European Commission

Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change

Final report

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Preface

This Final Report of the study: “Investment needs for future adaptation measures of in EU nuclear power plants and other electricity generation technologies due to the effects of climate change” is based on previous comments received from the Commission on the Draft Final Report, on feedback from the stakeholder consultation the Consortium conducted among a representative distribution of power plants throughout the EU and on the Ecorys Risk Assessment Model for analyzing the potential climate change risk thresholds for EU power plants and necessary accompanying investments.

The emphasis of this report is to present key preconditions for EU power plants (depending on technology) to operate successfully, to present the selected climate change and electricity scenarios for this study, to present the results of the consultation with EU power plant operators and to present a coherent risk assessment framework for analyzing the investments needed for power plants to adapt to future climate change effects. Furthermore, the synthesis will frame the results of the study and put them in perspective.

This Final Report was written by Ecorys, ECN and NRG. Several people within each of these organisations contributed to this report.

We would like to thank at this point the representatives of industry associations, power plants and other interested, whom have shared their views and provided valuable information to the team in the stakeholder consultation and more in-depth interviews.

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Rotterdam, 10 December 2010

Executive summary

Policy summary

Climate change is expected to have an impact on the electricity sector, leading to a need to invest in adaptation measures for electricity facilities in the near future. This study aims at specifying and quantifying these needs.

Thermal generation technologies, falling from a share in the generation mix of 85% in 2010 to 73% in 2050, can largely be considered as one homogeneous group as far as the impacts of climate change are concerned. The thermal technologies need to be protected from flooding and have a need for cooling and NPPs already have severe safety requirements in place. Renewable technologies are very heterogeneous and variable in their sensitivity towards climate change. Grids are quite susceptible to weather conditions and will be in need of precautionary measures to adapt to climate change.

To study the possible impacts of climate change at a regional level, three climate change scenarios (for different climatic zones) are chosen, which vary in their focus concerning three key climate change indicators, namely wind, temperature, and precipitation. Moreover, eight climate change indicators have been identified, namely water and air temperature, precipitation, average wind speed, sea level and extreme events like floods, heat waves and storms. In this way, the power sector can prepare for those climate changes that might impact on their day to day operations. In addition, Europe is divided into four climatic zones in order to show the regional differences in climate change impacts across Europe, without getting lost in too much detail.

For four defined climatic European zones, the baseline energy scenario of Eurelectric is employed in order to determine the size and generation mix of the power sector in the EU-27. From the Eurelectric scenarios, the baseline scenario has been chosen, as this scenario best follows the IPCC A1B scenario assumptions and is, for the time being, the only available energy scenario for Europe with a longer time horizon than 2030, and is also being used for EU policy making.

Utilities and power plant operators of all generation technologies across Europe have been interviewed using a questionnaire. A representative population of stakeholders of the different electricity generation technologies (across the EU-27 Member States) has been identified and were asked whether the impacts of climate change have been assessed and incorporated in their long term strategies, how the different effects influence daily operations and which costs, risks and investments are perceived due to climate change. One of the key results of the stakeholder consultation was that respondents and interviewees often found it hard to indicate precise values for the costs of climate change. To have a better indication of such costs, estimates have been made which were verified with a representative share of the stakeholders interviewed. The climate change and energy scenarios and the adaptation cost estimates have been joined together in the Ecorys Risk Assessment Model.

In this study, investment needs are identified in four of the eight considered climate change indicators and these are considered as severe climate change impacts:

- A decrease in precipitation will require preventive investments for hydro power plants in the Mediterranean region;

- An increase in the sea level will require preventive investments for offshore wind power plants in all European Seas;
- An increase in the occurrence of floods will require preventive investments for thermal generation technologies all over Europe, except for the North Sea region;
- An increase in the occurrence of storms will require preventive investments for networks all over Europe, except for the North Sea region.

Two other climate change impacts are categorized as medium, meaning that these climate change impacts are not yet expected to require investments for the scenarios consulted, but would require investments in the event that climate change impacts prove to be more severe than expected:
- An increase in water temperature would decrease the output of all thermal generation technologies;
- The changes in the level of precipitation is mixed, with increases in the North, largely unaffected in the North Sea and Central European Regions, while there is a projected decrease in the south (already mentioned under severe impacts).

Finally, a number of climate change impacts will only have a minor impact on power plant operation leading to a relatively small drop in generation output:
- An increase in air temperature would decrease the output of all thermal generation technologies;
- A decrease in average wind speeds (in the North Sea and Mediterranean regions) would decrease the output of onshore and offshore wind parks;
- An increased frequency of flooding events could pose a threat to concentrated solar power, geothermal and grids;
- An increased frequency of heat waves would decrease the output of all thermal generation technologies, but also of solar PV and would additionally increase the resistance of electricity transmission through grids with consequent increased transmission losses;
- An increased frequency of storm events would decrease the output of some renewable generation technologies, namely hydro, onshore and offshore wind, solar PV and concentrated solar power.

Planning for new generation technologies in Member States should prepare the power plant operator for the possible impacts of climate change and avoid unexpected disruption of generation, where, in addition to the climate change impacts mentioned above, the expected lifetime of a power plant is an important aspect to consider. For renewable energy plant operators the unit adaptation costs (= climate adaptation costs per installation in Euro) are about three times higher than for nuclear energy and over two time higher than for fossil fuel fired power plants.

Technical summary

Climate change, as indicated in the IPCC’s Fourth Assessment Report is likely to heavily impact on today’s society, including the electricity sector. Effects of climate change include an increase in the frequency of extreme weather conditions, an increase in mean temperature and modification of the regional water and wind cycles. These climate change indicators are expected to have an impact on the electricity sector such as causing supplementary infrastructural needs or not allowing machinery operations at 100% due to the impacts of climate change. For these reasons, it is foreseen that there will be a need to invest in adaptation measures for electricity facilities in the near future, which this report has tried to quantify.

The main research question of this study is: what are the possible climate change impacts on electricity generation technologies and how severe are these? To address this research question, this study sets out to detail the possible impacts of climate change effects for each electricity generation technology. From a policy perspective, this study aims at detailing actions that can be taken by Member States to adapt to possible climate change impacts in the power sector. This is done by pointing out the differences in climate change impacts per technology and climate zone, since the technology mix and the local conditions differ between the zones.

Background

According to the Eurelectric data, the technology mix of electricity generation in EU-27 in 2010 will be 28% nuclear, 53% fossil, 10% hydro and 9% other renewable energy sources. If biomass is also included the share of thermal in the generation mix goes up to 85% in 2010. Thermal generation technologies can be considered as one homogeneous group when the impacts of climate change are concerned. All thermal technologies need to be protected from flooding and have a need for cooling. Of the remaining 15% in the generation technology mix, 10% is generated by hydro. Hydro will be particularly sensitive to the water cycle, which is itself particularly sensitive to climate change. The remaining, mostly intermittent renewable technologies are relatively new and largely independent of temperature increases. The transmission and distribution grid, however, even today, is already quite susceptible to weather conditions and will be in need of precautionary measures to adapt to climate change.

Climate change scenarios

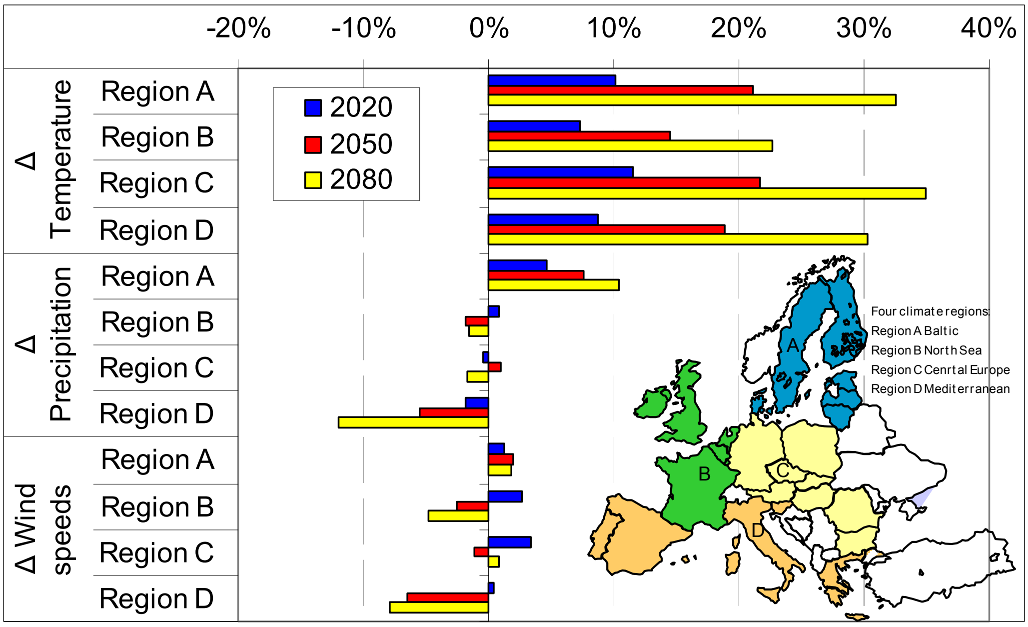
In order to estimate the possible impact of climate change, the A1B scenario of IPCC is used as the basis for future climatic variation. The main reason for working with this particular scenario is that the human induced pressures on the climate system will be most severe in this possible future and that planning of new generation capacity has to take into account this possibility. Moreover, this scenario is also commonly used in the scientific community and the more regional-based scenarios, which will be used in this study, also take the A1B scenario as starting point.

In this study three climate change scenarios have been developed using the ENSEMBLES RT2b database and its underlying climate experiments, based on a very comprehensive and well-known Commission’s FP6 funded research programme. These scenarios have been selected so that a wide coverage is possible for three key climate change variables for wind, temperature and precipitation, namely:

1. Wind scenario (CNRM experiment); name: WIND;
2. Temperature scenario (HadRM3Q0 experiment); name: TEMP;
3. Precipitation scenario (KNMI experiment); name: RAIN.

For these three scenarios, values of climate variables have been constructed, namely water and air temperature, precipitation, average wind speeds, sea level and extreme events like floods, heat waves and storms. The next figure reports the results for three key climate variables by taking the average values from the three regional climate change scenarios and indicates how Europe has been divided into four climatic zones using the principles: minimizing the climatic differences within the zone and maximizing the climatic differences among the zones.

Values of three key climate change variables and different climate zones in Europe



Note: Variable values are the average of the three selected regional climate change scenarios (WIND, TEMP, RAIN).

Energy scenarios

In order to estimate the size of the power sector, the endpoint of the baseline scenario of Eurelectric is used. The main reason for working with this particular scenario is that this is the only available scenario with a longer time horizon than 2030, includes all existing climate and energy policies implemented or planned to be installed by 2020, and is also being used for EU policy making. In addition, the choice of baseline scenario rather than the more ambitious Eurelectric Power Choices scenario (which has 80% greenhouse gas emission reduction in 2050) is that the baseline scenario is in line with the IPCC A1B climate change scenario. However, since the Eurelectric Power Choices scenario provides valuable insight in the impact of climate change in a situation of more ambitious and successfully implemented mitigation measures, the scenario has been analyzed as an alternative.

According to the Eurelectric baseline scenario, the technology mix of electricity generation in the EU-27 in 2050 is projected to be 28% nuclear, 39% fossil, 8% hydro and 25% other renewable energy sources. Furthermore, the Eurelectric baseline scenario projects that the generation need (= electricity demand) for the EU-27 will grow by 42% from 2010 to 2050. If electricity generation from biomass is also included, the share of thermal in the generation mix goes up to 73% in 2050.

Stakeholder consultation

Utilities (i.e. operators of thermal and renewable energy generation units and networks) were interviewed by using pre-developed questionnaires and by face to face interviews. The majority of these utilities are not considering the effects of climate change as a separate issue and these effects are, in most nuclear cases, addressed in the framework of Safety Reviews that are part of the licensing regime. Climate change will result in relatively small changes in efficiency that do not justify major investments in existing power plants. However, future power plants designs will incorporate the necessary adaptations to address future changes in climatic conditions.

From the interviews, it became also clear that climate change is having a minor effect on electricity generation with thermal power plants (representing 73% of the generation mix in 2050). It is therefore not a big issue on the agenda of the daily business of the power plants. Still, a minority of the power plants in Europe evaluated the risks to, and vulnerability of, their power plants to climate change and formulated a long-term strategy regarding these risks.

The three most influencing climatic effects on thermal power plants in Europe are:

- Flooding risks;
- Water temperature increase and cooling water availability decrease;
- Ambient air temperature increase.

These effects impact thermal power plants differently, thereby demanding different investments to cope with these problems.

Risk assessment

For the remaining 27% of generation needed in 2050, the climate change sensitivities vary considerably among renewable technologies. The following table summarizes the qualitative results of this study, being a combination of literature survey, stakeholder consultation and expert judgment.

The table shows that the water cycle is particularly important for hydro, where floods are graded as the most serious threat for which dams need to be further strengthened. Changes in precipitation patterns, which will increase by about 10% in the Baltic region and decrease by more than 10% in the Mediterranean region, will also pose a challenge for hydro. In addition, offshore wind is considered to be particularly sensitive to sea level rise. Obviously, wind is also sensitive to changes in average wind speeds (which will not change significantly in the climate change scenarios) and storms. Next, as previously pointed out, biomass has the same climate change sensitivities as thermal generation technologies. Furthermore, the relatively new solar technologies and geothermal only show minor climate change sensitivities, namely towards some extreme events. Finally, grids are the most sensitive to climate changes, with high sensitivities for air temperature (increased resistance) and increased storm damage, whereas other extreme events also need to be taken into consideration even though the climate sensitivity is relatively low.

Qualitative link between technologies and climate change effect

Technology	Δ air temp.	Δ water temp.	Δ precip.	Δ wind speeds	Δ sea level	Flood	Heat waves	Storms
Nuclear	1	2		-	-	3	1	-
Hydro	-	-	2	-		3	-	1
Wind (onshore)	-	-	-	1	-	-	-	1
Wind (offshore)	-	-	-	1	3	-	-	1
Biomass	1	2	-	-	-	3	1	-
PV	-	-	-	-	-		1	1
CSP	-	-	-	-	-	1	-	1
Geothermal	-	-	-	-	-	1	-	-
Natural gas	1	2	-	-	-	3	1	-
Coal	1	2	-	-	-	3	1	-
Oil	1	2	-	-	-	3	1	-
Grids	3	-	-	-		1	1	3

Note: 3 = Severe impact, 2 = Medium impact, 1 = Small impact, - = No Significant impact;

In addition to the qualitative climate change risk assessment, this study has taken the analysis one step further by undertaking a quantitative risk assessment as well, where the quantitative climate change and energy scenarios are joined together with adaptation cost estimates in the Ecorys Risk Assessment Model.

The figure below presents the results of this risk assessment analysis in monetary terms for the four climatic zones in the EU in 2080. The figure presents the aggregated (investment needs) results over the three regional climate change scenarios, expressed per generation technology and the transmission grid and the predefined climatic zones. The bars indicate the significance and size of the investment needs, however, a distinction has to be made between 'necessary' investment needs and 'potential' investment needs. The striped bars indicate that there is a 'necessary' investment need as the critical climate change threshold value for that technology and region has been crossed. In other words, investments for that technology in that region are critical for the continuation of successful electricity generation as operations otherwise have to be shutdown. The 'normal' bars indicate that there are 'potential' investments needed as the electricity generation technology in that climatic zone faces efficiency losses, however, the critical climate change threshold value for that technology and climatic zone are not surpassed and are as such not critical for the successful continuation of electricity generation operations.

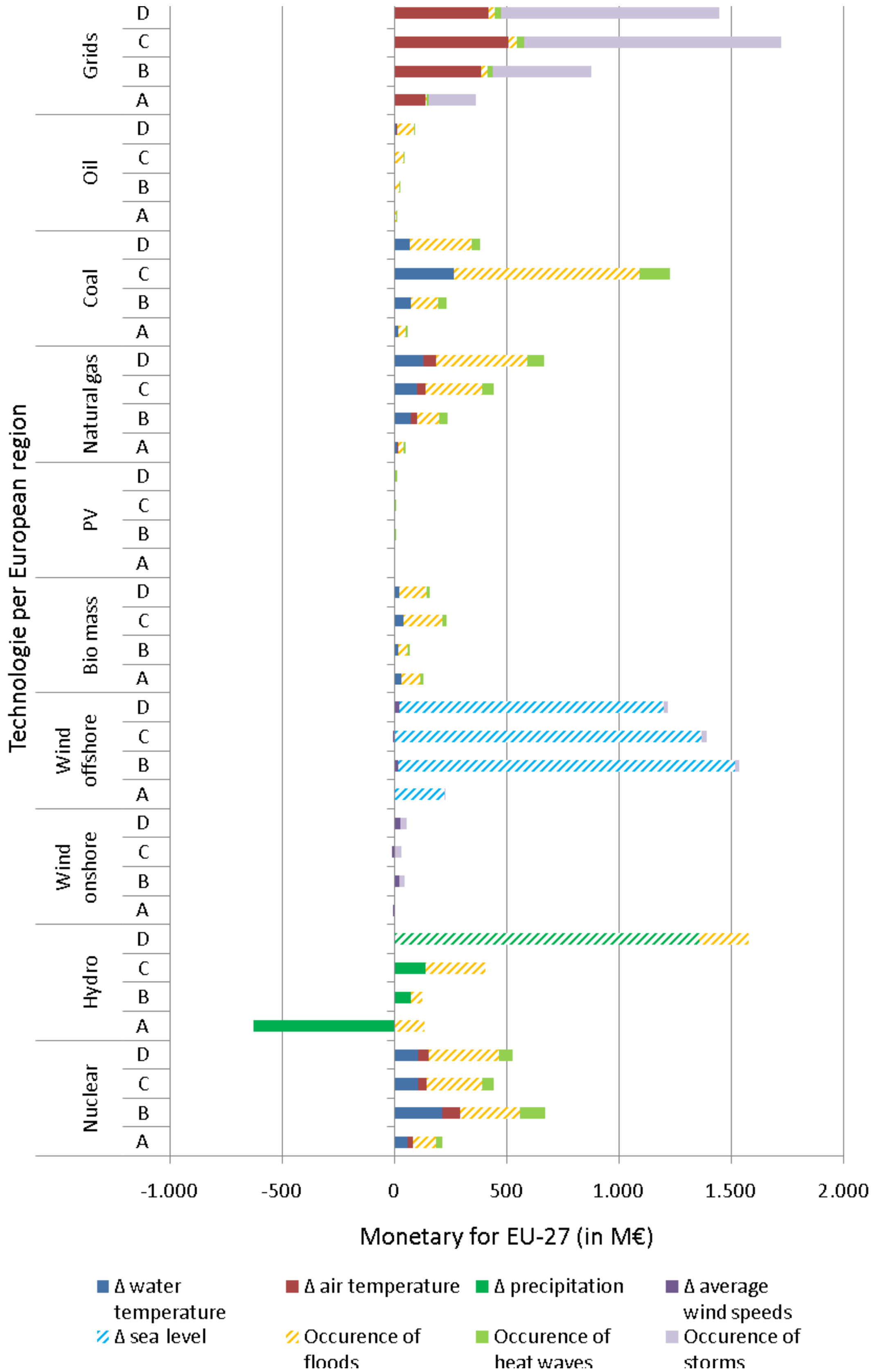
The main results in terms of climate change adaptation costs by power plants in the EU in the year 2080 are as follows:

- The average or gradual increases due to climate change, will reduce output, but do not require investments, except for:
  - lower precipitation severely affecting hydro in the South;
  - Sea level rise affecting off-shore wind.
- Changes in precipitation benefits the North, but the cost to the South is at least two times greater;
- Extreme events pose the greatest adaptation challenge:
  - Floods would affect nuclear, hydro & biomass and fossil fuel fired power plants;
  - Storms would mainly affect networks;
  - Extreme events cost most to Central Europe and the South, whereas only the North Sea region needs no investments in this respect.

