducing operational costs compared with alternative gate systems. PKWs can manage much higher flow levels and provide a safer solution than gated systems, with minimal risk of malfunction and easier evacuation of floating debris. PKWs also avoid human error, because they do not require human operators. However, each hydropower dam presents different risk levels, and the suitability and effectiveness of PKW systems must be evaluated on a case-by-case basis.

Past trends show an increase in extreme daily rainfall in southern France, which can lead to flash floods. This trend is expected to continue in the future. Snow and glacier melt are also expected

Box 4.6 Adapting the cooling of nuclear power plants in France to a changing climate

Increasing temperatures and localised water scarcity place pressures on thermal energy production by limiting cooling water sources. Following a series of exceptional heat waves in France, the French utility company *Electricité de France* (EDF) initiated the '*Grands Chauds*' plan in 2008. The aim of this plan is to ensure the safety and supply security of EDF's nuclear power plants in the face of increasing temperatures. A case study on the adaptation of EDF's hydropower plants to climate change is presented in Section 4.5.2.

The *Grand Chauds* plan includes a re-assessment of maximum water temperatures expected at each nuclear power plant up to 2030. Revised temperature estimates have informed the revision of engineering guidelines for extreme weather situations and of safety standards taking into account climate change impacts. EDF has also improved the cooling efficiency of its nuclear power plants through a range of measures, including closed-loop cooling systems. These systems require less cooling water than conventional cooling technologies, albeit at higher costs. Furthermore, EDF has established a risk management unit that supports operational teams in determining the need for derogations from regulated limits for thermal discharges during exceptional heat waves (SFEN, 2015).

to have an impact on reservoir inflow and outflow in the longer term. Glacier mass loss already shows a consistent acceleration across the Alps. Releasing water safely from dams during floods or heavy precipitation presents a critical operational challenge at hydropower facilities. The goals of flood management are to prevent or minimise the impacts of dam overtopping on downstream communities, property, agriculture and ecosystems, and to protect the dams themselves against operational failure and other damage.

The Malarce dam (2.3 million m^3, 16 MW) is located in the department of Ardèche in the Auvergne-Rhône-Alpes region of France. It features a PKW that increases the dam's maximum discharge capacity to a total of 4 600 m^3/s. When dam water levels exceed the level in the inlet tanks, water automatically flows over the PKW into outlet tanks that run straight into the spillway channel and downstream. The PKW in the Malarce dam helps to reduce the risk of costly damage to dam infrastructure and to downstream communities.

The PKW has already been implemented in various hydropower facilities globally (e.g. in Algeria, South Africa and the United States), thanks to the collaborative approach of the original developers who did not patent this technology.

Further information on this case study is available on Climate-ADAPT (EEA, 2018c).

4.5.3 Hydropower expansion in response to increased glacier melt

***Landsvirkjun*, the national power company of Iceland, has included adaptations to climate change in managing, designing, updating and expanding its hydropower assets.** Almost all Icelandic glaciers have been losing mass since the early 1990s, and this trend is expected to continue with the warming climate. It has been projected that almost no Icelandic glaciers will be left by 2200. As a result of this increased melting, increased river flows and changes in their seasonal distribution have been observed over past decades. Further increases in flows are expected in the next 50 years, after which the runoff from glacial melt is expected to decline. Hydropower stands to gain from increased water flow caused by climate change-induced glacier melt in the coming decades, but reservoir management will have to be adjusted to account for this increased flow.

Landsvirkjun has improved projections of water flows under climate change. Overall inflow volume is projected to increase by an additional 15 % by 2050, compared with 2015. The existing power system can utilise only 30 % of that increase. Without increasing installed turbine capacity and reservoir storage at existing hydropower plants, the rest of the increased flow would be spilled over the spillways. The improved projections facilitate adaptation measures that minimise unnecessary water spills through the spillways. These measures include the modification of reservoir-management plans, the installation of additional infrastructure, and/or the re-design of existing infrastructure to manage increased runoff. A co-benefit is increased flood protection, as the reservoirs can function as extra buffer capacity in the case of extreme flooding. *Landsvirkjun* uses hydrological modelling to project future water flow, taking climate change impacts into consideration. In essence, the management and design of existing and planned assets is adjusted to take advantage of increased glacier flows, based on improved data on current and future flows.

At the Búrfell plant, improved water flow data were used to plan a capacity increase from 70 MW to 100 MW. This increase was implemented by building a new hydropower plant, which extends the original power capacity and reduces its load. Furthermore, the capacity of the Búðarháls hydropower plant, a new project commissioned in 2014, was increased from the originally planned 80 MW to 95 MW in response to climate change. Key factors in achieving these results have been the involvement of the Executive Board of *Landsvirkjun* in the adaptation process and collaboration with other power companies, universities and institutions.

The current expansion is economically sound given the project's time horizon of 50 years. Moreover, increased reservoir capacity installations can ensure increased general flood protection. The most extreme flood events in Iceland are glacial outburst floods caused by volcanic eruptions. By 2080, the volume of the glaciers is projected to have decreased so much that water flows will decline. At that point in time, existing hydropower plants may have higher capacity than needed.

Further information on this case study is available on Climate-ADAPT (EEA, 2018d).