Conclusions

The analysis of this report has mainly focused on potential vulnerability of power generation technologies in Europe. Planning of new generation technologies is needed, which could prepare the power plant operator for the possible impacts of climate change and avoid unexpected disruption of generation. Ideally, older power plants will ultimately be retired and replaced – in time– with the latest technologies, which are presumably more resistant to climate change. This will be true both for thermal and renewable generation technologies. Especially the generation technologies and plants with a relatively short lifetime, like wind, have the capability to adjust as time progresses. The challenge will be greater for technologies and plants with relatively long lifetimes, like nuclear and coal. Here all possible climate change impacts will have to be anticipated in the long lifetime ahead and there are great uncertainties about the rate that climate change impacts might materialize. Hence, it can be concluded that for planned or installed power plants it is key that climate change impact risk assessments are considered and undertaken, however, a change in awareness behavior is a necessary condition.

EU wide monetary impacts of climate change on power plant operation for four climatic regions



Note: On the vertical axis the electricity generation technologies are listed, including the climatic zones classification: A = Baltic region, B = North Sea region, C = Central and Eastern European region, D = Mediterranean region. On the horizontal axis the investment needs in monetary terms are flagged, where a 'positive' investment need means an increase in operational costs and a 'negative' investment need means an increase in operational benefits.

Table of figures and tables

Figures

Tables

1 Introduction

The IPCC's Fourth Assessment Report (AR4) indicates that climate change is likely to generate substantial impacts on society, including the electricity sector. Climate change effects include an increase in the frequency of extreme weather conditions, an increase in mean temperature, and modification of the regional water and wind cycles. These impacts are expected to have a strong impact on the electricity sector through increased need for infrastructure or by reducing the operating efficiency of machinery due to increased temperatures. It will accordingly be necessary to invest in adaptation measures for electricity facilities in the near future. This study aims at specifying and quantifying these needs.

1.1 Policy context

This section provides an overview of the policy context of the study and looks at the current state of climate change adaptation in the electricity sector. It concludes with an assessment of the possible impacts of climate change effects per electricity generation technology, which is elaborated upon in Chapter 2 and Annex A.

1.1.1 Background

The 'Green Paper on Adapting to Climate Change' [COM (2007) 354] established climate change adaptation as a core feature of the EU's climate change policy[1]. Climate change mitigation aims to reduce possible future impacts by dealing with the drivers of climate change (e.g. reducing greenhouse gas emissions), while climate change adaptation aims to minimise the impacts and negative consequences of climate change by building resilience into sensitive systems or by exploiting potential benefits.

The electricity sector is particularly sensitive to climate change effects, as its successful operation depends on a number of climate-related conditions. Changes to these conditions could impact strongly on the entire value chain of the power sector, affecting power generation capacity and infrastructure, and electricity consumption patterns.

The 'Green Paper on Adapting to Climate Change' recommends immediate action to achieve cost-effective results. Interaction between different governance levels in all Member States will be needed given the size of the problems and variability of context involved. EU-level coordination of such efforts and the integration of adaptation goals within a larger framework of common policies will prove important.

The Green Paper identifies four pillars for EU action. The first is the integration of adaptation goals in legislation, executive policies and existing Community funding programmes. It further suggests that new policies should be developed for potentially affected areas that are not covered by EU action. It also highlights the connection between water supply and electricity, urging for measures such as diversification or better demand and supply management. Other policy focal areas are the coastal zone, dyke management and water supply.

[1] Commission of the European Communities, 'Green Paper: Adapting to Climate Change in Europe – Options for EU Actions', June 2007, Brussels.

The ‘White Paper on Adapting to Climate Change’ [COM (2009) 174] proposes a framework for an EU-wide adaptation strategy[2]. It underlines climate change impacts on the electricity sector, particularly through its link to water supply, and rising sea levels and coastal areas management. A Commission Staff Working Document [SEC (2009) 338] accompanying the white paper, focused entirely on water, coasts and marine issues[3] and suggests that existing legislation (i.e. Water Framework Directive, Floods Directive, Marine Strategy Framework Directive) should be integrated. It also sheds some light on future policy developments.

1.1.2 *Climate change and the electricity sector*

The last impact assessment report from the Intergovernmental Panel on Climate Change (IPCC) (2007) forecasts a global average temperature increase of about 0,2ºC per decade for the next two decades[4]. Northern Europe is likely to experience increased annual precipitation and winter temperatures, while Mediterranean Europe is likely to experience decreased precipitation and increased summer temperatures and droughts. The average wind speed is likely to increase, leading to an increase of extreme weather events. In Central-Eastern Europe, precipitation is likely to decrease in summer, with more frequent droughts, and increase in winter. The snow season is very likely to become shorter and snow depth across most of Europe to decrease.

The latest IPCC impact assessment report on impacts, adaptation and vulnerability provides a detailed overview of possible effects on the electricity sector in the course of this century and variation between different regions of the continent[5]. This is important as the regions have different electricity generation mixes, available resources and climate- or electricity-related policies and agreements. Table 1 summarises the impacts on electricity supply, distribution and seasonal demand.

Table 1 Summary of main expected impacts of climate change on the electricity sector in Europe during the 21st century

Area of Europe	Northern	Atlantic	Central	Mediterranean	Eastern
Electricity supply and distribution	+	++	+	-	+
Winter electricity demand	++	++	+	++	+
Summer electricity demand	-	-	--	---	--

Source: IPCC 2007 AR4 WG II. The plus sign indicates a positive impact and the minus sign a negative impact, the number of signs indicates the size of the impact.

The IPCC report further notes that electricity demand patterns should be one of the first to be changed. The demand for electricity in winter would decline due to a reduced need for space heating, and increase in summer in response to an increased need for cooling. The productive capacity of renewable energy, heavily relying on environmental conditions, is expected to change dramatically. Traditional energy sources and the infrastructure and grid system for electricity transportation, though less sensitive to environmental conditions, may also be affected. Some non-comprehensive examples such climate change impacts are given in Table 2.

2 Commission of the European Communities, ‘White Paper: Adapting to Climate Change – Towards a European framework for action, April 2009, Brussels.

3 Commission of the European Communities, ‘Commission Staff Working Document *accompanying the* White Paper: Adapting to Climate Change – Towards a European framework for action, April 2009, Brussels.

4 IPCC, Solomon, S. et al.(eds), Climate Change 2007: The Physical science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change, 2007, Cambridge University Press, Cambridge.

5 IPCC, Pary, M. et al.(eds), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment report of the Intergovernmental Panel on Climate Change, 2007, Cambridge University Press, Cambridge.

Table 2 Expected impacts due to Climate Change

Area of analysis	Expected impact due to climate change
Thermal power production	Reduced availability of cooling water, negative impact on performance and production of all traditional sources.
Distribution	Increase of mean temperatures implies an increase in line resistance; increase of maximum temperatures will impact negatively on line sag and gas pipeline compressor efficiency.
Hydropower	With the temperature increase, potential is expected to grow in northern countries and to decline in southern ones with an overall negative effect: decline by 6% by 2070.
Wind power	Small increase in wind production in Northern and Atlantic Europe.
Biomass-based power	Plant designs allow for absorption of climate impacts to some extent but less cooling water may be negatively impact operation.
Solar PV	Increased cloud cover will decrease the yield of solar PV in Scandinavia, whereas a higher solar irradiance is assumed to increase the yield in southern Europe.
Concentrating Solar Power (CSP)	CC impacts on future CSP projects will probably be relatively minor, as the need for low cooling water demands is already factored in at the design of the plan.

Source: AR4 WGII, Ch.12.

Cause-consequence patterns between environmental climate change modifications, the impacts on electricity generating operations, and the consequent needs for adaptation measures are becoming increasingly evident. It is worth stressing how this rapidly increasing evidence is taken as an indication for intervention through adaptation policies, aimed at minimizing the impact of these environmental changes on Europe's electricity sector.

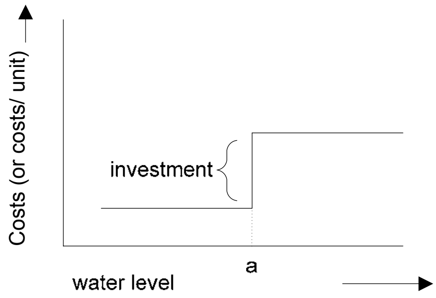
1.1.3 Impact of climate change effects on electricity generation technologies

Climate change impacts will vary depending on the electricity generation technology concerned (i.e. fossil fuels, RES and nuclear). This study therefore categorises and assesses the impact of the different climate change effects per electricity generation technology. The categorisation and pre-conditions for successful operation of the different electricity generation technologies are elaborated in detail in Annex A.

Climate change results in a changing behaviour of the climate system as a whole. Changing weather patterns and climatic characteristics may generate different ‘large-scale’ climate change effects, depending on factors such as the local geography and climate system. Examples of relevant climate change effects include changes in precipitation, cloud cover, temperature profiles, and wind speed and flows. All of these effects could have an impact on electricity generation. The increased occurrence of heat waves, for instance, is likely to affect the cooling of nuclear and gas-fired power plants; also lead to increased demand from peak plants (gas turbines and pumping stations), and hamper the efficiency of hydro-plants as a result of a lack of water. Electricity networks may further overload because of sudden increases in the power demand for cooling, which increases also the chances of contingencies because of the extraordinary hot temperature. The impact of a changing weather conditions is described in more detail in Chapter 3.

There is a complex relationship between climate change and investments needed to adapt to the potential climate change effects (i.e. differences on regional levels). Therefore, the impact of climate change effects should be treated in different manners. For example, depending on the impact, a threshold point should be concluded where investments are necessary for power plants to make (e.g. water level threshold value).

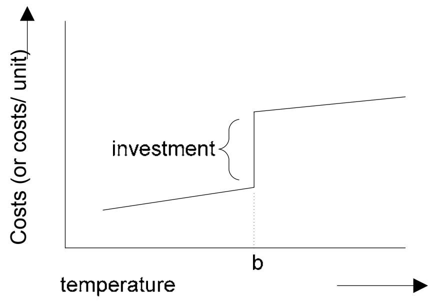
Figure 1 Fictitious relation between a water-level increase and costs



The discontinuity in the figure above (a) shows the extra investment that would be needed at a certain increased water level with an associated climate change effect value, such as an investment in a dike. In this example the costs do not gradually increase with rising water level, but show a sharp discontinuity.

Another example is a rise in water temperature, giving rise to cooling problems. The figure below shows a gradual increase in costs with rising temperature.

Figure 2 Fictitious relationship between a temperature increase and costs



These costs are caused by the reduced efficiency associated with running at lower capacity to cope with the cooling problems. It also leads to the need for extra investment, into an extra cooling plant for instance, at a certain point (b) to avoid having to shut down the plant.

1.2 Objectives and output of the study

The general objective of this study is to assess climate change-related investments needs of EU nuclear power plants, fossil and renewable electricity generation technologies. The following methods were used:

- Collection of information and data collection about the present climate-related conditions (or pre-conditions) for fuel supply and electricity demand patterns and for electricity production (nuclear, fossil, renewable), nuclear fuel cycle operations and planned future nuclear power plants and electricity distribution infrastructures;
- Compilation of realistic climate change scenarios for different climatic zones of the EU;
- Collect and analyse information and data about climate change-impacts on the identified pre-conditions;
- Identification and evaluation of adaptation needs for the identified technologies and infrastructure;
- Assessment of the investment needs of the various technologies and infrastructures.

The study will generate the following outputs:

1. Main pre-conditions for successful operation of current electricity generation technologies and distribution infrastructure in the EU;
2. Main causes and consequences patterns generated by these pressures on the successful operation of generation technologies and distribution infrastructures, taking into account the security of supply, electricity prices and the environment;
3. Risk assessment of the potential loss of successful operation for the different technologies and distribution infrastructures;
4. Corresponding investments needs in different climatic zones of the EU for different electricity generation technologies;
5. Recommendations on new requirements at national and EU levels on the siting of installations, construction design parameters, and assessment of the effects on construction, operation, maintenance costs when relevant.

1.3 Structure of the report

The report is structured as follows:

- Chapter 2 provides the a background on electricity generation technologies in the scope of this study, followed by a discussion of the methods used for stakeholder consultation;
- Chapter 3 describes the different climate change scenarios for Europe and those selected for this study;
- Chapter 4 describes the electricity supply patterns in Europe and explains which electricity scenario projection was chosen for this study;
- Chapter 5 presents and analyses the views of stakeholders, such as the European electricity generation and transportation industry, on climate change impacts and associated costs;
- Chapter 6 presents the cause-consequence patterns of climate change effects on electricity generation operations and a risk assessment for the different generation technologies. This is followed by an estimation of the investment needs per electricity generation technology and climate zone using the Ecorys Risk Assessment Model;
- Chapter 7 presents a synthesis of the results, the conclusions and associated policy recommendations.

2 Background on electricity generation technologies

2.1 General approach

In this chapter we introduce the different power sectors, viz.

- Nuclear power;
- Fossil-fuelled power;
- Renewable electricity, namely:
  - Hydropower;
  - Wind power, on- and offshore;
  - Photo Voltaic (PV) power;
  - Concentrating Solar Power (CSP);
  - Biomass-based power.
- Electricity transmission and distribution.

All these sectors are described below in terms of their current status and role in Europe, physical and technical characteristics and sensitivity to weather and climatic effects. These descriptions are based on our own experience and expertise, supplemented with scientific literature.

From this information we have formulated questionnaires, different for each type of stakeholder per electricity sector. These can be found in Annex D.

2.2 Nuclear electricity generation

2.2.1 Introduction

Over the last 20 years nuclear power plants have contributed a steady 30% of electricity generation in Europe. The process to generate electricity is thermal, where steam is created to drive a turbine, similar to plants that are powered by fossil fuels. The essential difference lies in the heat source for steam production, which in a nuclear power plant is provided by the heat from nuclear fission.

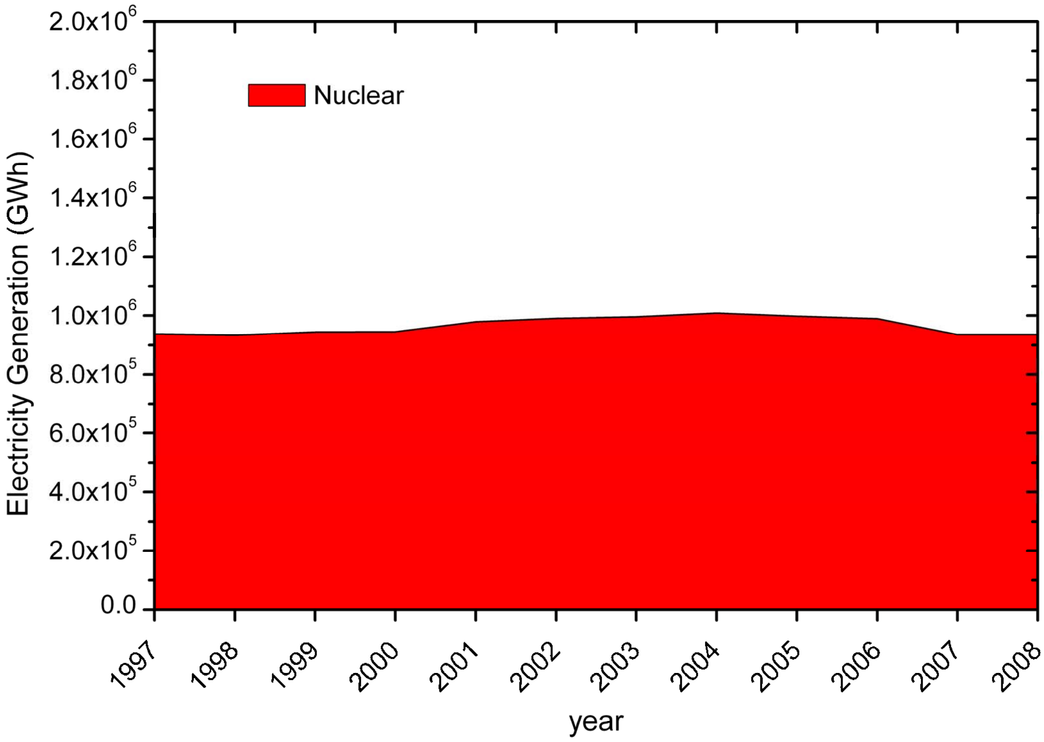
2.2.2 Role of nuclear electricity generation in Europe

The use of nuclear power in Europe shows a large variation over the EU member countries. While 12 of the Member States do not use nuclear power at all, in the remaining 15 states nuclear power contributes from 4 % (Netherlands) up to almost 80 % (France) of the electricity production.

Following accidents with nuclear power plants elsewhere in the world, notably at Three Mile Island in 1979 and at Chernobyl in 1986, the growth of nuclear power for electricity production came to a halt. Recently, however, the interest in nuclear power has revived and several countries, both in Europe and elsewhere in the world, are considering lifetime extension of NPPs, replacement of older plants by new ones, and in some cases an increase of the installed nuclear capacity. This renewed interest is partly driven by the fact that operating nuclear power plants does not cause CO_2 emissions.

As can be seen in the figure below during recent years there has been a slight decrease in electricity production by nuclear power mainly caused by power plants that have reached the end of their lifetime and have been decommissioned, while no replacements have been installed.

Figure 3 Nuclear electricity generation in the EU-27



Source: Eurostat, 2010.

2.2.3 *Electricity generation from nuclear fission*

Like electricity generation by conventional thermal power plants (see section 2.3), electricity generation by a nuclear plant is based on the Carnot cycle and the efficiency of the conversion process is proportional to the difference in temperature between the heat source and the heat sink. The heat source is a controlled nuclear fission process that takes place in the nuclear reactor core. The heat sink is either river water or sea water or a large cooling pond, similar to conventional thermal plants. Some details of the design and operation of a nuclear power plant are presented in Annex A of this report.

Because of the thermodynamics of the power generation process, the efficiency of electricity production from nuclear power depends, among other factors, on the temperature of the cooling water inlet, whether cooling towers are used and on the ambient air temperature. Hence nuclear power generation will be susceptible to climate change effects.

Various nuclear reactor designs have been developed and built in Europe. Calder Hall in the U.K. was the first nuclear power plant (NPP) in Western Europe that became operational in 1956. This NPP and several others that were built between the late fifties and early seventies, belong to the so called generation I reactor designs, which have nearly all been decommissioned. Most currently operating nuclear power plants in EU Member States have generation II reactor designs and have a design life of 30 to 40 years. Almost all these plants have been upgraded to improve the efficiency and safety level of operation.

Presently, two nuclear power plants using a generation III reactor design, with a lifetime of up to 60 years, are being built and several others are planned. Compared to earlier designs, generation III reactors have improved fuel technology, superior thermal efficiency, passive safety and standardized design for reduced maintenance and capital costs.

Compared to conventional thermal plants, operation of a nuclear power plant requires additional pre- and post processes. These are discussed in more details in section 2.2.5 and in Annex A.

2.2.4 *Climate change impacts on nuclear energy generation*

In this section are described the potential climate change effects on normal operation of nuclear power plants. The main issues of relevance are the effects of water temperature and availability, air temperature and floods.

Cooling water temperature and availability

As explained above, nuclear power plants, like most fossil-fuelled power plants, need water in the production of electricity.

For power plants at inland river locations, the availability and temperature of cooling water may give rise to problems, particularly during heat waves. In such cases, the power plants have to reduce their operating power or even completely stop production, usually in response to environmental regulations, which leads to a loss of revenue. However, if there exists an urgent need for electricity production, regulatory bodies are sometimes willing to grant a temporary exemption from the cooling water restrictions.

For inland power plants additional cooling can be provided by cooling towers, but for most utilities the required investment does not outweigh the loss of profit, since - by present standards - heat waves are exceptional events. However, with increasing temperature, as predicted by climate scenarios, high cooling water temperatures are expected to occur more frequently, so that future nuclear power plants might increasingly make use of cooling towers or other cooling facilities.

For power plants situated on the coast, which use sea water for cooling, there is hardly any climate impact to be expected, since the predicted rise of the sea water temperature is very moderate. For power plants located on the Baltic Sea, where water temperatures may occasionally rise above 20 ^{o}C during the summer, it has been suggested that a deep water intake might secure the availability of sufficiently cold (4 ^{o}C) water.

Ambient air temperature

Higher ambient air temperatures, particularly affect those nuclear power plants that make use of cooling towers, in a negative way. This is because the efficiency of the plant is proportional to the temperature difference between the steam inlet and the condenser temperature and is ultimately governed by the ambient air temperature. It is estimated that an increase of air temperature by 1 ^{o}C leads to power loss of 0.1 %.

In addition a rise in ambient air temperature might give rise to higher temperatures at working locations within the power plant, and may also influence the proper functioning of safety related equipment like the emergency diesel generators. In such cases the installation of additional cooling units could readily solve these problems.

Floods

Floods are perceived as a major threat to the operation and safety of nuclear power plants. Possible causes are heavy rainfalls as well as an increase of sea water levels, such as caused by high tides in combination with storm surges as has happened in 1999 at the Blayais nuclear power plant at the Gironde estuary in France. On this occasion safety related equipment was affected by the flood, while at the same time the power plant became inaccessible since access roads were submerged and air access was impossible because of heavy storms. Mainly as a result of this event, a worldwide re-evaluation of the safety risks due to flooding was carried out.

The safety of nuclear power plants is evaluated every 10 years in the framework of a Periodic Safety Review (PSR), and in many European countries protection against flooding is assumed to be sufficient for even longer periods.

While future climatic changes may lead to a more frequent occurrence of floods, the associated risks have been taken care of for periods of at least 10 years, in some countries even extending up to the year 2100.

2.2.5 Climate change impacts on nuclear fuel cycle aspects in Europe

Compared to conventional thermal plants, operation of a nuclear power plant requires additional pre- and post processes, called respectively the front-end and the back-end of the nuclear fuel cycle. The front-end comprised mining and milling of the uranium ore, extraction of uranium (compounds) from the ore, fuel enrichment and fuel fabrication. The back-end consists of intermediate storage, reprocessing and final disposal of spent fuel elements and the management of liquid and solid radioactive waste.

Although mine and milling of uranium ore takes mostly place outside the European Union, all processes of the nuclear fuel cycle are carried out in at least one of the EU Member States.

However, as for nuclear power plants, Periodic Safety Reviews are carried out for front and back end nuclear facilities every 10 years, where safety issues, including the impacts of climate change during the next 20 years, have to be assessed. Presently there is no concern for the operation of any front- or back-end process or facility due to the possible impact of climate change.

2.3 Electricity generation from fossil fuels

2.3.1 Introduction

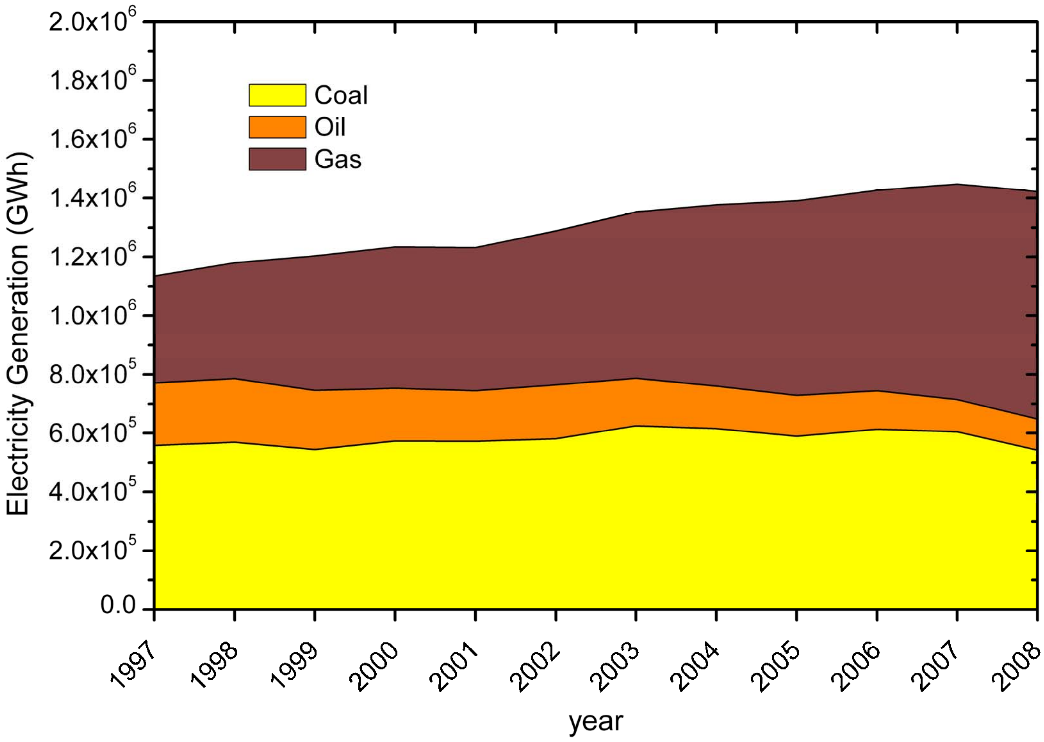
Fossil fuels have remained the primary source of electricity generation in the world. To generate electricity these fuels are burned in order to create steam or combustion gases that make the blades of a turbine spin. Fossil fuels can be categorized into three main groups:

- Coal;
- Natural gas;
- Petroleum products (oil).

2.3.2 Role of fossil fuels in electricity generation in Europe

In Europe, as in the rest of the world, fossil fuels still play a major role in the generation of electricity. Over the last 10 years, the percentage of electricity generated by means of fossil fuels has remained more or less stable around 55 percent of the total electricity generation. Although the total use of fossil fuels increased slightly, the share of the individual categories – viz. coal, petroleum products and natural gas – has changed remarkably. As can be seen in the figure below there has been a tendency towards the use of natural gas, at the expense of both coal and petroleum products. The most predominant reasons are the increasing oil prices and, of all fossil fuels, natural gas is the cleanest in terms of air pollution and CO_2 emissions.

Figure 4 Electricity generation from fossil fuels in the EU-27



Source: Eurostat, 2010.

2.3.3 Electricity generation from coal

In a conventional coal-fired plant water under high pressure is pumped into a boiler. By burning finely ground coal (pulverised coal) the water is heated. There are also coal-fired plants that operate via an Integrated Gasification Combined Cycle (IGCC) procedure. During this procedure, the coal will first be gasified. Subsequently, the gas is burned in a gas turbine and the remaining heat is again used to generate steam heat.

The water in many parts of the boiler is heated until it becomes superheated steam with a temperature of about 550 °C and a pressure of 180 bar. When the steam from the boiler is drawn in a steam turbine the energy in the steam is converted into rotational energy. The pressure and temperature of the steam below are considerably reduced. With rotational energy of the steam turbine a generator is driven that generates the electricity.

The steam from the high-pressure steam turbine is led again to the boiler to increase the energy content, and then in the medium and low pressure steam turbines to further expand thereby driving the generator further. When the steam is fully expanded, it will be condensed into water and can be used again. During this condensation process, a lot of heat is produced. To cool the condenser, often cooling water is used, and possibly even aided by cooling towers. In a few cases, the facility is cooled-down by air. The cooling agent ultimately depends on the type of plant, surrounding water temperature or ambient air temperature, and the availability of abundant water supply.

A modern coal plant can achieve an efficiency of 46 percent using (ultra) super critical technology with temperatures going up to 566–593 °C. This means that 46 percent of the energy content of the coal is converted into electricity. The efficiency of older plants is often about 35 percent. The remaining part is transferred into heat losses that cannot be converted into electricity.

2.3.4 *Electricity generation from natural gas*

In conventional gas-fired power plants, water under a high pressure (about 180 bar) is fed into the boiler and heated by burning the natural gas. The water converts into steam and will be heated further to approximately 550 °C. The energy content of the steam is converted into mechanical rotational energy by a turbine to drive the generator that generates electricity in its turn. The steam from the high pressure steam turbine is reheated and used again. When the steam is fully expanded a condenser is employed, where the condensed steam turns into water and is reused. For cooling the condenser often cooling water or cooling towers are used. The most common technology for gas-fired plants is to operate via a Combined Cycle Gas Turbine (CCGT) procedure. In this way an efficiency of over 60% is possible for the most modern plants.

2.3.5 *Electricity generation from oil*

An oil-fired power plant operates on different types of oil, and works similar to a coal fired power plant. The oil is heated with steam and mixed with air after which the mixture is combusted to heat the water in the boiler.

2.3.6 *Climate change impacts on fossil-fuelled electricity generation*

In this section we have described the potential climate (change) effects upon normal operation of fossil-fuelled power plants. We focussed on impacts that are specific for these types of plants, thereby omitting obvious extreme climatic impacts such as hurricanes, floods, etc. The issues under scrutiny are the effects of water temperature and availability, coal supply and air temperature.

Cooling water temperature and availability

As explained above, most fossil-fuelled power plants need water to cool their equipment. However, the waste water produced during this cooling process is potentially harmful for the water temperature and the local ecosystem. To overcome these harmful effects on the environment governments or water boards impose legal constraints on the power plants on cooling water usage. These regulations can be restrictions of water usage by stipulating the inlet capacity. Another example is that there is a maximum tolerated difference between the inlet and outlet temperature or the power plant cooling water temperature output has to be within specified ranges, so to prevent warming of the water body (Rothstein and Halbig, 2010).

Although depending on the geographical location, climate change can have a serious impact on the operation of the fossil-fuelled power plants through the effects on cooling water. These effects can be of a legal nature when the inlet water is too warm. In that case, the power plants need additional water to cool their equipment, or have to discharge cooling water of a higher temperature. In order to comply with the legal constraints, the power plants have to reduce the electricity generation or come to a full stop. Thereby, the plants reduce their revenues and make costs (Rothstein and Parey, 2009).

The effect of climate change on cooling water can also be a physical constraint when due to dry periods the water level of the water bodies decreases. In that case, the water availability is not enough to cool the equipment down sufficiently and the plants need stop electricity generation to prevent overheating. This can be especially the case for fossil-fuelled power plants that are cooled by river water (Rothstein and Halbig, 2010).

An additional problem climate change induced cooling water issues is the combined effect of the legal and physical constraints. For example, during the hot summer of 2003 in west and central Europe, high water temperatures and low river levels occurred simultaneously. This resulted at the restriction that only fossil-fuelled power plants could stay in operation that had cooling towers (Eyster, 2004).

Water level for coal supply

An additional problem can arise for the supply of coal for coal-fired plants due to climate change. Coal-fired plants can only operate economically if they are constructed closely to a coal mine or when the coal can be transported in via waterways. In case the water level of the water ways drops too low the coal-fired plants risk that their coal supply is delayed or hindered. In that case, coal must be supplied via train or truck which brings high costs with it (Rothstein and Halbig, 2010).

Ambient air temperature

Higher ambient air temperatures affect fossil-fuelled power plants – especially natural gas-fired facilities – in a negative way. There a basically two effects. Firstly, the power needed to drive the compressor that compresses the inlet fuel mixture is based on the difference between the inlet and outlet pressure of the gas. Since warmer air is harder to compress than colder air, the compressor needs additional power. This will ultimately affect the efficiency of the whole plant, since more of the electricity generated is needed for additional power for the compressor, thereby producing less net electricity output.

Secondly, all fossil-fuelled power stations need air (oxygen) to burn the fuel and release the heat to warm the boilers. Since warm air contains less oxygen as the same volume of cold air, additional air, and thus compressing and pumping power, is needed to produce the same amount of electricity, thereby affecting the efficiency of the fossil-fuelled power plants negatively.

As in general it can be expected that the air temperatures will rise due to climate change over the coming years, the costs can theoretically increase dramatically. It has been mentioned that increases of ambient air temperature of 10 °C can lead to several percentages of efficiency losses (Leopold, 1984). These effects are already observed for the differences between winters and summers.

2.4 Electricity generation from renewable electricity sources

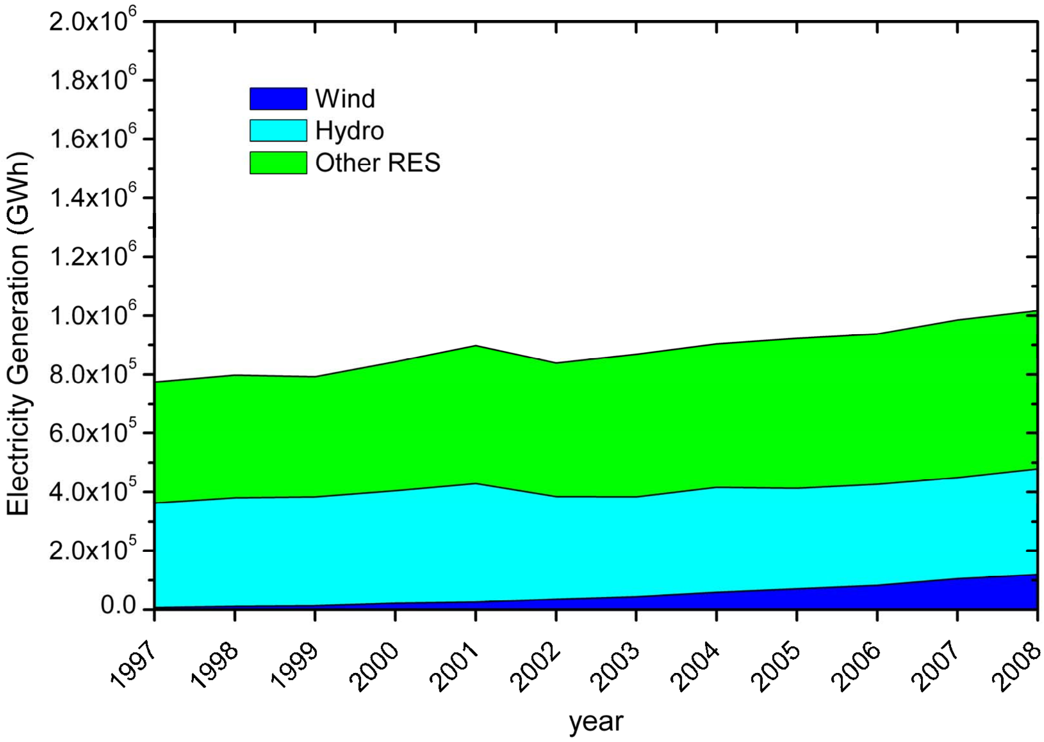
2.4.1 *Introduction*

Renewable electricity sources currently meet approximately 14 percent of the global electricity demand and are poised to play an even greater role in the future. They are categorized as follows:

- Wind power (onshore and offshore);
- Hydropower;
- Biomass-based electricity;
- Photovoltaic electricity (PV);
- Concentrating Solar Power (CSP).

In the figure below, the contribution of renewable energy sources to the European electricity mix is graphed.

Figure 5 Renewable electricity generation in the EU-27



Source: Eurostat, 2010.

2.4.2 *Wind power*

Of the renewable energy technologies applied to electricity generation, wind electricity ranks second only to hydroelectric in terms of installed capacity and is experiencing rapid growth. Aside from its role in mitigation, wind electricity will also experience effects of climate change itself.