4.5.4 Improved resilience of the biomass fuel supply chain

Drax Power Limited, a power company in the United Kingdom, has improved the resilience of its supply chain for biomass power plants. Three boilers at their large thermoelectric power plant in Immingham have recently been converted to be powered by biomass pellets. For a reliable stream of biomass, Drax relies on the maritime transport of wood pellets from North America. The United Kingdom has experienced several storm surges and coastal flooding in recent years; such events are expected to become more frequent and stronger under future climate change. The impacts of such events on energy infrastructure are significant. They include damage to supply lines, such as port infrastructure, and impacts to coastal or river-based power stations themselves. For example, Immingham port lost power in significant areas during a storm surge event in 2013 owing to localised flooding in substations.

Drax has implemented a multi-port strategy in order to alleviate the threat of supply chain backlog if its primary harbour is temporarily inoperable due to a weather-related event or other causes by means of additional biomass terminals at the ports of Tyne, Hull and Liverpool. Moreover, terminal designs at these harbours have been structurally adapted to avoid localised flooding events. Adaptation measures implemented at the Immingham site include raising power plant equipment above potential storm surge water levels, constructing protective sea walls, fitting subterranean tunnels with storm surge barriers, and planning above-ground construction of future tunnels. Similar measures have been implemented at the other locations. The geographic spread of ports and flood management measures in ports has allowed Drax to significantly increase its import capacity for wood pellet biomass. The adaptation benefits of this project are clear, and they seem transferable to other regions and projects.

The overall emissions balance of renewable fuel crops are often unclear, especially if existing forest or other carbon-rich habitat is cleared for energy crop production (Gasparatos et al., 2017; EASAC, 2019). Drax claims to source all wood pellets from sustainable, working forests to minimise net carbon releases to the atmosphere. An analysis of the climate benefits and potential biodiversity impacts of the fuel change from fossil fuels to biomass in this case study is beyond the scope of this report. For a discussion of the synergies and trade-offs between climate change adaptation, mitigation and other environmental and social concerns, see Section 4.1.4.

Further information on this case study is available on Climate-ADAPT (EEA, 2018e).

4.5.5 Adapting overhead lines to increasing temperatures

Western Power Distribution (WPD), a large electric utility in the United Kingdom, has cooperated with the Energy Network Association (ENA) in order to operationalise adaptation measures in its transmission and distribution infrastructure. Electric transmission and distribution network providers in the United Kingdom and elsewhere face increasing risks from heat waves, which pose a threat to their power infrastructure. Thermal expansion can cause power lines to sag, hence their clearance from land can become a danger to the general public. Sagging may also result in contact with trees and other structures, and hence in electrocution or fires. Furthermore, the electrical current that passes through overhead power lines must be reduced under high ambient temperatures to prevent the overheating of equipment. Finally, warmer power lines can result in decreased efficiency due to a process known as de-rating. All of these impacts ultimately result in risks of accidents, power cuts and revenue losses, as well as cascading network failures.

Adaptation measures by WPD include increasing the height of poles supporting power lines, installing conductors with hotter operating limits and implementing the use of 'low-sag' conductors. The most cost-effective measure identified was to increase the minimum design temperature of new overhead lines, which requires increasing the design height of wooden poles by 0.5 m. This adaptation accommodates the projected increases in sagging without exceeding legal limits on the height of overhead lines. WPD also participated in a project that updated the United Kingdom's distribution industry's understanding of conductor ratings for overhead lines, which is expected to lead to an update of national standards. Finally, WPD and various other British energy companies are developing a software tool that will allow energy companies to optimise their overhead line ratings.

Cooperation among relevant institutions turns out to be the major enabling factor for this initiative. Members of electricity network operators have been brought together with government and regulating agencies in the ENA-led Climate Change Adaptation Task Group. The task group develops approaches to identify impacts of climate change on electricity TSO and DSO networks, and to develop and select cost-effective and efficient adaptation measures.

Further information on this case study is available on Climate-ADAPT (EEA, 2018a).

4.5.6 Replacing overhead lines with underground cables

Elenia, the second largest electricity distribution system operator in Finland, is investing substantially in underground cabling. Expected climate change impacts in Finland include increased frequency and intensity of precipitation events, storms and snow loads. Furthermore, increasing temperatures are projected to lead to increased growth and age of trees and increased leaf coverage, which can result in hazards for aerial power lines. The collapse of power lines causes temporary loss of power to users and results in repair costs for power providers. In order to adapt to increasingly frequent and extreme weather events and to adhere to the outage requirements of Finland's Electricity Market Act, Elenia plans to increase the share of underground cables in its network from 41 % currently to 75 % by 2028. The planned investments for 2018 were EUR 140 million.

Underground cabling protects electricity transmission and distribution systems from the most frequent adverse weather conditions, in particular storms and excessive snow and ice loads. It can alleviate the requirement for further and more frequent investments in infrastructure maintenance and repairs. In addition to a more secure energy supply, additional benefits of underground cabling include lower visual impact and reduced accident risk (e.g. fires and impact associated with broken or fallen cables).

The key success factor for underground cabling is the availability of the correct technology for underground cabling with regard to installation, monitoring and management. There are three main approaches: placing cabling in concrete-reinforced troughs, placing the cables in underground tunnels, or directly burying the cables. The technique used by Elenia involves the construction of trenches ranging from around 0.45 m to 1 m in depth, with the cabling then buried within the soil layer. Elenia cooperates with other underground cabling entities such as telecommunications companies to reduce costs through collaboration and to minimise disturbance to populations.

Excavation due to other construction or maintenance activity represents a key risk of damage to underground cables. Elenia applies digitisation and geographical information systems to inform excavators about the location of underground cables. Underground cabling could also be exposed to new climate hazards, in particular flooding, soil compaction and soil movements related to landslides, but these risks were considered to be low in Finland. When the application of underground cabling is considered in other locations, its costs and benefits would need to be compared with those of other adaptation options, such as improved vegetation management or reinforced overhead pylons and cables, on a case-by-case basis.

Further information on this case study is available on Climate-ADAPT (EEA, 2018h).

5 Conclusions and outlook

Key messages

- The European energy system increasingly needs to adapt and become more climate resilience in the context of continuing climate change, modern societies' increased dependence on a reliable energy supply and an increasing share of climate-sensitive renewable energy sources.
- Adaptation in the energy system should consider synergies and trade-offs with other sustainability concerns, in particular climate change mitigation, and land and water use.
- Many asset owners and managers, as well as policy-makers at the EU, national and regional levels, and other stakeholders are already addressing adaptation needs in the energy system, but there is scope for further action.
- The development of the Energy Union and the EU long-term strategy on climate action provide important opportunities for mainstreaming climate change adaptation in the planning and implementation of a decarbonised energy system in Europe through more coordinated actions, reporting and mutual learning among all involved actors.
- All countries should consider the impacts of climate change on the current and future energy system in the development of their national climate and energy plans and long-term strategies under the Energy Union, and in the development and update of their national adaptation strategies and action plans.
- All market actors in the energy sector, including business associations, should consider strengthening climate resilience as an integral part of their business.
- Governments can facilitate market actors in the energy sector in overcoming adaptation barriers through the regulation of energy markets and other policy interventions, as well as through 'soft' measures that focus on information provision and exchange. Such activities can be supported by reporting requirements on climate change risks and adaptation actions for critical infrastructure providers, in particular, where such information is not available from other sources.

The European energy system faces increasing climate adaptation needs

Adaptation to climate change and building climate resilience are becoming increasingly important for the European energy system. First, global climate change implies that past climate conditions are no longer a reliable proxy for the future. Second, modern societies are increasingly dependent on a stable energy supply. Even short disruptions in electricity supply can have large economic and social costs, which can be up to one hundred times larger than the direct costs to the energy sector. Finally, the clean energy transition involves a rapidly growing share of renewable energy sources, most of which are sensitive to weather and climate variations at different time scales.

Climate change and extreme weather events are increasingly impacting all components of the energy system. Such events affect the availability of primary energy sources (in particular renewable energy sources), the transformation, transmission, distribution and storage of energy, and energy demand.

Climate change impacts and related adaptation needs vary significantly across energy system components and European regions. Some impacts can be economically beneficial, such as reduced energy demand for heating. However, many impacts are adverse for the energy sector and/or society as a whole, such as reduced cooling water availability for thermal power plants in many regions, increasing risks for energy infrastructure from extreme weather events and sea level rise. At a regional level, southern Europe faces the strongest adverse impacts due to increasing heat waves and decreasing water supply.

Building climate resilience comprises addressing the impacts of weather hazards on existing energy infrastructure and its operation, as well as

considering the impacts of long-term climate change on newly planned infrastructure. It is generally more efficient to address adaptation needs early in the investment cycle rather than through the costly retrofitting of existing infrastructure.

The further development of the European energy system needs to address climate change adaptation and mitigation jointly in the context of wider sustainability concerns. There can be synergies as well as trade-offs between climate change mitigation and adaptation, depending on the particular technological or policy option and the regional context. On the one hand, replacing coal-fired power plants by photovoltaics and wind power radically reduces greenhouse gas emissions and water consumption, thus contributing to mitigation as well as adaptation in water-scarce regions. The same is generally true for increasing energy efficiency. On the other hand, biofuels or carbon capture and storage have a larger need for water withdrawals, water consumption and/or arable land than many conventional energy technologies. Similarly, hydropower generation can have adverse impacts on local and regional biodiversity.

The clean energy transition in Europe presents both challenges and opportunities for climate change adaptation. On the one hand, adaptation could be seen as an additional burden that needs to be managed on top of other challenges related to rapid decarbonisation and changes in the market and regulatory environment. On the other hand, the massive investments made in the energy system allow adaptation needs to be addressed early in the investment cycle. A careful assessment of the relevant risks and adaptation options, as well as coordinated action by a wide range of public and private stakeholders, is necessary to ensure the clean energy transition is also climate-resilient.

Policy-makers and stakeholders are already addressing adaptation needs in the energy system

Key EU climate and energy policies and strategies promote the mainstreaming of climate change adaptation into energy policies. These include the EU adaptation strategy, the Regulation on the Energy Union and Climate Governance, the Commission proposal for a long-term strategy 'A Clean Planet for All' and the Regulation on risk-preparedness in the electricity sector. The Energy Union implies a stronger role for the EU to monitor and coordinate energy planning, reduction of greenhouse gas emissions and adaptation actions in its Member States. On a mandate from the European Commission, standardisation bodies are adapting standards for climate-sensitive infrastructure. The Regulation on the guidelines for trans-European energy infrastructure also contains provisions on the management of climate risks. The EU also supports building climate resilience in the energy system by funding relevant research and innovation projects, and developing climate services for the energy sector as part of the Copernicus services.

Most European countries have addressed the energy sector in national climate change impact, vulnerability and risk assessments, national adaptation strategies and/or action plans. Particular attention is given to the impacts of extreme events on energy infrastructure and services. However, some countries do not currently regard energy as a priority sector for adaptation. An assessment whether countries are considering adaptation needs in their long-term energy planning was not possible in the context of this report. However, such an assessment could be done in 2020 based on Member States' reporting under the Regulation on the Governance of the Energy Union and climate action.