(Long-term) climate change impacts on wind electricity

Given the energy in the wind is the cube of wind speed, a small change in the wind climate can have substantial consequences for the wind energy resource. For a change in wind speed at turbine hub-height from 5.0 to 5.5 m/s (i.e. a 10 percent change), the energy density increases by over 30 percent. In general, however, the impact on wind energy will be much more limited. Global Climate Models (GCMs) indicate an absence of significant changes in wind energy density to the middle of the 21st century, and that changes by the end of the 21st century in the mean and 90th percentile wind speeds and energy density are small (<±10%) and comparable to the natural variability within the climate system (Pryor and Barthelmie, 2010).

Other factors

Pryor and Barthelmie (2010) also reviewed possible impacts of climate change on offshore wind energy. An increasing air temperature and more extreme temperatures do not impact (offshore and onshore) wind energy significantly. This also seems to hold for vertical wind shear, and changes in land cover. For offshore wind relevant phenomena may be changes in sea level and/or salinity and changes in the 20-year return period wave. The impacts thereof on offshore wind energy appear to be limited, at least on the timescale of the lifetime of offshore wind farms.

2.4.3 *Hydropower*

Hydropower is the most important source of renewable electricity today. Impacts from climate change on hydropower are related to glacier cover, precipitation patterns, and resulting changes in (annual) discharge and river run-off. Climate change may significantly impact the hydropower resource in the timeframe until 2050. Changes will be less significant on the medium term.

Geographical differences

Due to climate change, *Northern Europe* may benefit from an increase in discharge and river run-off. Additional precipitation may benefit Belgium, the Netherlands, and the UK, as well as the Baltic and Nordic states. The potential for hydroelectric generation is hence expected to grow by more than 25 percent by 2050 and up to 30 percent by the 2070s (Alcamo, Moreno, and Nováky, 2007; Lehner, Czisch, and Vassolo, 2005), with the largest increases in Scandinavia (EEA, 2008).

Mediterranean and even *Central and Eastern Europe* may experience a decrease in hydroelectric generation of around 25 percent by 2050 (Jochem & Schade, 2009) and up to 50 percent by the 2070s (Alcamo, Moreno, and Nováky, 2007). Hydropower is likely to suffer from reduced annual precipitation, especially in winter, due to changing climate patterns, except in the Alps and in Portugal where run-off water may raise generation. At the same time, Alpine run-off would become subject to greater intra-annual variability as summers grow hotter (Jochem & Schade, 2009).

2.4.4 Biomass-based electricity

Biomass is a common source of renewable energy. It can be combusted in dedicated biomass-based power plants where the heat produced by combustion in a boiler can be used to generate electricity or in combined heat and power (CHP) plants, where the waste heat is recovered (IEA Bioelectricity, 2009). Biomass can also be co-fired, predominantly in coal-fired power plants.

Availability of biomass

Climate change is expected to have a manifold influence on the supply of biomass, mainly through its effects on land use patterns and biological productivity (Mideksa & Kallbekken, 2010). Wood contributes most to biomass-based electricity generation. With regard to forest-biomass, most models project that moderate temperature growth will positively impact the global forest sector, increasing timber supply (Kirilenko & Sedjo, 2007). However, the reliability of such predictions is limited by factors such as pests, weeds, competition for resources, soil water, air quality, etc. (Kirilenko & Sedjo, 2007). Karjalainen et al (2003) assume that active forest management will increase felling across Europe by 0.3 percent per annum until 2020-2030 and stabilize afterwards.

2.4.5 Photovoltaic electricity

Photovoltaic electricity (PV) is a young renewable electricity generation technology, mainly based on solar panels installed on roofs of buildings. Pašičko (2010) analysed the impact of climate change on PV in Slovenia. For crystalline silicon based cells, for each 1°C temperature raise the cell efficiency decreases by 0.4-0.5 percent in relative terms. Therefore, if the ambient temperature would increase by 2°C in Mediterranean countries - factoring in the large share of solar electricity in the summer compared to other seasons - the impact on the efficiency of solar cells in the Mediterranean would be -1 percent, e.g. a reduction from 15 percent to 14 percent efficiency.

(Fidje and Martinsen, 2006) analysed the impact of climate change on solar electricity (PV) in Scandinavia. In contrast to the projections for the Mediterranean, the solar irradiance in Scandinavia is expected to decrease by 2 percent. According to the authors, there are other factors that negatively impact the yield of solar PV, e.g. decreased reflection due to less snow cover, a disproportionate decrease in diffuse solar irradiation which relatively strongly impacts the yield due to a higher reflection of the diffuse component of diffuse solar irradiation compared to direct solar irradiation. The combined effect would entail a reduction of the yield of PV systems of 6 percent.

2.4.6 Concentrating Solar Power (CSP)

Concentrating Solar Power (CSP) is a young renewable electricity generation technology that can only be applied in lower latitudes based on direct solar irradiance. There are only a few literature studies that shed light on the question of possible impacts from climate change.

Cooling water temperature and availability

The main impact of climate change on CSP plants is reduced availability or absence of cooling water. This problem can be more serious than for conventional thermal power stations, as CSP plants are usually located in arid regions already suffering from water shortages, while thermal plants are located with cooling needs in mind. CSP plants are designed with either wet or dry cooling systems, but if water availability decreases dry cooling may be favoured. A number of future CSP plants in the Mediterranean region will also be built with dry cooling. Also, the solar dish technology (based on Stirling engines) lays claim to significantly lower water usage than other CSP technologies. This technology, however, is not as well as developed as other CSP technologies.

2.5 Electricity transmission and distribution facilities

2.5.1 Safe and reliable electricity networks

A climate-proof grid is essential for a reliable[6] electricity system, as electricity networks form the link between supply facilities and end users and are as such essential for an effective supply of power. If a single power plant fails, others can fill the gap, but alternative network routes are not always available. Moreover, supply and demand must be balanced, excessive voltages and frequency fluctuations must be avoided, and the systems should not pose a threat to health, safety or the environment. This means that operating temperature must be kept at safe levels, grids should not be interrupted, and maintain a safe distance from people and buildings.

Climate conditions affect this in four ways – through wind and storms, temperature, drought and flooding. For the purpose of this analysis, network infrastructure is divided into lines and nodes. The nodes consist of facilities like substations, generating facilities and demand centres. They are connected by lines, usually overhead transmission lines or underground cables.

2.5.2 Wind speed and storms

Network operators are most concerned about a potential increasing frequency of high winds and storms due to climate change. This can cause serious damage, toppling pylons and downing overhead lines, as has already occurred in the past:

- RWE Netz had to re-enforce 28,000 pylons of its transmission grid following icy winter storms in 2005. This cost the company €500 million;
- France suffered severe storms in January 1999, with gusts of up to 200 km per hour, during which 3.5 million customers lost power. The resulting costs to EdF were €1.1 billion (Peters et al, 2006);
- In the Netherlands, five pylons of Tennet's transmission grid were blown over in a thunder storm in July 2010. The pylons were installed in 1971, and should have lasted 50 to 100 years. Tennet has since engaged in a comprehensive analysis of the potential impacts of climate change on electricity transmission.

[6] Two common measures of network reliability exist. The System Average Interruption Frequency Index (SAIFI) represents the share of connected customers that experiences power interruption in a given year. The System Average Interruption Duration Index (SAIDI) indicates the average outage time per connected customer. Usually, neither includes storm-related outages (Peters et al, 2006).

Table 3 Impacts of increasing wind speed and storms on electricity networks

Impact	System affected	Threshold	Level of impact	Area affected
Wind and storm damage	Overhead lines and pylons	Variable	Variable: estimates range from €1.600 per fault to €17,000 per pylon and attached lines	North sea & Baltic
Increasing heat convection	Overhead lines	Continuous	+20% possible load (A) with each m/s rise in wind speed	North sea & Baltic

Network operators in vulnerable areas are prepared for such events, and most systems are fairly resilient already. Moreover, storm disruption is often highly localised, so that only a small share of electricity supply is affected, if power flows can be re-routed. For example, one respondent expects that even with a 50 km/h (13.8 m/s) increase in wind speed 90 percent of electricity could still be transported.

Strengthening networks to prevent storm damage is considered important by several network operators in (Western) Europe. In France, RTE is improving the 'mechanical security' of its network following extensive storm damage in 1999. By 2017, it will have strengthened 45.000 km of overhead lines, and developed a strategy to restore power within five days if outages occur. The €2.4 billion programme is already bearing fruit. In January 2009, during storms comparable to the 1999 event, outages occurred on only half the number of overhead lines and one-third of the number of substations (RTE, 2010).

Threshold values for wind and storm damage are difficult to define, and the costs of the damage vary widely, depending on the design of the grid and the local environments. Maximum design wind speed ranges from around 130 km/h for older lines to 180 km/h for critical lines in vulnerable areas (Peters et al, 2006). Damage cost estimates range from €1,600 per fault for a single line breakage (Martikainen et al, 2007) to €17,000 per pylon and attached lines in cases of widespread disruption (ADAM, 2009).

Increasing wind speeds can also have a minor positive effect on overhead lines. Provided winds remain below damage levels, stronger winds help cool overhead lines by increasing heat convection. Lines can then carry a larger electric load while staying within temperature limits (usually 80°C). Additional capacity can be as much as 20 percent for each m/s increase in wind speed (Verbund Austrian Power Grid, 2005).

2.5.3 *Temperature*

Electricity networks are also affected by temperature. The regulated maximum temperature at which network equipment is bounded is usually 80°C, at the conductor surface. If this is exceeded, overheating can damage the systems and poses a fire hazard. Apart from safety concerns, network capacity declines with rising temperature, as the resistance of metals increases and the systems sooner reach their maximum operating temperature.

The safe load on network technologies decreases when ambient temperature rises, because the systems sooner reach their maximum operating temperature. The capacity of transformers, for example, can decrease by up to 1 percent for each 1°C (Martikainen et al, 2007). Similarly, the resistance of copper lines increases by approximately 0.4 percent for each 1°C. Altogether, network capacity falls by around 1 percent for each for each 1°C. Consequently, network losses can increase 1 percent if temperature increases 3°C, in a network with initial losses of 8 percent (IEA, 2008).

Table 4 Impacts of increasing temperature rises on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
De-rating	Transformers	Continuous	Approx. -1% load per °C rise	All, especially Mediterranean
Decreased conductivity	Overhead lines & underground cables	Continuous	Resistance increase approx. 0.4% for each °C temperature rise -0,5 to -1% line load (A) per °C rise	All, especially Mediterranean
Sag	Overhead lines	50°C	Approx. 4.5 cm per °C rise at the conductor surface[7].	All, especially Mediterranean
Thawing permafrost	Substations & pylons	Variable with local conditions	Potentially full loss of supply locally	Baltic

Regulation specifies a minimum ground clearance for transmission lines to limit potential harmful effects of magnetic fields[8]. This can be exceeded when the material expands with temperature, so that sag of the line increases. The extent of sagging depends on the conductor material; the span width and other environmental conditions like wind-speed. For conventional aluminium cables it is approximately 4.5 cm per 1°C rise at the conductor surface.

In Nordic regions, higher temperatures can cause permafrost to thaw. Consequently, the foundations of network assets like substations that are built on permafrost can start to shift and break up, necessitating major repairs. In extreme cases the whole substation must be rebuilt. This problem is limited to the sparsely populated North of Scandinavia.

2.5.4 Drought

Drought due to changing precipitation patterns and/or increasing evaporation may cause soil around underground cables to dry out[9]. This lowers the conductivity of the cable, and thereby the carrying capacity. Cable rating can drop by up to 29 percent if the soil around it dries out thoroughly (Gouda et al, 1997). This starts when the surface temperature of the cable reaches around 55°C, depending on soil conditions. Ambient air temperature must rise above 30 - 35°C for this to happen (Gouda et al, 1997).

[7] Taking a conventional aluminium conductor at an ambient temperature of 35°C and a span of 400 m (Pink, 2010).

[8] Transmission lines create magnetic fields in their direct environment. The impact of these fields on humans and the environment is still disputed, but regulation stipulates that overhead lines must pass at a minimum distance from the ground and surrounding buildings as a precaution. Typically, minimum layout clearances range from 7.0 meter for medium voltage (110 – 132 kV) to 9.5 meter for extra-high voltage (>330 kV).

[9] Such ‘moisture migration’ occurs automatically as heat dissipated by the cables causes water to move away from the surrounding soil.

Table 5 Impacts of drought on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
Moisture migration	Underground cables	>55°C at cable surface	-29% cable capacity	All, especially Mediterranean
Dry soil movement	Underground cables	Variable	Repair costs approx. €3.200 per fault[10]	All, especially Mediterranean

Underground cables can be damaged as a result of dilatation and underground soil movement in extremely dry soils during droughts. In August 2003, 4,000 people in the Bordeaux region of France were left without power for several hours as a result.

2.5.5 *Flooding*

Flooding can increase in areas of Europe as a result of climate change because of changing precipitation patterns and extreme weather events. Northwest Europe, and the British Isles in particular, are vulnerable.

Network assets in flood-prone areas can be damaged during flooding. Like storms, these are inherently infrequent events, so a general threshold at which damage occurs, and their impact varies with local conditions. At worst, floods disrupt all electricity supply locally, and the effects spread into the network, leading to outages in areas unaffected by the water. At best, damage remains restricted to a few minor assets, and supply can be re-routed. The impacts of supply at a national level are limited in most cases. Extreme flooding due to extreme precipitation (for example, a doubling of average precipitation over a short period) or significant sea level rise (0,5 m) would affect only 0-10 percent of supplies in most countries.

Flooding has been a particular concern in the UK because of flood events in 2007[11]. Since the events of 2007, National Grid has reviewed flood risk of its transmission infrastructure, finding that 28 electricity substations are at significant risk (greater than 1 in 75 risk of flooding in any year). When designing new substations, it now evaluates local flood contour information from the Environment Agency. It is also investing in mobile flood defences to provide interim cover for low-probability events (House of Commons Select Committee, 2008).

Table 6 Impacts of flooding on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
Inundation	Substations	Varies with local conditions	Potentially 100% loss of supply locally	North sea & Baltic
Cable breakage	Underground cables	Varies with local conditions	Potentially 100% loss of supply locally Repair costs from €3.200 per fault[12]	North sea & Baltic

10 Martikainen et al, 2007.

11 In June 2007, National Grid's Neepsend substation in South Yorkshire was flooded, affecting supply to the CE Electric distribution grid and 36,000 domestic and commercial customers lost supply (House of Commons Select Committee, 2008). The subsequent month, the company prevented such extensive impact when Walham substation in Gloucester came close to flooding. Long-lasting damage to the transformers and switchgear could only be avoided through placing sandbags and continuous pumping for several days.

12 Martikainen et al, 2007.

Underground cables can be damaged when flooding causes ground to subside. As with soil movement due to drought, local conditions determine the level of risk and potential damage.

2.6 Stakeholder consultation

In the sections above we have described the status of the different electricity generating and transmission sectors in function of their role in Europe, physical properties and sensitivity to weather and climatic effects. From there we wanted the input from the industries itself to understand how the stakeholders perceive and cope with these potential effects on their daily business.

We constructed questionnaires – different for every sector – and used these as guidelines during the interviews we held. Typical interviewees were heads of operations, plant managers, heads of investments, health, safety and environment managers, but also regulators, electricity union managers and electricity production association representatives. Most interviews were held telephonically and some physically when it concerned stakeholders in the nuclear sector.

The purpose of this questionnaire is to identify the needs for technical measures to mitigate the potential impacts on the nuclear power plants and other power stations (fossil fuels, renewable energy sources) from climate changes such as predicted for the near future and far future. While the focus is on nuclear electricity, a systematic approach is also needed for other electricity technologies. Therefore, each electricity plant is sent an individual (separate) questionnaire. The questionnaire is also instrumental in obtaining insight in the investment plans of the operator for the period till 2030 (near future) and till 2050 and 2080 (far future) for financing these measures. In addition, we tried to identify how the costs of the (perceived) risk of climate change is addressed by the power plants is.

The general categories of questions in the questionnaire are the mainly following:

- Technology of the generation or network facility;
- Strategy regarding climate change;
- Cooling water effects (if applicable);
- Specific climate change impacts;
- Change in ambient air temperature;
- Change in water level;
- Change in precipitation;
- Change in wind speed;
- Other effects;
- Extreme weather conditions (flooding, etc.);
- Regulation regarding investments.

Specific climate change effects have been identified, i.e. changes in temperature, water level, wind speed, precipitation and extreme weather conditions. Each one of these effects carries relevance for a number of stakeholders, including different facilities, but the relevance of such effects is different for each stakeholders. For this reason, according to the type of stakeholder, these effects are included in different combinations. For example, a set of questions related to wind speed may be relevant (and is thus included) for wind farms but would have negligible impacts on biomass facilities (and thus is not included).

In the table below are the number of stakeholders we have interviewed listed.

Figure 6 Number of interviews conducted per electricity sector

Electricity sector	Number of interviews
Nuclear power	37
Fossil-fuelled power	31
Renewable electricity	21
Transmission and distribution	8
Total	**97**

For a detailed overview of the questionnaires sent to the different stakeholders, refer to Annex D. In these questionnaires the specific questions we have asked can be observed. The results of this stakeholder consultation is detailed and discussed in Chapter 5.

3 Climate change scenarios for Europe

This chapter describes the scenario projections for climate change in Europe as used in this study. The chapter explains how the selected climate change scenarios were developed and why they were developed this way. The projections are further be adjusted to reflect specific climate change effects and climatic zones.

3.1 Existing climate change scenarios

3.1.1 Global climate change scenarios

The starting point for global climate change scenarios is the Intergovernmental Panel on Climate Change (IPCC), established by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) in 1988. The initial objective of the IPCC was to develop recommendations based on a comprehensive review of the state of knowledge of climate change science; social and economic climate change impacts, and possible response strategies for a possible future international convention on climate, the United Nations Framework Convention on Climate Change (UNFCCC).

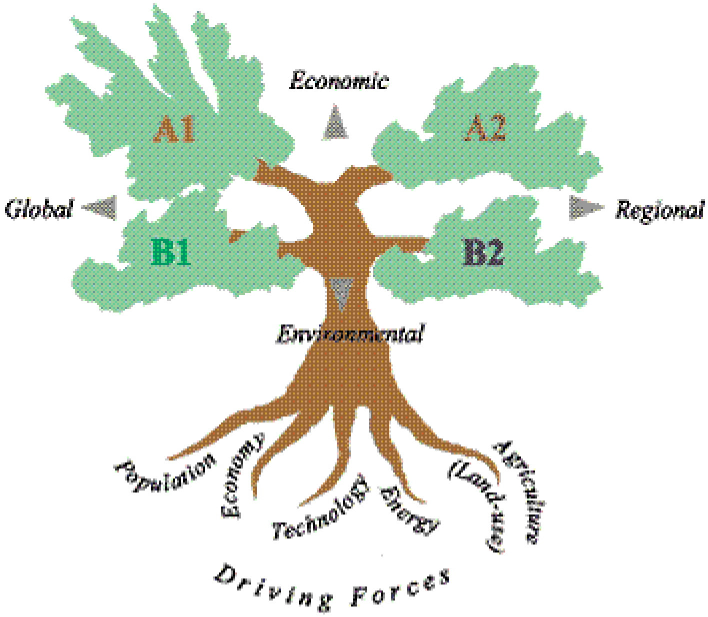
The IPCC delivers comprehensive scientific Assessment Reports about changes in global climate systems, on a regular basis. The most recent of these, IPCC AR4 (2007), is accepted globally as the most reliable review of climate change Research Working Groups operating within the IPCC framework focus on different aspects of climate change research, which are then integrated in the Assessment Reports:

- Working Group I assesses the physical aspects of climate change;
- Working Group II assesses the vulnerability of socio-economic and natural systems to climate change; and
- Working Group III assesses options to mitigate climate change effects by preventing greenhouse gas emissions from the atmosphere.

The IPCC Working Group II focuses on impact assessments and the vulnerability of the global socio-economic to changed environmental conditions. The Working Group developed multiple scenarios for modelling economic growth factors and climatic characteristics and researchers (e.g. Tyndall Centre for Climate Change Research), meteorological (e.g. KNMI) and other interested institutes all make regular use of the IPCC scenarios to run long-term climate system projections.

The different IPCC scenarios can be divided into several families (
Figure 7) based on the Assessment Reports and Special Reports on Emission Scenarios (SRES). The assumptions of these climate change scenario families differ in respect of population and economy growth, technological change, policy orientation, etc. The four mostly used scenario families are A1, A2, B1 and B2. Within each of these there are multiple sub scenarios, like the A1B or A1F scenarios. The IPCC A1B scenario is 'the' worst-case scenario in terms of climate change effects and the most commonly used. It provides a balanced picture of the future in respect of economic growth, greenhouse gas emissions and technological development. It projects that carbon emissions will continue to grow until 2050 after which they will begin to decline and that global surface temperatures will increase by 3.4ºC by the end of the century. Sea levels are expected to rise in the range of 0.23-0.51m compared to 1980-1999 levels (Figure 8).

Figure 7 IPCC SRES scenario families



The A1 scenario family

"The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B)."[13]

The A2 scenario family

"The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change is more fragmented and slower than in other storylines."[14]

The B1 scenario family

"The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives."[15]

The B2 scenario family

"The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less

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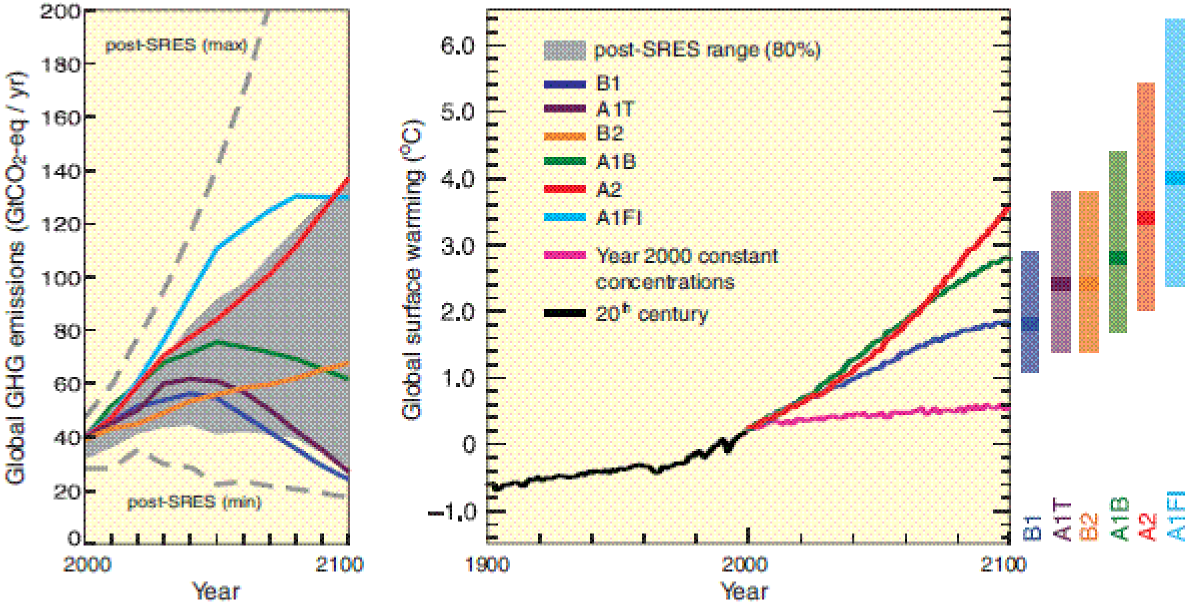
13 IPCC, Nakicenovic, N. at al., ibid.
14 IPCC, Nakicenovic, N. at al., ibid.
15 IPCC, Nakicenovic, N. at al., ibid.

rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels."[16]

Figure 8 SRES scenario projections for GHG emissions and surface temperature



Source: IPCC AR4 assessment report

3.1.2 *European climate change scenarios*

The IPCC work has been taken further by a number of regional climate change research initiatives. The ENSEMBLES programme is most comprehensive European climate change research initiative, funded under the FP6 EC Framework Programme under the title 'Global Change and Ecosystems'. The programme aims to:

- Develop a prediction system for global and regional Earth System Climate Change models, validated against quality controlled and high-resolution gridded datasets, like the IPCC Data Centre, to produce probabilistic estimates of future uncertainty about climate change in Europe;
- Quantify and reduce the uncertainty in the representation of physical, chemical and biological and human related variables in the Earth System model;
- Maximise the use of the results by linking outputs of the prediction system to a range of sectoral applications, including energy, water resources, weather risk management and health.

Most of the European meteorological institutes and other well-known climate change research institutes are linked with the ENSEMBLES programme, which covers virtually all EU-27 Member States. There are different research themes within the ENSEMBLES programme, each focussing on a specific climate change topic or angle. Most research themes are linked by subject or timeline. For example:

- The ENSEMBLES RT1 research theme focuses on the development of a high resolution, comprehensive modelling system to predict climate change events across different time scales;
- The ENSEMBLES RT2b research theme (successor of RT1) focuses on the prediction of climate variables based within an ERA-40 framework (European Research Areas) or within the boundaries of the IPCC A1B climate change scenario on a monthly basis.

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16 IPCC, Nakicenovic, N. at al., ibid.

In the latter case the IPCC A1B scenario assumptions are applied on a regionalized scale, but connected to regional climate data variables instead of global IPCC datasets. Therefore, regional relevant changes in climate variables can be localized and highlighted.

3.2 Climate change modelling in perspective

The selection and development of climate change scenarios depend on an understanding of the complexity of climate data, assumptions, uncertainties and restrictions. Particularly the conditions for using global or regional climate change scenarios are important.

There is no single global climate model that can project all relevant climate variables. The dynamism of climate systems and exogenous influences leads to incredible complexity which can be predicted (long) at forehand (e.g. earth quake). Thus there are multiple Global Climate Models (GCMs) with accompanying scenarios which illuminate a specific climate change relevant issues that may be relevant for any specific region. For instance, to date it has not been possible to project climate change onto a global level due to the enormous number of assumptions (globally and locally) that cannot be subsumed by any one model or scenario.

As such the IPCC scenarios are projected by about 25 GCMs leading to multiple outcomes for the IPCC scenarios. These should always be reviewed and analyzed in relation to one another. In consequence, overall uncertainty about the climate system and scenario assumptions is contained within the regional climate scenarios. The main result, especially since IPCC scenarios try to fit the complete world, is that the overall uncertainty, as the result is an overall aggregate and the indicated broad ranges will fit with a 'higher' accuracy.

Also on a regional level there is no single climate model that can project all relevant regionalized climate variables. The complexity of Regional Climate Models (RCMs) differ from that of the global climate models in that they trace more localised climate change effects which are filtered out of the GCMs. However, the uncertainty about the projected output is higher than in GCMs as the range of scenario output is smaller, and as such is the explanatory power of these models less significant. In other words, the accuracy level of RCM output is lower than that of GCMs.

The dynamic character of climate and weather also plays a role. Tracing the impacts of wind, for instance, is very difficult due to changing wind direction. Winds from the Atlantic normally blow faster than land winds. Relief formation is an important indicator of precipitation levels. The planet's crust, furthermore, is dynamic and tectonic shifts could influence sea levels and the occurrence of floods. All these dynamic interrelations and variables cannot be covered in one model or scenario.

Working with climate change scenarios, therefore, involves uncertainty. In practice this means that different climate change scenarios (both GCMs as RCMs) are used in combination with reservations. For the purposes of this study climate change scenarios are used to back-test climate thresholds as a way to determine investment needs. The following approach was taken to develop the climate change scenarios:

- The IPCC A1B scenario is the point of departure. This is because it is viewed as the most likely and most troubling realistic GCM scenario in the academic sector and is referred and used in comparable studies;
- The ENSEMBLES RT2b project scenario data will be used as input for this study's climate change scenarios and for framing down the IPCC A1B scenario. The ENSEMBLES RT2b (RCM) project scenario projects monthly data for the European climate system within the IPCC

A1B scenario boundaries until 2100. In other words, the RT2b data is scaled down to a regionalized level from the global IPCC A1B scenario (GCM).

3.3 Definition of climate zones

To develop the climate change scenarios for this study, the Consortium divided the EU-27 into different regions based on local/regional climate systems, the occurrence of relevant CC effects and (non-)coastal location of a Member State. Bundling EU 27 Member States into 'climate zones' helps to distinguish relevant aspects regarding energy technologies, climate change impacts and investment needs on a regionalized scale. For example, the conditions for generating electricity are different in the Northern part of the EU compared to the Mediterranean region. Furthermore, the electricity generation technology mix in broad terms varies greatly within the EU borders.

The criteria for allocating EU-27 Member States to a climate zone were as follows:
- North vs. South Europe;
- Coastal vs. Non-coastal location;
- Limiting the climatic differences within a region and maximising the differences between regions.

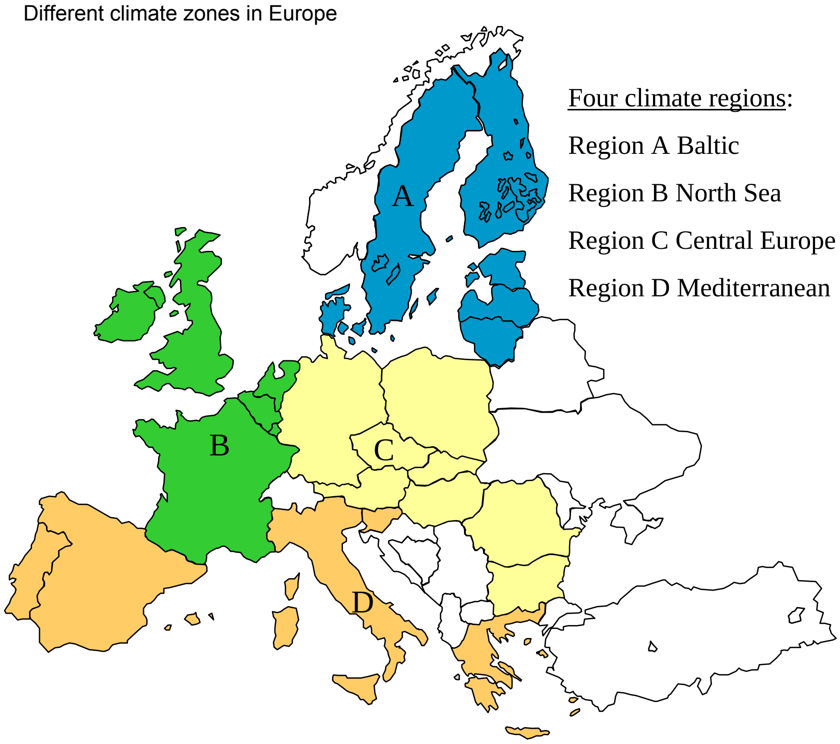
Some EU-27 Member States that are indifferent to these criteria (e.g. Luxembourg) were allocated to a climate zone which is most familiar with their neighbouring countries. The following climate zones were defined on this basis:
- Baltic region (Region A);
- North Sea region (Region B);
- Central and Eastern Europe (Region C); and
- Mediterranean region (Region D).

Table 7 and Figure 9 show which EU Member States are allocated to which climate zone.

Table 7 Disaggregating the EU-27 into different climate zones

Baltic region	North Sea region	Central and Eastern Europe	Mediterranean region
Denmark	Belgium	Austria	Cyprus
Estonia	France	Bulgaria	Greece
Finland	Ireland	Czech Republic	Italy
Latvia	Luxembourg	Germany	Malta
Lithuania	The Netherlands	Hungary	Portugal
Sweden	The United Kingdom	Poland	Slovenia
		Romania	Spain
		Slovakia	

Figure 9	Different climate zones in Europe



Data for the climate change scenarios was collected within each of the zones and by bounding their global longitudes and latitudes. Since climate change data is collected by meteorological data point observations and are not pre-defined towards the climate zones defined for this study. Table 8 shows the longitude and latitude of each of the climate zones. Since the latitudes and longitudes have been selected such that the country borders of all allocated EU Member States are included, there can be some overlay between the different climate zones.

Table 8	Latitudes and longitudes for climate zones

	Baltic region		North Sea region		Central and Eastern Europe		Mediterranean region	
Latitude	54,13	70,13	43,63	57,88	41,38	54,63	35,88	46,63
Longitude	7,88	30,63	-10,63	6,88	7,13	27,88	-9,88	25,63

3.4 Selected climate change scenario and experiments

3.4.1 Rationale for climate change scenario and experiments

The selected climate change scenario and experiments for this study come from the ENSEMBLES RT2b and have been established via the Climate Data Explorer of the Dutch Meteorological Institute of The Netherlands (KNMI). The following experiments were selected in close consultation with the KNMI, other meteorological institutes (e.g. Meteo de France), different industry associations (e.g. EnergieNed in The Netherlands) and other interested.

The Climate Data Explorer of KNMI covers several datasets of the ENSEMBLES framework programme, among them the RT2b datasets. The most obvious option for streamlining the climate data from global level (GCM) to European level (RCM), was to make use of these RT2b datasets as they are framed within the IPCC A1B scenario assumptions. Several experiments are available within these RT2b datasets. These experiments are projected by different European meteorological institutes with different RCMs and even different sensitivity levels for the climate variables. The Consortium therefore first mapped the different experiments in terms of assumptions and output data (with respect to wind, precipitation and surface temperature). Three main climate aspects/variables were identified as relevant or more important for electricity generation, namely wind speed, temperature and precipitation.

The climate change scenarios were accordingly developed within the ENSEMBLES RT2b data, based on the extremes (in terms of experiment data outputs) for these climatic properties. Also, three ENSEMBLES RT2b experiments with extreme values for precipitation, wind and temperature, were selected:
- Wind scenario (CNRM experiment); name: WIND;
- Temperature scenario (HadRM3Q0 experiment); name: TEMP;
- Precipitation scenario (KNMI experiment); name: RAIN.

The data for climate change variables (discussed in the next section) for each of the climate zones were obtained from these experiments. In other words, monthly data (1950-2100) per climate variable and climate zone was downloaded, and aggregated on an annual basis.

Climate is a continuous feature and weather a static feature. Climate data should therefore be averaged over a longer time period for meaningful analysis. The data range (1950-2100) of the retrieved climate variables was therefore averaged out in three aggregates, in which the time intervals were kept as consistent as possible:
- 2020 (2010-2030);
- 2050 (2030-2060);
- 2080 (2060-2100).

For the energy scenarios the energy mix in the gross level of generation in 2050 is used for the long term situation because this is the farthest date in the future for which official and detailed scenarios are readily available (see Chapter 4 for further details).

3.4.2 Climate change variables

The most relevant climate change variables were selected based on the selected experiments from the ENSEMBLES RT2b database as proxy for the WIND, TEMP and RAIN climate change scenarios. The final selection of climate change variables was made in close consultation with the Dutch meteorological institute KNMI.

Eight relevant climate change variables were identified and follow the cycle that changing weather patterns have an impact on e.g. the level of precipitation, the cloud coverage, temperature profiles, wind intensities and flows. These have the following climate change effects:
- Water temperature changes (proxy: sea surface temperature);
- Air temperature changes (proxy: 2-meter land surface temperature);
- Precipitation changes (proxy: % change in precipitation levels);
- Wind speed changes (proxy: 10-meter land surface wind speed);
- Sea level changes (proxy: average temperature (air + water) changes times IPCC sea level increase factor (0,13));
- Occurrence of floods (proxy: % change in large-scale precipitation);
- Occurrence of heat waves (proxy: % change in 2-meter land surface daily maximum air temperature);
- Occurrence of storms (proxy: % change in 10-meter land surface daily maximum wind speeds including gust).

The climate change variables were listed in the data tables for each of the defined scenarios, WIND, TEMP and RAIN for the different climate zones in Annex B.

4 Electricity supply patterns in Europe

This chapter scenario discusses projections for electricity supply in Europe. First, it presents three existing scenarios, explaining which is most suitable for use in this study. Subsequently, it describes developments in electricity demand and supply will be highlighted for the defined climatic regions.

4.1 Existing scenarios for European electricity demand and supply

4.1.1 DG Energy projections and the NTUA

At the moment the E3M Lab of the National Technical University of Athens (NTUA) is the main official provider of projections of electricity demand and supply in Europe on behalf of DG Energy of the Commission, among others. Their modeling tool, the PRIMES model, provides electricity supply and demand numbers broken down by generation technology. The NTUA updated its projections for DG Energy in December 2009, published in 2010 (Capros et al., 2010), providing the most recent baseline projection and reference scenario for all Member States.