Many other stakeholders have also started to address adaptation needs in the energy system. Energy regulators have performed stress tests and increased regional cooperation. Sector associations are developing guidelines for climate vulnerability assessment, sometimes with the support of international organisations or national governments. Electric utilities are performing risk assessments and use the results as the basis for retrofitting more water-efficient cooling technologies, updating management procedures and improving contingency plans. Network providers are adapting design standards for overhead lines and investing substantial amounts for underground cabling.

There is scope for further adaptation action by all involved actors

Considerable action has happened already, but more can and should be done to ensure that the energy system in Europe is climate resilient now and in the future. The challenges, opportunities and most suitable actions differ across countries and regions, depending on the physical and management structure of the energy system, climatic and environmental factors, and socio-economic conditions.

Some stakeholders in the energy system are only beginning to acknowledge the relevance of climate change impacts on their activities, or they are experiencing barriers to taking action. They may feel that the uncertainties about future climate change and its impacts are too large to justify significant investments at the present time with uncertain benefits in the future. They may be interested in action, but do not know where to find accessible and reliable information. They may not see the business case for adaptation investments given the asymmetric distribution of benefits and costs. They may prefer to postpone investments in adaptation technologies in the hope of reduced uncertainties, technological advances and falling prices. Following careful analysis, some energy system stakeholders may indeed come to the conclusion that they do not face urgent adaptation needs at the moment. However, all actors will benefit from assessing climate change-related risks and opportunities, given the climate sensitivity of many energy system components and the importance of energy for modern societies.

Governments are crucial for overcoming adaptation barriers by market actors

Building climate resilience is a shared responsibility between infrastructure and service providers in the energy sector, regulators, national and regional governments, and the EU. Many adaptation actions in the energy system make a business case for market actors, because they increase revenues or reduce costs and/or reputational risks. However, other actions may require government or regulatory interventions, because their costs and benefits are unevenly distributed, or because their success depends on co-ordinated action by many actors, possibly across national borders.

Most barriers to efficient and effective climate change adaptation in the energy system can be addressed by government policies. Some policy mechanisms require cooperation at the transnational or European level due to the increasingly interconnected nature of the European energy system.

Opportunities for further action by European policy-makers

The Energy Union provides important opportunities for mainstreaming climate change adaptation in the planning and implementation of a decarbonised energy system at the EU and Member State level.

The **Regulation on the Governance of the Energy Union and climate action** ('Governance Regulation') requires EU Member States to prepare and publish integrated national energy and climate plans (NECPs) (for the period up to 2030) and long-term strategies (e.g. up to 2050). These integrated planning processes call for addressing climate change mitigation and adaptation in the energy system jointly, and they facilitate learning from good practices across Europe. The Commission is currently (up to June 2019) assessing the draft NECPs, which address climate adaptation and resilience under the 'Decarbonisation' and the 'Energy Security' dimension. When issuing recommendations to Member States, the Commission may consider to what extent the draft NECPs address the impacts of climate change under the dimension 'Energy Security'.

The Commission is also developing implementing acts that specify in more detail the reporting requirements under the Governance Regulation. The implementing act under Article 17 — currently under development with assistance of the Energy Union Committee — could foresee that countries report on their consideration of climate change impacts in the implementation of the NECPs under the 'Energy Security' dimension. The implementing act under Article 19 —currently under development with assistance of the Climate Change Committee — could foresee that countries report on their adaptation-related activities in selected sectors. For example, in its 'horizontal assessment' of adaptation preparedness country fiches, the evaluation of the EU Adaptation Strategy included a selection of sectors with transboundary relevance or where EU policies play a strong role, including energy.

The Commission and Member States are encouraged to consider the impacts of climate change when preparing and elaborating long-term strategies. The planned EU long-term strategy for climate action (due by early 2020) is currently being debated, based on the Commission proposal 'A Clean Planet for All' and views from EU Member States. The Governance Regulation also requires Member States to prepare national long-term strategies, which shall include 'adaptation policies and measures'. According to Article 15, 'the Commission shall support Member States in the preparation of their long-term strategies by providing information on the state of the underlying scientific knowledge and opportunities for sharing knowledge and best practices, including, where relevant, guidance for Member States during the development and implementation phase of their strategies'. The Commission is encouraged to support Member States in considering the impacts of climate change in the preparation of their national long-term strategies.

The Regulation on risk-preparedness in the electricity sector, the proposed Regulation establishing the Connecting Europe Facility and market regulation in the energy sector provide further opportunities for increasing climate resilience. Such regulation should ensure that market participants in the energy sector have a business case for building climate resilience at a level that reflects the importance of a secure and stable energy supply for modern societies.

Opportunities for further action by national policy-makers

National (and sub-national) governments have a wide range of options for facilitating climate change adaptation in the energy system. These options include funding targeted research and development, providing climate services, building communities of practice, public-private partnerships, market regulation, reporting requirements and others.