4.1.2 Eurelectric Power Choices Scenarios

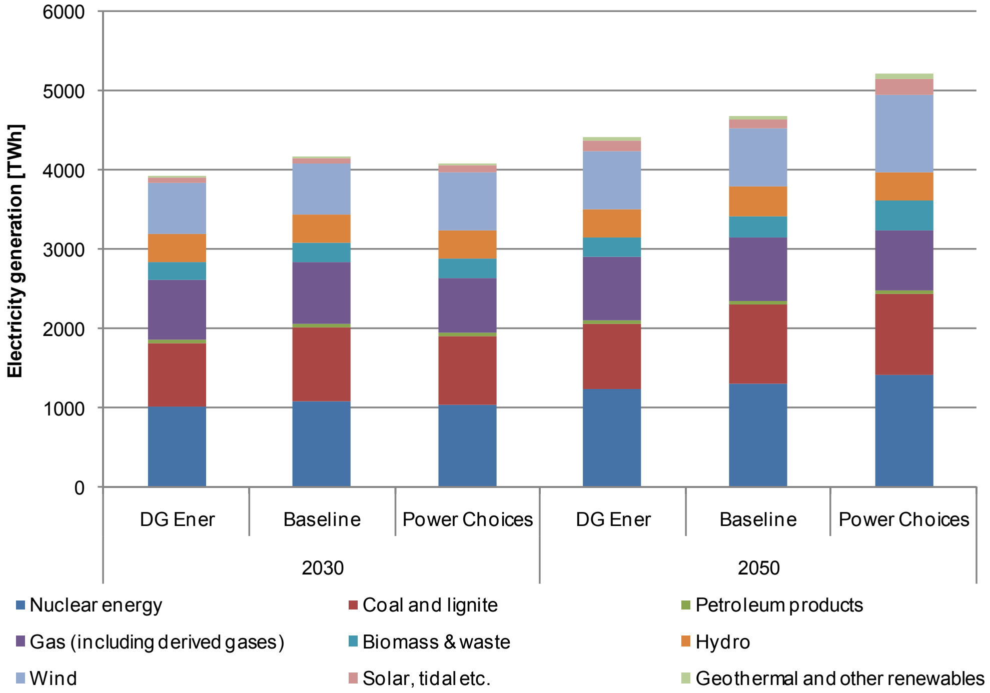
Eurelectric, the association of European electricity companies, has developed its own electricity scenarios for development the European power sector using the PRIMES model. In 2007 the association published its report on the ‘Role of Electricity in Europe’, followed by the publication ‘Power Choices’ in 2010 (Rega, 2010).

The ‘Power Choices’ report presents two scenarios for the electricity sector in the EU to 2050, a baseline projection and the specified more ambitious Power Choices scenario. The baseline shows the projected electricity trends assuming that all existing relevant EU policies affecting European electricity demand and supply are implemented in the Member States. The Power Choices scenario explores the technical developments and policy changes necessary to reduce greenhouse gas (GHG) emissions by 75% by 2050.

4.1.3 Comparison of existing scenarios

The Consortium has extrapolated the most recent DG Energy projections(Capros et al., 2010) from 2030 to 2050, and compared these with the Eurelectric projections. Overall, the Eurelectric scenarios are broadly in line with DG Energy’s projections to 2030 (Figure 10). However, Eurelectric expects a slightly higher growth in electricity demand and a larger contribution from nuclear power and renewable energy sources. These differences become more pronounced in the period 2030 to 2050, especially between the DG Energy scenario and the Power Choices scenario. Annex C provides a full discussion of this comparison.

Figure 10 Comparison between the DG Energy and Eurelectric scenarios in 2030 and 2050



4.2 Selection of the electricity scenario

As the only available PRIMES scenario to 2050, the Consortium considers the Eurelectric baseline scenario as the best candidate for the central baseline scenario for this study. Three arguments speak in its favour.

Firstly, the DG Energy projections to 2030 would need to be extrapolated to 2050 before they could be used. This would introduce new assumptions and uncertainties in the electricity scenarios, which might obscure the possible effects of climate change.

Secondly, the Eurelectric baseline scenario broadly follows DG Energy's own assumptions. Electricity generation grows more rapidly to 2050 in the Eurelectric case, but the composition is not radically different. This could be an effect when the extrapolation method would be used. The impacts of climate change on the two systems are therefore likely to be comparable, apart from a slight difference in magnitude. The impacts and costs will be around 5-10% larger in the Eurelectric baseline case than in the Commission's baseline. This relatively small difference is preferable to the uncertainties resulting from an extrapolation of the DG Energy projections.

Thirdly, in the Eurelectric baseline all existing climate and energy policies are implemented as planned to 2020. Subsequently, the trend in GHG emission reduction is assumed to continue linearly. As such it presents a business-as-usual (BAU) case for the electricity sector. These assumptions fit within the overall BAU approach of the IPCC A1B scenario which is the basis for the described climate projections in Chapter 3.

The Eurelectric Power Choices presents a radical different vision of the future. Particularly the electrification of end-use and the uptake of nuclear power and renewable energy sources are much larger. As such, it can provide valuable insight in the impacts of climate change on a scenario with more ambitious mitigation measures. Therefore, the Eurelectric Power Choices scenario has also been analyzed in Chapter 6, as an alternative scenario to the baseline scenario used in this study.

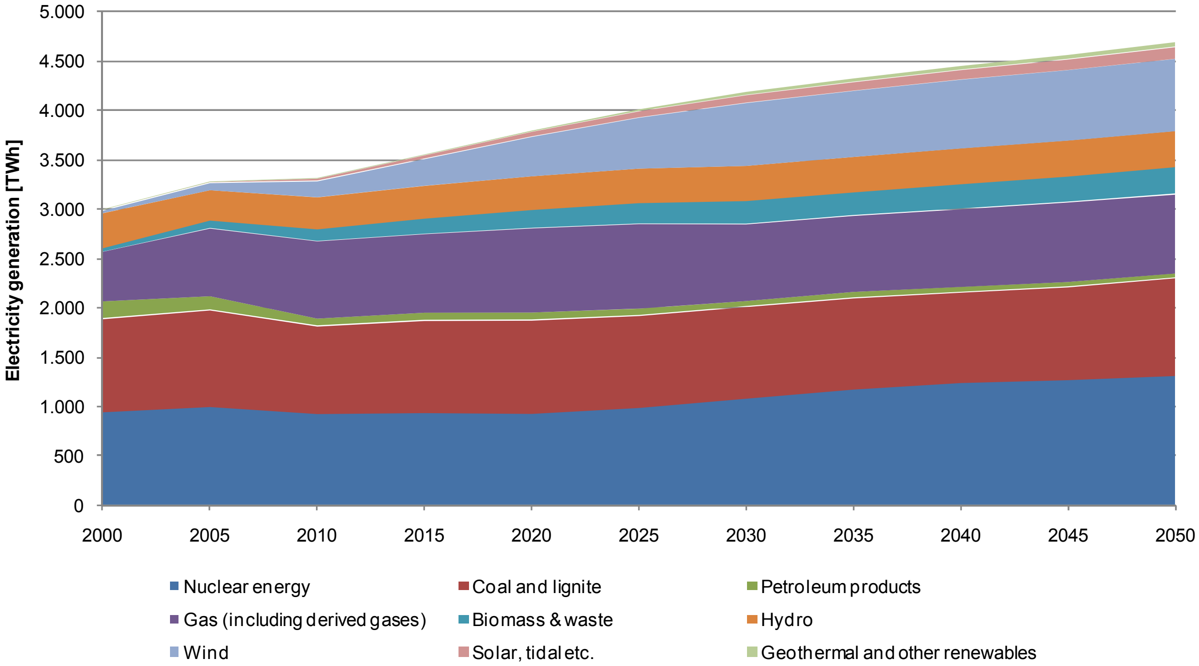
4.3 Description of the electricity scenario – Eurelectric baseline scenario

4.3.1 Overall development of the European electricity sector

The Eurelectric baseline scenario provides an intermediate projection of the development of the European electricity sector to 2050, reflecting existing trends and policies. The European Emissions Trading Scheme (EU ETS)determines the carbon emission reduction to 2020, after which the trend continues linearly (-1,74% per year). Nuclear energy policies remain unchanged in the baseline, so the then-expected phase-outs in Germany and Belgium take place as planned. Consequently, the carbon intensity of the electricity sector declines by 40% to 2050 through energy efficiency measures and deployment of renewable energy sources. Electricity use for road transport remains limited.

Figure 11 shows the development of electricity generation to 2050 in the Eurelectric baseline scenario. Conventional power sources remain dominant. The contribution from coal and natural gas remain roughly constant, while nuclear electricity production declines slightly to the mid 2020s, as existing plants are decommissioned, after which the sector expands again. Electricity generation from renewable energy sources grows strongly, especially wind power, which increases from 161 TWh in 2010 to 731 TWh in 2050. It thereby generates almost half of all renewable generated electricity.

Figure 11 Electricity generation in the EU-27 to 2050 in the baseline scenario



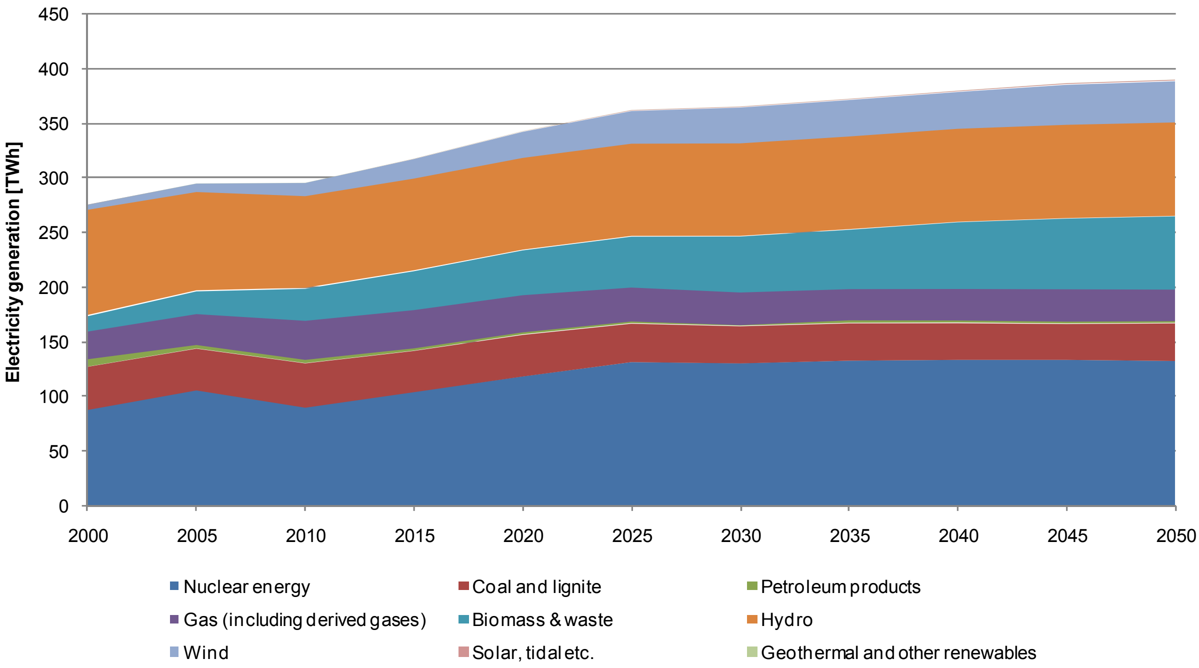
4.3.2 Supply patterns and regional distribution

The contribution of different sources (energy mix) to the overall electricity generation is different per region. The following paragraphs and tables show the split by electricity generation technology for the four regions defined in Chapter 3 of this report.

Baltic region

In the Eurelectric baseline scenario, electricity generation in the Baltic region grows from 295 TWh in 2010 to 390 TWh in 2050 (Figure 12). This is due to the increasing use of generated electricity from biomass and nuclear power plants. Unlike in the other regions, wind is not the largest source of renewable energy, while the relative contributions of biomass and hydro are larger than elsewhere. This reflects the good potential for these types of generation in Northern Europe. Electricity generated from fossil fuels (coal and natural gas) declines slightly, while hydropower production remains unchanged.

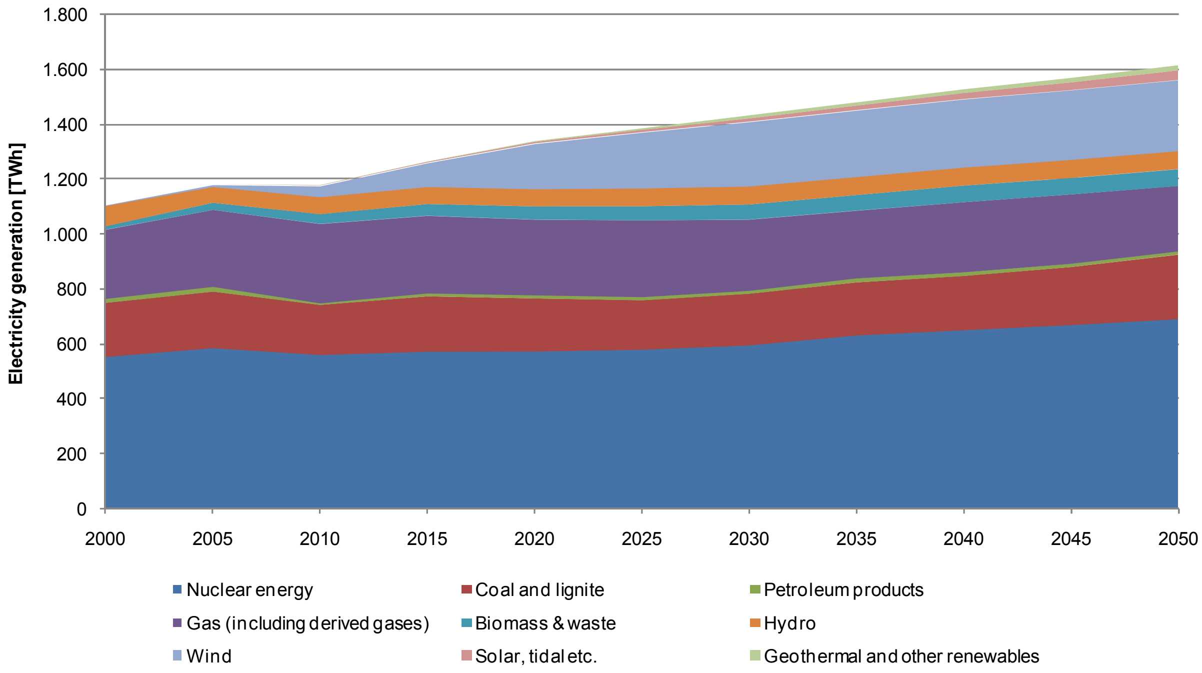
Figure 12 Electricity generation in the Baltic region to 2050 in the baseline scenario



North Sea region

In the North Sea region, electricity generation from wind farms is expected to increase rapidly to 2050 (Figure 13). Electricity generation from conventional sources (coal, natural gas and nuclear) remains largely unchanged, although their relative share declines as total power production grows. By 2050 wind power will have overtaken electricity generation from both coal and natural gas, producing 258 TWh per year, becoming the second largest electricity source after nuclear. Wind thereby generates close to 60% of renewable generated electricity.

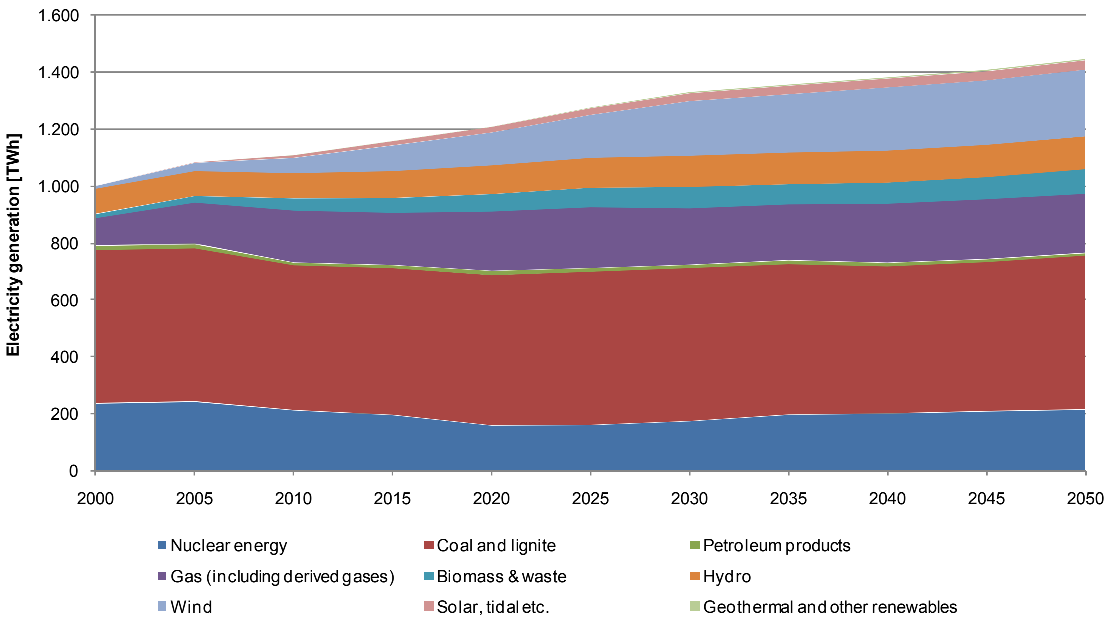
Figure 13 Electricity generation in the North Sea region to 2050 in the baseline scenario



Central and Eastern region

Overall electricity generation increases from 1,108 TWh in 2010 to 1,447 TWh in 2050 in the Central and Eastern region (Figure 14), as additional demand through economic development outweighs the effect of measures to reduce consumption. Coal and lignite remain dominant, still accounting for 37% of the total electricity supply in 2050. The relative contribution of nuclear electricity in 2050 is smaller than in 2010. Gas and renewable power generation rises to meet growing demand. With 235 TWh, wind power constitutes 50% of renewable electricity generation in 2050.

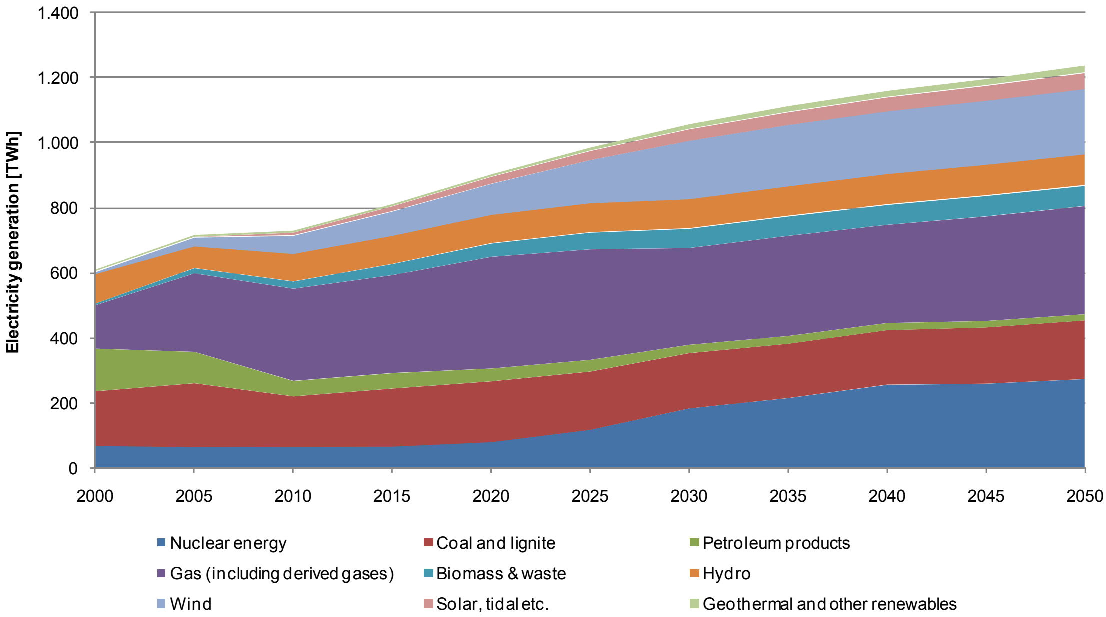
Figure 14 Electricity generation in the Central and Eastern region to 2050 in the baseline scenario



Mediterranean region

Power generation increases rapidly in the Mediterranean according to the Eurelectric baseline scenario, reaching 1,236 TWh in 2050, compared to 728 TWh in 2010 (Figure 15). It is the only region with substantial growth in nuclear power generation, which more than triples to 273 TWh in 2050. Among other things, this reflects the decision by the Italian government to repeal the nuclear moratorium and plan for building nuclear power plants. The share of electricity generated from renewable energy sources also grows – from 24% now to 35% in 2050. Wind and solar power are the main sources contributing to the increase, as the potential for these sources in the Mediterranean is large.

Figure 15 Electricity generation in the Mediterranean region to 2050 in the baseline scenario



5 Results and analysis of stakeholder consultation

5.1 Introduction

In this chapter we will present the results of the stakeholder analysis. All stakeholders have been interviewed using the pre-developed questionnaires as a guideline. These questionnaires can be found in Annex D. In short, the stakeholders were asked whether the impacts of climate change have been assessed and incorporated in their long term strategies, how the different effects affect the daily operation and which costs, risks and investments they expect due to climate change. Stakeholders were interviewed either physically or by telephone.

Interviewees often found it hard to indicate precise values for the costs of climate change. To have a better indication of these costs, we have made cost estimations which we have verified with the stakeholders. We have detailed the methodology and results of these estimations in Chapter 6.

The rest of this chapter is divided in the 4 stakeholder groups, viz:
- Nuclear power plant operators and regulators;
- Fossil-fuelled power plant operators;
- Renewable electricity power plant operators;
- Electricity transmission and distribution operators.

5.2 Nuclear power plants

Three quarters of the utilities and 85 percent of the regulators that were contacted responded on the questionnaires, thereby providing a good European coverage. In addition, even utilities that generate electricity from nuclear fuels were interviewed. All nuclear reactor designs (PWR, BWR, PHWR, and AGR) and cooling technologies (open and closed loop using sea- and river water and cooling towers) were covered by our survey.

Typically, interviewees were members of the senior management of the utilities, such as managers of operations, of environmental departments, strategic managers and project managers for safety reviews.

The sections below show the detailed results of the stakeholder consultation and the discussion of these results. They describe current practice in risk and vulnerability evaluations, the presence of long term strategies and expectations for the impact of different climate change effects. This division reflects the design of the questionnaire (Appendix D).

5.2.1 Risk and vulnerability evaluations

Periodic Safety Reviews (PSRs) of nuclear power plants are part of the license requirements and are carried out every 10 years or on request. Safety issues related to impacts of climate change are regarded as part of the PSR. Thus, **the impacts of climate change are assessed for all European nuclear power plants**. Costs of modifications as a result of the outcome of these assessments are considered as part of the regular maintenance costs, including those due to impacts of foreseen climate changes.

Included in the PSRs are, for example, issues related to the temperature of cooling water and air and the effects of extreme situations on the nuclear power plants. In addition, the effects of the plants on the environment are described. Implementations of measures that follow from the Periodic Safety Review are mandatory.

In France and the UK, EdF and EdF/UK have studied the effects of climate change on the electricity generation by nuclear power plants in detail. Also the Scandinavian utilities TVO and Fortum have studied the impacts of climate changes over the next 60 years or more for their investments plans to build and operate new nuclear units.

Generally, the utilities do not foresee any drastic safety or operability related problems due to climate change. Regulators share this view. The utilities have indicated an intention to invest in adaptation of the plants to cope with climate change if they can extend the lifetime of the plant as a result.

Research by stakeholders suggests that an increase in temperature, water and air, results in only a marginal loss in efficiency (Table 9).

Table 9 The effect of increasing temperatures on the nuclear power plant efficiency

Cooling agent	ΔT (K)	Efficiency
water	+5	-1%
air (cooling towers)	+1	-0.1%

5.2.2 Long-term strategy

Approximately **50 percent of the stakeholders have formulated a long-term strategy** to respond to climate-related disruptions, all in the North Sea region. For most utilities these emerge from the Periodic Safety Reviews and generally involve safety and environmental issues concerning life-time extension.

Additionally, conclusions on a long term strategy have followed from the study on climate change performed by EdF and EdF UK, mentioned above. They have implemented a broad programme of measures to reduce impacts of climate changes following extreme weather events, such as flooding and heat wave issues. Further adaptation measures to ensure power plants can withstand extreme weather conditions will be made by 2014.

5.2.3 Surface water temperature

Higher surface water temperature can lead to cooling problems for nuclear power facilities. The impacts differ between coastal and river side locations. Stakeholders rated the level of impact on average at 3.7 for coastal locations and 3.3 for river side locations, on a scale from 0 to 6.

In most cases, a higher coolant temperature will result in a reduction in efficiency, implying a loss of output. Relaxation of the temperature limits is sometimes allowed during short periods, if there is sufficiently large electricity demand. Some stakeholders indicated that they shut down the nuclear plants during some periods in summer. The loss of power can be avoided by increasing coolant pumping capacity, adaptations in the cooling process and improved heat exchange mechanisms, for instance.

In most cases, structural relaxation of the permissible maximum temperature at the cooling water outlet by national regulation (which is based on the European Directive on Biodiversity) is not yet considered or not foreseen.

Compared with all other potential climate change impacts, the rising surface water temperatures, particular during summers, is considered to have the largest impact on the operation of nuclear power plants. Some utilities mentioned installing alternative and improved cooling mechanisms or additional pumps as potential investments to cope with this temperature problem. In some cases modification of the cooling water inlet is considered. Additional cooling towers to counterbalance the loss in efficiency are also seen as a potential future investment.

Differences between the outcome of the questionnaires of coastal and river-side locations are relatively small. When surface water temperature rises, both encounter the same effects. However, river temperatures are more susceptible to changes in regional climatic conditions. Only in case of bays or estuaries the temperature of sea water strongly depends on local climate conditions. Particular nuclear sites located on rivers in the south of Europe will become increasingly susceptible to climate conditions, such as hot summers (Spain and France), because that would lead to relatively small differences between inlet and outlet water temperature, resulting in lower thermal efficiency.

Inlet and outlet water temperatures are a standard element of the mandatory safety and environmental reviews for nuclear power facilities in Europe.

5.2.4 *Ambient air temperature*

Extreme ambient air temperatures are a low threat for the safety and operability in nuclear power plants. Stakeholders rated the level of impact at 1.4 on a scale of 0 to 6, as nuclear power plants are designed to withstand extreme situations, such as human intervention and extreme weather conditions. Moreover, problems of extreme ambient air temperatures on the working conditions inside the plants can be solved easily by air-conditioning.

The air temperatures can affect the operating business of the plants. When the temperatures get too low, freezing problems occur. When air is used as a cooling agent, high ambient air temperatures will decrease the efficiency of the plant. Modification programs are implemented in several countries to cope with (future) heat waves.

Impact of the temperature of the ambient air on the safety (because of the cooling of electronic devices and other safety related equipment) are part of the mandatory safety reviews.

5.2.5 *Precipitation*

Change in precipitation in itself is not seen as a risk for the safety and operability of nuclear power plants. However, an increase in precipitation, causing *significant* changes in river water levels, leads to an increased risk of flooding, such as happened in the past at Blayais, France[17]. At locations at risk of flooding, drainage system must be evaluated. If the drainage system is insufficient protection or moving the location of some equipment may be necessary. Flooding can also pose a threat to transport and to the accessibility and availability of the site and essential commodities. **Flooding is seen as the most harmful climate change effect on the operation of nuclear facilities.**

In the Mediterranean region, precipitation may decrease due to climate change, leading to a decrease in cooling water availability (for river side locations) and a decrease in output. Alternative cooling agents would have to be provided.

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[17] A. Gorbatchev, J.M. Mattéi, V. Rebour and E. Vial. Report on flooding of Le Blayais power plant on 27 December 1999.

5.2.6 *Other extreme weather conditions*

Other extreme weather conditions considered include hail and rain storms, higher wind speeds, more frequent lightning, and external fires. In general, these are not an issue for the safety and operability of nuclear power plants. Wind speed is considered to be most likely to affect the facilities of the plants. One utility commented that the present switch yards would not withstand these extreme weather conditions. In a worst case scenario they would have to be rebuilt completely.

Extreme weather conditions are part of the mandatory safety reviews for nuclear power facilities in Europe.

5.2.7 *Costs and investments*

The main costs of climate change result from the reduced efficiency of the nuclear power plants. Most utilities state that with higher temperatures, the plants cannot run on full capacity, due to higher inlet temperatures of the cooling agent and legal limits on the outlet temperature. As mentioned in the sections above, the reduction in efficiency on the total electricity production is relatively small. This reduction in terms of costs is rather complex, inter alia depending on the current electricity demand and electricity prices.

Large investments are involved in life-time extension and upgrade programmes as part of the licence regime. These could be of the order of several hundreds of million euros. Examples are building additional cooling towers, of approximately M€ 50 to M€ 60 each, and modifications to the cooling water inlet of coastal locations, of approximately M€ 100, so deeper, cooler seawater can be used. Smaller investments involve, for example the development of more efficient pumps and heat exchangers. Only part of such investments is related to climate change measures. Therefore, investments in safety because of climate change are difficult to determine.

Investments in the efficiency of the nuclear power plants are related to national policies on nuclear electricity (for instance ‘phase outs’) and electricity demand. If investments are not considered to be viable, the plant will be closed. If national legislation allows, new nuclear power plants can replace older facilities, rather than investing in life-time extension. Amelioration of the effects of climate change will be then incorporated in the design.

5.2.8 *Conclusion*

The questionnaires and the interviews show that **climate change has limited impact on the electricity generation of nuclear power plants**. It is not an important point of interest for the utilities, for a number of reasons:

- Due to higher water and ambient air temperatures a loss of efficiency is expected, but this is only a small amount of the total electricity produced with nuclear power plants;
- Most modifications and investments result from the Periodic Safety Reviews (PSR), which are part of the licence regime and which are carried out every 10 years or on request. They are considered as part of the regular maintenance cost;
- National policies regarding nuclear electricity production, such as ‘phase-outs’ and electricity demands are important considerations for utilities to invest in modifications to the nuclear power plants or the building of new plant. These outweigh the importance of climate change impacts.

Apart from the PSRs, only a few utilities have performed extensive risk and vulnerability assessments on the effects of climate change, though measures that result from the PSR’s and the additional assessments will be implemented within the next decade.

From the climate change effects addressed in the questionnaire the most imported effects of climate change on nuclear power are:

1. Water temperature increase and cooling water availability decrease;
2. Ambient air temperature increase;
3. Flooding risks from increased precipitation.

Utilities could not or would not give us detailed information on the investments related to climate change required for complying with licensing requirements. Investments for a new cooling tower or modifications to the cooling water inlet are in the order of M€ 50 and M€ 100, respectively.

5.2.9 Summary nuclear power plants

Nuclear utilities were interviewed by using the pre-developed questionnaires, and during face-to-face interviews. The majority of the utilities is not considering the effects of climate change as a separate issue, since these effects are in most cases addressed in the framework of Safety Reviews, that are part of the licensing regime. Climate change will result in relatively small changes in efficiency, that do not justify major additional investments in existing power plants. However, future power plants designs will incorporate the necessary adaptations to address changing climatic conditions.

5.3 Fossil-fuelled power plants

We have interviewed 29 plants that generate electricity from fossil fuels. Most EU Member States are represented, thereby providing a good European coverage. Typically, interviewees were plants managers, heads of investments or health, safety and environment engineers. Moreover, all common technologies have been covered, including combined cycle gas turbines (CCGT), oil-based plants, pulverised-coal fired plants, and coal plants co-firing biomass. In some cases, the plants cogenerate useful heat.

In the sections below the results of the stakeholder consultation are described and discussed. They describe current practice in risk and vulnerability evaluations, the presence of long term strategies and expectations for the impact of different climate change effects. This division i reflects the design of the questionnaire, shown in Annex D.

5.3.1 Risk and vulnerability evaluations

Of all interviewed plants **30 percent have evaluated the risks and vulnerability of their fossil-fuelled power generation facilities to climate-related disruptions**. Some plants responded that risk and vulnerability analyses have been carried out, but not specifically with respect to climate-change. This prevented the power plants from making any clear statements on the presumed impacts thereof, as reflected in the interviews.

Plant operators can deal with risks (including climate change) by opening an insurance account. The interviews suggest that insurance accounts are mostly opened by companies that manage a large portfolio of power plants so that risks can be shared within that portfolio. Transferring risks from a power plant operator to a so-called off-taker or toiler, which also decides when to undertake investments, is another way to mitigate risk. However, often climate change risks have not yet been factored in separately. Reducing CO_2 emissions is currently still the main concern for many utilities, as they can earn carbon credits with co-firing with biomass in coal base power plants. Other short term environmental concerns like NO_X and SO_X emission control also receive much attention and major investments are taken to mitigate these. Some power plants operators emphasized the importance of regulatory changes due to climate change effects, which could create additional (financial) risk. One interviewee suggested that old power plants can be retired and replaced by the latest, best available technologies to adapt to climate change.

Studies assessing vulnerability to climate change are usually performed when new plants are designed and installed, especially for plants that became operational less than 5 years ago. These evaluations primarily focused on water temperatures, flooding risks and storms. In all cases, the evaluations drew the conclusion that there is no major immediate threat to the plants, even under a range of possible climate scenarios. The evaluations also concluded that the plants would have enough spare capacity within the range of normal operations under these presumed scenarios. In summary, climate change-related disruptions are not anticipated to present a large and immediate threat to the power generation facilities in question, at least in the foreseeable future. This is reflected in the outcome of evaluations that were carried out, as well as in the fact that evaluations were not considered pressing enough to necessary in other cases, which represented 70 percent of the responses.

5.3.2 *Long-term strategy*

In addition to the risk evaluation, **26 percent of stakeholders have formulated a long-term strategy** to respond to climate-related disruptions. In most cases, this strategy has been developed at a company-level, and is therefore not plant-specific, or necessarily relevant if a particular facility is affected. Moreover, response strategies are often confused with strategies targeting reduction of CO_2 emissions. Measures mentioned in this context are , for example, co-firing biomass, Carbon Capture and Storage (CCS), Combined Heat and Power generation (CHP), and an increased orientation towards Renewable Energy Sources (RES). These issues are, however, not related to adapting to the risks of climate-related disruptions, but are oriented towards mitigating the forthcoming climate challenges that have been identified.

5.3.3 *Daily business*

Generally, **provisions to adapt to climate change are generally not considered in the daily activities** in terms of normal business planning, lifetime extension programmes, contingency plans, etc. On a scale from one to ten, one being no consideration at all and 10 indicating that climate-change adaptation is considered a highly integrated part of daily activities, respondents rated the importance at 2.5 on average. This illustrates that the issue is not deemed threatening or important enough to incorporate into the daily business of the plant facilities. The general approach towards potential effects of climate change on the plants is to react ad hoc, as and when the situation demands. Moreover, for some plants, especially the publicly owned facilities, the future, in terms of strategies, is less important than simply complying with current legislation. Part of the reason for this attitude is also that the expected lifetime of the existing plants – 10 to 15 years – determines the planning horizon. In this context, large capital expenditure for climate change adaptation activities for individual plants cannot be justified.

5.3.4 *Water surface temperature*

Rising water surface temperatures is affecting the water cooled plants through (reduced) cooling capacity. On a scale from one to ten, one being no effect at all and ten having a large effect, stakeholders rated the importance of this issue at 4.4. In most cases, plants need to decrease their production or come to a full stop as water temperature increases, depending on the local legislation. At 4.4, the rating is low because some of the plants have not encountered cooling problems in the past, or because surface water temperatures need to increase dramatically to affect plants.

Still, compared with other potential climate change impacts, **the rise in water temperature has the largest impact on fossil fuel-fired power plants**. The plant managers suggested air coolers or additional pumps as potential adaptation measures to cope with this problem. Adding cooling towers to secure cooling water of sufficient low temperature was mentioned as well.

Inland power plants in the Mediterranean could also be affected by “thermal inversion”. Thermal inversion occurs at temperatures around 45 °C resulting in a full shutdown of the power plant. Building big walls around the chimney, a relatively small investment (less than 1 m€), addresses this problem. This measure has been used in Portugal.