National climate change impact, vulnerability and risk (CCIV) assessments of the energy system with a strong forward-looking component are essential inputs for making the clean energy transition climate-resilient. Such assessments should consider, as a minimum, the impacts of changing water availability on the availability of renewable energy sources and on electricity generation, the impacts of increasing temperatures on electricity generation, transmission and demand, and the impacts of extreme climate-related events (including coastal and marine hazards where relevant) on various types of energy infrastructure. The rapid changes in the energy system in the context of the clean energy transition imply that the future energy system in Europe will be very different from the current one. The long-lived nature of most energy infrastructure requires assessing the impacts of climate change — not only on the current energy system, but also on different scenarios of a future low-carbon energy system, where renewable energy sources, electricity and potentially hydrogen as energy carriers, and energy storage play a stronger role. The assessment should also address different plausible climate change scenarios, including scenarios that overshoot the temperature stabilisation target of the Paris Agreement.

Countries that have not addressed energy as a priority sector or policy area in their national CCIV assessment are encouraged to do so in the future. There are also opportunities for countries that already have addressed the energy system in multi-sectoral or sectoral CCIV assessments, in particular, to strengthen the resilience assessment of alternative decarbonisation scenarios.

All countries are encouraged to consider the impacts of climate change on the energy system in their national energy and adaptation planning. Specifically, EU Member States would benefit from addressing them in the preparation of their NECPs and long-term decarbonisation strategies under the Energy Union (see above for details).

Reporting requirements on climate change risks and adaptation actions for critical infrastructure providers can facilitate the building of climate resilience in the energy system, in particular, where such information is not available from other sources. For example, the United Kingdom has introduced systematic reporting requirements regarding climate change risks and adaptation actions for public and private providers of critical infrastructure, which include energy infrastructure. The experiences are generally positive, and independent reviews showed significant investments in improving the climate resilience of the UK energy infrastructure.

Countries can also facilitate the building of climate resilience in the energy system through 'soft' measures. Such measures include providing relevant information (e.g. through climate services), facilitating knowledge transfer (e.g. through adaptation platforms) and establishing communities of practice. Dialogue fora with energy system stakeholders can help identify barriers for adaptation action and options for overcoming them, e.g. through changes in legislation or regulation.

Opportunities for further action by industry and other market actors

All market actors in the energy sector should consider building climate resilience as an integral part of their business. This consideration is particularly important because of the large investments in long-lived infrastructure that are being made in the context of the clean energy transition. However, also existing energy infrastructure may require climate proofing. Climate risk assessments are an important first step in addressing the impacts of climate change and variability on current and planned energy infrastructure and its operation.

Business associations in the energy sector can support their members in building climate resilience. They can do this by raising awareness of climate change impacts and adaptation needs, developing guidelines and tools, facilitating mutual learning, and encouraging and finding cooperative solutions, among others.

Annex 1 Information sources for country overview table

This annex provides further information on the information sources for Table 4.4 Coverage of the energy system in key national adaptation documents in Section 4.3.1. Specific information sources and the colour codes are explained in the main text.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/or NAP	Adaptation measures implemented in the energy sector	
Austria	🟩	The Austrian Assessment Report 2014 (AAR 14) contains a whole section on energy and transport (APCC, 2014).	🟩	The NAP includes an action field 'Energy' with a focus on 'Power supply' (Government of Austria, 2017).	Climate adaptation is reported as being integrated into sectoral policies for energy (among others), but no specific information is provided.	No adaptation actions reported.
Belgium	🟩	The national CCIV assessment includes a section on energy (Technum, 2013).	🟩	The NAP includes energy as one of the priority areas (National Climate Commission, 2017a).	The Benelux countries have organised workshops on adaptation in several sectors, including energy. The drafting of the New Industrial Policy to be introduced in the Flemish Region will incorporate the risks of volatile energy costs attributable to climate change (Government of Flanders, 2016).	Studies on 'Needs in adequation and flexibility of electric system (2016)' and the promotion of sustainable energy generation methods independent of the availability of water resources (National Climate Commission, 2017b).
Bulgaria	🟩	The national CCIV assessment focuses on natural disasters. It does not include a specific section on energy, but the energy sector is covered to a limited degree (Government of Bulgaria, 2013)	🟥	The draft NAS/NAP document includes a section on energy (Dale et al., 2018).	No adaptation actions reported.	No adaptation actions reported.
Croatia	🟩	The national CCIV assessment includes various sections on energy sector vulnerabilities to climate change, with high-risk areas throughout the sector identified (Government of Croatia, 2017b).	🟥	The draft NAS contains a section on energy (Government of Croatia, 2017a).	No adaptation actions reported.	No adaptation actions reported.
Cyprus	🟩	The national CCIV assessment includes a focus on energy (Government of Cyprus, 2016).	🟩	The NAP includes a section on energy (Government of Cyprus, 2017).	No adaptation actions reported.	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/ or NAP	Adaptation measures implemented in the energy sector	
Czechia	🟩	The national CCIV assessment includes a section on climate change risks to Czech industry and energy (Government of Czech Republic, 2015).	🟩	The NAP includes 'industry and energy' as one of its priority sectors (Government of Czech Republic, 2017).	No adaptation actions reported.	No adaptation actions reported.
Denmark	🟩	The national CCIV assessment includes a section on energy, which addresses energy consumption, energy production, wind changes, import/export changes and biomass production (Government of Denmark, 2012b).	🟩	The NAS includes energy as one of the sectors where climate change will have a significant impact (Government of Denmark, 2008). The NAP focuses on managing pluvial floods and does not specifically address the energy system (Government of Denmark, 2012a).	No adaptation actions reported.	No adaptation actions reported.
Estonia	🟩	The national CCIV assessment (a part of the NAS) includes a section on the security of the energy supply, including energy independence, security, resources, energy efficiency, heat generation and electricity generation (Government of Estonia, 2017).	🟩	The NAP includes a section on energy and security of supply (Government of Estonia, 2017). More specific objectives are included in the Estonian climate adaptation strategy for infrastructure and energy and in the national strategy for climate change in the infrastructure and the energy sector 2017-2030 (Lahtvee et al., 2015a, 2015b).	No adaptation actions reported.	No adaptation actions reported.
Finland	🟩	The national CCIV assessment includes a section on energy distribution and production, which identifies risks such as disturbances to energy production and distribution, maintenance cost increases in the energy network, flood risks to nuclear power plants, weaker solar power and increased need for cooling (Government of Finland, 2013).	🟩	The NAP acknowledges climate change impacts on energy, but no specific actions are suggested (Government of Finland, 2014).	Long-term climate changes have been included in the legislation on water resources, among which the Dam Safety Act (2009) may be relevant for hydropower. The country fiche mentions that electricity market legislation includes security of supply provisions, but it is not clear whether these cover climate-related issues.	The Electricity Market Act includes regulations aimed at improving the security of the energy supply in network fault situations. Specifically, the distribution network must be designed, built and maintained in such a way that when the network is damaged due to a storm or snow, the loss of power to customers should not exceed 6 hours in urban areas and 36 hours in other areas.
France	🟩	The national CCIV assessment includes a section on energy, which addresses climate change impacts on energy consumption, hydropower production and energy transport (Government of France, 2009).	🟩	Energy and industry are included as key sectors within the NAP (Government of France, 2011).	No adaptation actions reported.	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/ or NAP adopted	Coverage of the energy sector in NAS and/ or NAP	Adaptation measures implemented in the energy sector	
Germany	🟩	The national CCIV assessment includes a section on the action field 'Energy industry', with 'strong changes' projected for heating energy demand, cooling energy demand, cooling water for thermal power stations, damage to power stations and production facilities (Government of Germany, 2015b).	🟩	The NAP includes energy (conversion, transport and supply) as one of 15 sectors covered (Government of Germany, 2011).	The progress report on the implementation of the NAP mentions adaptation activities in the climate proofing of the energy sector, e.g. in terms of water use for cooling of thermal plants and for hydropower (Government of Germany, 2015a).	The government is implementing 'a comprehensive portfolio of services addressing climate change and adaptation'. This includes the establishment of the German Climate Service in 2015. This service addresses many sectors and impact domains, including energy.
Greece	🟩	The national CCIV assessment includes a section on the built environment, which includes power supply networks. Impacts include, among other things, an increase in summer energy demand, a decrease in winter energy demand and damage from fires (Bank of Greece, 2011).	🟨	The NAS includes energy as one of the 15 sectors covered (Government of Greece, 2016).	No significant adaptation actions reported.	No adaptation actions reported.
Hungary	🟩	The national CCIV assessment includes a section on the energy sector (Government of Hungary, 2017b).	🟨	The draft second national climate change strategy contains energy as a priority sector for adaptation actions (Government of Hungary, 2017a).	No significant adaptation actions reported.	No adaptation actions reported.
Iceland	🟥	No information available.	🟥	No information available.	Country fiches applicable only to EU Member States.	No adaptation actions reported.
Ireland	🟩	The most recent national CCIV assessment includes a section on critical infrastructure and the built environment, which includes climate change impacts on energy demand, supply, transport and transmission (Desmond et al., 2017). The NAP for the electricity and gas networks sector also includes a chapter on vulnerability assessment (Government of Ireland, 2018a)	🟨	An electricity and gas networks NAP will be prepared by the Department of Communications, Climate Action and Environment for 2019 (Government of Ireland, 2018b). A previous version of this plan was released under the National Climate Change Adaptation Framework of 2012. The focus of the current plan is on electricity generation and electricity and gas transmission and distribution infrastructures and interconnectors.	No adaptation actions reported.	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/ or NAP adopted	Coverage of the energy sector in NAS and/ or NAP	Adaptation measures implemented in the energy sector	
Italy	🟩	CCIV assessment includes a section on climate change impacts on heating and cooling, electricity demand, production of electricity, transmission and distribution (Government of Italy, 2014).	🟨	Both the NAS (Government of Italy, 2014) and the first draft of the NAP include a specific section on energy (CMCC, 2017). The NAP includes a priority ranking of measures for energy transformation, transmission, distribution and demand.	No adaptation actions reported.	No adaptation actions reported.
Latvia	🟩	The national CCIV assessment includes sections on the power transmission and distribution systems and on natural gas infrastructure (Government of Latvia, 2017).	🟥	No information available. A national Adaptation Strategy is under preparation.	No adaptation actions reported.	No adaptation actions reported.
Liechtenstein	🟥	The seventh national communication to the UNFCCC mentions energy as a vulnerable sector in relation to energy consumption and hydropower generation (Government of Liechtenstein, 2017).	🟨	The NAS mentions specific adaptation actions relating to energy (Government of Liechtenstein, 2018).	Country fiches applicable only to EU Member States.	One of Liechtenstein's hydroelectric power plants (Samina) has been transformed into a pumped-storage plant. This measure increases flexibility in power production and facilitates adaptation to expected changes in the runoff regime due to climate change.
Lithuania	🟩	The national CCIV assessment includes a section that sets out various threats to the energy sector (Government of Lithuania, 2015).	🟩	The latest NAP includes various adaptation actions related to the energy sector (Government of Lithuania, 2018).	No adaptation actions reported.	No adaptation actions reported.
Luxembourg	🟩	The national CCIV assessment focuses on spatial planning. Potential climate change impacts on the energy sector are mentioned briefly in a table (Government of Luxembourg, 2012).	🟩	The NAS/NAP includes a dedicated section on energy (Government of Luxembourg, 2018).	No domestic adaptation actions were reported. However, Luxembourg participates in adaptation activities of the Benelux countries, which include the energy sector.	No adaptation actions reported.
Malta	🟩	The national CCIV assessment does not explicitly mention the energy sector (Malta Resources Authority, 2010).	🟨	Energy is not a priority sector within NAS (Government of Malta, 2012).	No adaptation actions reported.	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/or NAP	Adaptation measures implemented in the energy sector	
Netherlands	🟩	The national CCIV assessment includes energy as a key sector (Ligtvoet et al., 2015). In addition, a sectoral CCIV assessment for the energy sector is available (Vogel et al., 2014).	🟩	The NAS includes energy as one of nine priority sectors (Government of the Netherlands, 2016). The NAP refers to climate change impacts on the energy sector, but adaptation in this sector is not a priority for 2018-2019 (Government of the Netherlands, 2018).	There are systematic capacity-building initiatives on adaptation with regional and local governments and sector representatives from several sectors, including the energy sector. The Benelux countries have organised exploratory workshops and carried out cross-border risk analysis in several areas, including energy.	Several grid managers have conducted research to determine the potential impact of climate change events such as flooding on their section of the infrastructure. Research has also examined how a large-scale power outage would affect the chain of vital functions.
Norway	🟩	The national CCIV assessment includes a section on the vulnerabilities of power supply (Government of Norway, 2010).	🟨	The NAS includes aspects relevant to the energy sector in various places (Government of Norway, 2012).	Country fiches applicable only to EU Member States.	Several policies are in place to ensure a reliable power supply in a changing climate. For example, the NVE sets requirements to electricity utilities in terms of proper contingency planning, available spare parts, transport and communication systems, training, etc., to enable an efficient restoration of the electricity supply. Furthermore, NVE conducts research and development in the light of anticipated challenges to the energy sector as a result of climate change.
Poland	🟩	The national CCIV assessment includes a section on the energy sector (KLIMADA, 2013).	🟨	The NAS includes a separate action line on the energy sector (Government of Poland, 2013).	No significant adaptation actions reported.	No adaptation actions reported.
Portugal	🟩	The SIAM II project 'Climate Change in Portugal: Scenarios, Impacts, and Adaptation Measures' addressed climate change impacts on the energy sector, in particular on solar energy, water availability for power, and heating and cooling demand (Aguiar et al., 2006). Furthermore, a report drafted as supporting material for the NAS covers the vulnerabilities of the energy sector (Government of Portugal, 2012).	🟨	The latest NAS (ENAAC 2020) includes a separate section on energy (Government of Portugal, 2015).	The 2015-2016 interim evaluation of the implementation progress of the NAS (Government of Portugal, 2016), reports that 'Existing policy around security of energy supply and climate change mitigation are broadly in line with adaptation objectives, including policies to increase networks, adopt smart grids and promoted distributed production. An area identified for further policy development is climate proofing of energy assets.'	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/or NAP	Adaptation measures implemented in the energy sector	
Romania	🟩	The national climate strategy includes a section on energy (Government of Romania, 2016a).	🟩	The NAP includes a separate section on energy (Government of Romania, 2016b).	No significant adaptation actions reported.	No adaptation actions reported.
Slovakia	🟩	The national CCIV assessment includes a section on the energy system (Mindas et al., 2011).	🟨	The NAS includes a separate section on energy (Government of Slovakia, 2014).	No adaptation actions reported.	No adaptation actions reported.
Slovenia	🟩	The national CCIV assessment focuses on water; no energy- specific section could be identified (Government of Slovenia, 2010).	🟨	The NAS does not specifically address the energy sector (Government of Slovenia, 2016).	The Flood Risk Mitigation Plan 2017-2021 defines a large set of flood protection projects, which include adapting the energy infrastructure. However, this plan does not currently consider climate change scenarios. At the transnational level, the Water and Climate Adaptation Plan for the Sava River Basin acts as a guidance document to governments for climate adaptation measures in various water-related issues, including hydropower.	No adaptation actions reported.
Spain	🟩	The early national CCIV assessment includes a section on energy (Government of Spain, 2005). A detailed assessment for the energy sector was conducted later (Girardi et al., 2015).	🟩	The current NAP (PNACC WP3) includes a section on energy (Government of Spain, 2014).	National adaptation activities in Spain relating to the energy sector comprise a detailed sectoral CCIV assessment, a pilot project with Endesa (the largest electric utility company in Spain), capacity-building actions and networking with regional authorities and mainstreaming activities (Government of Spain, 2018).	No adaptation actions reported.

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/or NAP adopted	Coverage of the energy sector in NAS and/or NAP	Adaptation measures implemented in the energy sector	
Sweden	🟩	The national CCIV assessment includes sections on energy production, supply, heating and cooling needs, and dam safety (Andersson et al., 2015).	🟩	The Swedish Energy Agency has been requested to identify adaptation measures in the energy sector, but a comprehensive plan does not seem to exist at this time (Government of Sweden, 2019). Adaptation in the energy system may be addressed in some regional adaptation plans, but a comprehensive overview is not available.	The scope of environmental impact assessments, which includes amendments to hydropower, municipal energy planning, pipelines and nuclear activity, was broadened in order to consider climate change impacts (Government of Sweden, 2017). Furthermore, in 2018 the government tasked a number of agencies with creating a sectoral adaptation plan or report on their adaptation work, including the Swedish Energy Agency, Swedish grids and the National Electrical Safety Board.	No adaptation actions reported.
Switzerland	🟩	The national CCIV assessment addresses climate change impacts on cooling and heating needs, and the seasonal shift of hydropower generation (Köllner et al., 2017).	🟩	The NAP includes a section on energy (Government of Switzerland, 2014).	Country fiches applicable only to EU Member States.	Multiple adaptation measures have been reported at the cantonal level in relation to 'cooling of thermal power plants, hydropower production, thermal power production and energy', but it remains unclear what these measures are and how they relate to climate change projections. At the federal level, several adaptation measures are being planned and implemented, such as taking the changing climate into account in supervision and licensing processes for hydroelectric dams and reservoirs as well as for transmission and distribution networks for gas and electricity. More specific information is available in an annex to the NAP (Government of Switzerland, 2014, Annex A5).

Country	Document					
	Climate change impact, vulnerability and risk (CCIV) assessments		National adaptation strategies (NAS) and plans (NAP)		Country fiches	UNFCCC
	Availability of national CCIV assessment	Coverage of the energy sector in national CCIV assessments	NAS and/ or NAP adopted	Coverage of the energy sector in NAS and/ or NAP	Adaptation measures implemented in the energy sector	
Turkey	🟩	The national CCIV assessment focuses on water-related impacts, but energy-related impacts are addressed briefly in this context (Government of Turkey, 2016).	🟩	Energy-related aspects are mentioned in the section on water resources management of the NAS/NAP, with a focus on hydropower (Government of Turkey, 2011).	Country fiches applicable only to EU Member States.	No adaptation actions reported.
United Kingdom	🟩	The most recent national CCIV assessment includes a chapter on infrastructure, which covers energy infrastructure (Committee on Climate Change, 2017).	🟩	The most recent NAP includes a section on the energy sector (Government of the UK, 2018).	The 2017 progress report on the NAP acknowledged significant progress in increasing the climate resilience of the energy infrastructure, with a focus on flood risk management. A large range of measures have already been carried out, including critical upgrading of electric substations against flooding; investment in mobile flood protection; electricity generators addressing the risk of water scarcity; and risk assessment of nuclear installations and of gas networks. These measures were facilitated by government policies, including reporting requirements for critical infrastructure providers, mandatory climate risk assessments for new infrastructure projects and improved standards for network resilience (Committee on Climate Change, 2017).	The Climate Ready Support Service for England helped organisations to build their own capacity to adapt by incorporating climate risk management into their plans and decision-making and providing guidance tools and support to key sectors (including energy). A national risk assessment and sector resilience plans that consider climate change have identified key risks and vulnerabilities. The Adaptation Reporting Power enables the government to monitor the implementation of risk reduction strategies.

Notes: CCIV, climate change impact, vulnerability and risk; NAP, national adaptation plan; NAS, national adaptation strategy; NVE, Norwegian Water Resources and Energy Directorate.

Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
AR5	Fifth Assessment Report of the Intergovernmental Panel on Climate Change
ARP	Adaptation Reporting Power
C3S	Copernicus Climate Change Service
CCIV	Climate change impact, vulnerability and risk
CCS	Carbon capture and storage
CDD	Cooling degree day
CEER	Council of European Union Energy Regulators
CF	Cohesion Fund
CRI	Climate-resilient infrastructure
CSP	Concentrated solar power
DSO	Distribution system operator
EAD	Expected annual damage
EBRD	European Bank for Reconstruction and Development
EDF	Electricité de France
EEA	European Environment Agency
EIB	European Investment Bank
ENA	Energy Network Association
ENSREG	European Nuclear Safety Regulators Group
ENTSO-E	European Network of Transmission System Operators – Electricity
ENTSO-G	European Network of Transmission System Operators – Gas
EPCIP	European Programme for Critical Infrastructure Protection
ERA4CS	European Research Area for Climate Services
ERDF	European Regional Development Fund
ESF	European Social Fund
EU	European Union
EU-28	The 28 European Union Member States
EUFIWACC	EU Financial Institutions Working Group on Adaptation to Climate Change
FRMP	Flood risk management plan
GFCS	Global Framework for Climate Services
GHG	Greenhouse gas
HDD	Heating degree day
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre (of the European Commission)
LNG	Liquefied natural gas
LTS	Long-term strategy
NAO	North Atlantic Oscillation
NAP	National adaptation plan
NAS	National adaptation strategy
NC	National communication
NDC	Nationally determined contribution
NECP	National energy and climate plan
NGO	Non-governmental organisation
OECC	Spanish Office of Climate Change
OECD	Organisation for Economic Cooperation and Development

PBL	Netherlands Environmental Assessment Agency
PKW	Piano key weir
PV	Photovoltaics
RBMP	River basin management plan
RCP	Representative concentration pathway
RES	Renewable energy sources
TEN-E	Trans-European Networks for Energy
TNO	Dutch Organisation for Applied Scientific Research
TSO	Transmission system operator
TYNDP	Ten year network development plan
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOLL	Value of lost load
WBCSD	World Business Council for Sustainable Development
WEC	World Economic Council
WFD	Water Framework Directive
WPD	Western Power Distribution

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