Power plants located closely to the coast are less susceptible to climate change due to the thermal buffer characteristics of the sea. The temperature of the Atlantic rarely increases beyond 21 °C, while the Mediterranean rarely gets warmer than 25°C. Since southern Member States are most susceptible for too high cooling water temperatures, power plants in the Iberian Peninsula are usually constructed close to the sea. Overall, stakeholders agree that sea water temperature is not an issue at the moment and only increases in the range of 5 to 10 °C would require preventive investments. In case of such an extreme change, additional investments in cooling towers may be necessary, corresponding tot an investment of roughly 100 €/kW.

5.3.5 Ambient air temperature

Extreme ambient air temperatures can lead to problems and is identified as the third largest climate change effect that impacts the power plants. When the air temperature drops too low, icing problems can occur in the cooling towers, coal supply and other equipment. Conversely, high air temperatures lead to efficiency losses. Generally, temperatures below -20 °C and above 35 °C have a effect on the production process.

Especially CCGT plants suffer from an increase in ambient air temperature. In wintertime, CCGTs reach nearly 60 percent operating efficiency, whereas during a hot summer the efficiency can drop below 55 percent. This problem affects the fuel costs of generation, but not the level of output. As a rule of thumb, an increase of one degree leads to a decrease of 0.1 percent in plant operating efficiency.

Apart from plant operation, stakeholder emphasized that higher temperatures predominantly affect electricity demand more significantly than operation of the power plants. Moreover, high temperatures affect transmission lines, leading to higher transportation losses.

5.3.6 Precipitation

Of all interviewed power plants, **74 percent responded that changes in precipitation would not affect the generating process**. This winter, the Netherlands and UK have experienced some of the heaviest rains since a long time and no problems occurred. The 26 percent of interviewees that expects changes in precipitation would affect their plants, mentioned that decreased rainfall can cause draughts. This, in turn, causes the water levels to drop affecting cooling water supply. Especially plants cooled with water from rain-fed rivers expect cooling problems. Precipitation increasing risk of flooding was mentioned as a potential problem, although such events are considered very unlikely.

5.3.7 Other extreme weather conditions

When asked what other structural climate change effects would affect the normal operation and maintenance of the facility, **78 percent responded that other extreme weather conditions do not affect the facilities**. However, 22 percent of the respondents mentioned heavy snowfalls, flooding, lightning and storms as a potential effect on operation. Flooding caused by rising water levels instead of increased precipitation affects plants operating on the coastline and cooling with seawater in particular. **Flooding is the second major issue of concern**, as this could severely damage the power plant. In one example, a CCGT power plant operator installed a 5 meters higher foundation to protect the site from flooding. Other power plants have installed the crucial materials and equipment at higher levels, thereby being prepared for an extreme flood event.

Snowfalls can block access roads, overload roofs, etc., but large problems are not foreseen. Lightning could affect the plant's operation, although most plants are equipped with lightning rods. Heavy winds and storm events can potentially damage equipment. Although last winter some plants in the Northern part of Europe experienced very heavy storms, virtually no power plants were damaged. Even during hurricane Katrina in the US, with wind speeds exceeding 200 km/h, transmission lines collapsed, but the fossil power plants survived largely undamaged. These examples illustrate the low impact of an increase in the number of heavy storm events.

5.3.8 *Costs and investments*

All respondents had difficulties to express climate change effects in terms of costs. In most cases, the electricity output of the plants would be reduced, either because the plants cannot run on full capacity due to legal or technical issues, or more electricity is needed for production. In that sense, **costs can be expressed as reduced revenue from production**. Several interviewees indicated that a one degree increase in air temperature results in a 0.1 percent decrease in electricity output. In extreme cases, the plants can be damaged. The impacts differ from case to case, so it is hard to estimate the associated costs.

Investments to cope with climate change effects are uncommon for fossil fuel-fired plants. Increased pumping capacity or (additional) cooling towers are investments for adapting to increasing water and air temperatures, but currently such investments are rare. There are six reasons for this lack of investments:

1. The investments– such as in cooling towers – are costly compared with the reduction in revenues;
2. Many plants are relatively old, and will be decommissioned within a few years. Investments are therefore not economically sensible;
3. Investments to adapt to extreme weather events are usually done ad hoc, and the need for investment simply has not arisen yet;
4. Investments– such as in de-icing equipment – are not considered as climate change adaptation per se, and are therefore accounted for as climate change adaptation;
5. Legal limitations prevent some plants from investing in climate change adaptation. Limitations to allowed additional pumping capacity are one such example;
6. Costs associated with the investments are sensitive information, so the interviewees may not share this information. However, this has not been mentioned once during the interviews.

5.3.9 *Summary fossil fuelled power*

In conclusion, from the interviews it became clear that **climate change has only a minor effect on electricity generation in fossil-fuelled power plants**. It is therefore not a big issue on the agenda of the daily business of the power plant operators. Still, a minority of the power plants in Europe has evaluated vulnerability of their power plants and formulated a long-term strategy to address the associated risks.

The three most important climatic effects on fossil fuel power plants in Europe are:

1. Water temperature, which has the most severe impact;
2. Flooding, having a large impact;
3. Ambient air temperature with a medium impact.

All these effects impact power plants differently, thereby demanding different investments to cope with these problems.

5.4 Renewable electricity generation

Renewable electricity technologies considered in this project are:

- Hydropower;
- Onshore wind and offshore wind;
- Solar photovoltaic (PV) power;
- Concentrating Solar Power (CSP); and
- Biomass-based power.

Five different questionnaires have been sent out covering these five technologies. For all types of renewable electricity generation considered, information has been collected in three ways:

- Questionnaires received from stakeholders (on hydropower, onshore wind, offshore wind, CSP, and biomass-based power);
- Literature research (all renewable electricity generation options considered);
- Interviews (hydropower, and wind) or comments on draft notes of impacts on renewable electricity technologies (solar PV and Concentrating Solar Power).

In the following, the results from the consultation (questionnaires), literature research and interviews or comments by renewable electricity options are summarised and discussed. The section is divided first discusses the current practice of risk and vulnerability evaluations, followed by an assessment of long term strategies and the perception of all different climate change effects. Climate change impacts that not relevant for a specific technology are not covered in the corresponding section.

5.4.1 Risk and vulnerability evaluations

Hydropower

Two out of three respondents for hydropower have evaluated the risks and vulnerability to climate-related effects on their hydropower plants. These two respondents have been or are still involved in studies or R&D projects ('Climate Change and Natural Hazard Risk Management in Electricity Systems').

Impacts from climate change on hydropower are related to glacier cover, precipitation patterns, and resulting changes in (annual) discharge and river run-off. Impacts are estimated using complex models. The sensitivity of hydroelectric generation to changes in precipitation and river discharge is high: a 1 percent change in precipitation or river discharge typically results in 1 percent change in generation (ORNL, 2007). Due to climate change, *Northern Europe* may benefit from an increase in discharge and river run-off. Additional precipitation may benefit Belgium, the Netherlands, and the UK, as well as the Baltic and Nordic states. The potential for hydroelectric generation is hence expected to grow by more than 25 percent by 2050 and up to 30 percent by the 2070s (Alcamo, Moreno, and Nováky, 2007; Lehner, Czisch, and Vassolo, 2005), with the largest increases in Scandinavia (EEA, 2008).

Onshore and offshore wind

For wind, none of the respondents has assessed the risks and vulnerability to climate-related disruption of the wind farm. No answers were received on climate-related impacts on offshore wind farms. However, experience with onshore and offshore wind technology is much smaller than for, e.g., hydropower, as the market has only started developing in the 1980s for onshore wind, and in the 1990s for offshore wind.

Wind electricity, like many renewable technologies, is susceptible to climate change because the 'fuel' is related to the global energy balance and resulting atmospheric motion. Atmospheric conditions enter into the design and operation of wind turbines and wind farms largely under the rubric of 'external conditions'. The wind climate governs the energy density in the wind and hence the power that can potentially be harnessed.

The wind resource is largely dictated by the upper percentiles of the wind speed distribution, which is further amplified by the non-linear relationship between incident wind speed and power production from a wind turbine (Pryor and Barthelmie, 2010). Given the energy in the wind is the cube of wind speed, a small change in the wind climate can have substantial consequences for the wind energy resource. However, stakeholders and literature sources indicate that changes in weather patterns and concomitant changes in wind speeds may be so limited over the lifetime of wind turbines that changing wind speeds can be taken into account when replacing or repowering the installations.

Concentrating Solar Power

For Concentrating Solar Power, the three respondents do not expect that the technology will face significant disruption from climate change.

The main impact of climate change on CSP plants is reduced availability or absence of cooling water. This problem can be more serious than for fossil-fuelled power stations, as CSP plants are usually located in arid regions already suffering from water shortages, while thermal plants are located to satisfy cooling needs. CSP plants are designed with either wet or dry cooling systems. Dry cooling is favour if little water is available locally.

Biomass-based power

Most of the respondents (4 out of 6) have evaluated possible impacts of climate change on their biomass facilities and the related risks and vulnerabilities. For some this was only a part of wider regular risk management. Others evaluated the risk from climate change in relation to CO_2 emission reduction requirements rather than looking at the actual impact on the technology and fuel of the plants. All, however, consider climate change effects as too uncertain and too far into the future to be able to provide a robust quantitative assessment of likely costs.

Nevertheless, some valuable insights were provided regarding the technical limits of the equipment or plant design, which can be linked to the climate scenarios and potential climate impacts. Stakeholders considered cooling water availability as one of the most important vulnerabilities.

5.4.2 *Long-term strategy*

Hydropower

Only one of the three stakeholders has developed a long-term strategy to respond to climate-related effects. This covers measures to increase maximum output of turbines, to reduce the minimal difference of water levels, and to increase the performance due to a higher temperature of water in reservoir based hydropower plants. This indicates that changes needed in operation of hydropower plants related to climate change may be rather smoothly accommodated and do not deserve a long-term strategy at this point.

Observations and projections based on Global Circulation Models (GCMs) show that water flow is decreasing in some regions of Europe and will further decrease in the future (Wolf and Menne, 2007). Studies show a decrease in summer flows in the Alps. The volume of summer low flow may decrease by up to 50 percent in central Europe, and by up to 80 percent around the Mediterranean. Therefore, regions most prone to an increase in water stress are the Mediterranean (Portugal, Spain) and some parts of central and eastern Europe, where irrigation demand is likely to risen countries where they now hardly exist, partly influenced by changes in the amount and distribution of agricultural land as affected by the EU Common Agricultural Policy (CAP). In these affected regions, developing a long-term strategy is more relevant than for the rest of Europe.

Onshore and offshore wind

None of the respondents for wind power generation has developed a long-term strategy for responding to climate change.

No conclusive findings about changes in the variability of wind speeds exist. However, recent research suggests that (Pryor and Barthelmie, 2010):

- Wintertime energy density in the wind may increase in the North of Europe by the end of the 21st century, but decrease in the south. The changes are small, though, and the findings not significant within natural variability;
- Mean wind speeds in the US may declines by less than 3% in the next 50 years, and by less than 5 percent over the next 100 years.

Altogether, the findings point to a medium level of uncertainty, and suggest that the impact on wind electricity will be less than for other electricity generation technologies. Moreover, the timeframe over which changes may occur is likely to be long (50+ years) compared to the lifetime of wind farms.

Biomass-based power

Half of the respondents reported having a long-term strategy to respond to climate-related disruptions, all being developed at company-level. Two of those are again more related to diversification of the portfolio of power generating facilities towards more renewable sources as part of general risk management or in anticipation of higher carbon credits prices and only one (a company with only small-scale biomass CHP plants in its generation portfolio) reported a strategy focusing explicitly on diversification of biomass fuels and securing different types of biomass in anticipation of variability of biomass supply.

5.4.3 Daily business

Hydropower

All three respondents attributes a low priority to provisions to adapt to climate change effects in their daily business planning.

As highlighted in the preceding paragraph, the Mediterranean is most vulnerable to climate-related effects on hydropower. Mimikou and Baltas (1997) present an assessment of climate change impacts on critical water management issues such as reservoir storage and hydroelectric production for *Greece*. Two equilibrium scenarios referring to the years 2020, 2050 and 2100 and one transient scenario referring to the years 2032 and 2080 were applied to present both ‘greenhouse gas’ warming and induced changes in precipitation and potential evapo-transpiration. By using these scenarios, the sensitivity of the risk associated with the hydroelectric generation of a large multipurpose reservoir in northern Greece has been evaluated under conditions of altered runoff. They observe increasing risks associated with the annual quantities of electricity production. To maintain the same reliability for the minimum and average yields, reservoir storage must increase by 12 percent and 38 percent in 2050, respectively in the so-called ‘equilibrium scenarios’. In the ‘transient scenario’, the required increases are 25 percent and 50 percent in 2080, respectively.

Furthermore, climate change will have significant impacts on hydroelectric generation in *Turkey*. Global warming will likely cause a steady decline in water supply and concomitant hydroelectricity in southern Europe, including Turkey. Therefore, operators of hydropower plants in the

Mediterranean would need to adapt to climate change effects as part of normal business planning, lifetime extension programs, etc.

Onshore and offshore wind

to the stakeholders regarded provisions to adapt to climate change effects as part of normal business planning, lifetime extension programs, etc, as a low priority in their daily business planning.

Biomass-based power

On average, respondents assigned low priority to provisions to adapt to climate change in their normal business planning, lifetime extension programmes, contingency plans, etc. On a scale from one to ten, the average rating is only 2.3, because most plant operators foresee few tangible effects of climate change in the near to mid-term future. The only vulnerability perceived as real at this stage and already receiving some attention is the cooling process, which is likely to suffer from long-term increases of air and water temperatures.

5.4.4 Water level/sea level

Hydropower

The respondents did not report anticipated impacts of changing water levels on hydropower plants. Impacts primarily stem from, inter alia, changes in water flow and not so much water level (in reservoir-based hydropower plants).

Onshore and offshore wind

The respondents did not report anticipated impacts of changing water level.

Pryor and Barthelmie (2010) report four possible impacts from changes in water level/sea level and the like on offshore wind farms:

- Sea ice (drifting sea ice) can damage turbine foundations of wind turbines offshore. Studies of projected changes in sea ice days in the Gulf of Bothnia in the north Baltic Sea indicate a decrease from 130–170 days to 0–90 days in 2071–2100, with many areas becoming ice-free. A study conducted for the entire Baltic Sea indicated large decreases in sea ice extent by the middle to end of the twenty-first century under two SRES climate change scenarios;
- Sea level rise largely due to thermal expansion of 4.2 mm/year reported in the 4th Assessment Report of the IPCC may damage the foundations of wind turbines deployed in low-lying coastal areas and offshore if coastal flooding becomes more frequent;
- Corrosion of offshore wind turbines is expected to decrease as the fresh water loading to the oceans increases;
- An offshore wind turbine foundation is subject to the combined action of wind and wave loads, which in turn are a function of the wind speed and significant wave height. The wave state is in turn dictated in part by coupled wind-wave interactions, and thus may be modified by changing atmospheric circulation patterns. One study indicates that the current 20-year return period wave in the North Atlantic may occur every 4–12 years by 2080, so offshore turbines must then be able to withstand greater forces.

Concentrating Solar Power

Stakeholders do not anticipate any impacts of changing water levels on operation of CSP plants as these plants are predominantly sited in southern Europe (and North Africa) with a relatively dry climate (relatively modest precipitation).

5.4.5 *Ambient air temperature*

Hydropower

The three respondents anticipated only minor to relatively small (zero to three on a scale of seven) impacts on operation of hydropower plants due to ambient temperature change. Changes in precipitation, evapo-transpiration, and run-off are more important than air temperature.

Onshore and offshore wind

None of the respondents answered on the question on impacts from (higher) ambient air temperature. Pryor and Barthelmie (2010) state that an increase in air temperature of 5 °C, from 5 to 10 °C leads to a decrease in air density of 1–2 percent with a commensurate decline in energy density.

Concentrating Solar Power

Stakeholders reported none or minor impacts from a change in air temperature on operation of CSP plants.

Biomass-based power

Small scale biomass plants and CHP plants are mainly air cooled, which means they are more likely to be affected by any changes in air temperature than large facilities. Generally, electricity production increases as temperature falls, and vice versa. However, when facilities operate close to their maximum capacity factor, a lowering of air temperature is not expected to increase their power output, which is limited by the facility's operational permit. A lowering of air temperature thus does not represent a threat for the facilities and their power output.

The situation is reversed for increases in air temperature, which if significant enough, can decrease the power output of the facility. One of the respondents reported that a 5 °C increase in air temperature above the normal temperature can reduce electricity production by 5 percent. Another one estimates that for every °C of air temperature increase above normal, every operating hour produces ca 40 € less of output value. "Normal temperatures" depend on the plant location and the cooling technology specifications, but the respondents reported normal temperatures between 15 and 25 °C. Adapting to a significant increase in air temperature would mean investing in more or improved cooling units, which one of the respondents estimated to require an investment of ca €5 million for a 25 MW plant.

5.4.6 *Precipitation*

Hydropower

Respondents expect that precipitation would only have a small to relatively small (maximum three on a scale of seven) impact on the operation of their hydropower plants. However, the respondents did not explore this in detail.

Climate change related effects on water status add to the burden of existing anthropogenic pressures on water bodies, through rising water abstraction because of higher summer temperatures, or increasing diffuse pollution due to increasing rainfall intensities (EU, 2009). Climate change will therefore be fully integrated into the 2nd and 3rd river basin management (RBM) cycles of the EU's Water Framework Directive (WFD; EC, 2000). Specifically with regard to hydropower, the study (EU, 2009) gives the following recommendations:

- Existing hydropower dams can also contribute to flood risk management. This should be recognised in flood risk assessment and management;
- Dams and reservoirs, if properly planned and managed, can be considered as an important part of integrated water management schemes under climate change conditions. Such dams are

subject to operation licenses. The WFD requires that such permitting regimes of impoundments are regularly reviewed;

- Storage power plants have an important effect in reducing local floods, but run-of-river power plants can also have a positive effect, especially on small and medium flood events. The way the water flows are regulated in such rivers should take potential changed flood patterns into account, ensuring flood risk decreases rather than increases.

Biomass-based power

Changes in precipitation are not regarded as a significant threat mainly because they are unlikely to become significant in the foreseeable future. One of the respondents reported that the present average levels should at least triple for precipitation to become an issue, which is unlikely during the lifetime of existing plants. At the same time, precipitation levels might have an indirect effect on the cooling systems, especially for those plants relying on river water cooling, as it may affect water levels in river basins. Such effects have, however, not yet been quantified.

5.4.7 Other extreme weather conditions

Hydropower

Only one of the three respondents has evaluated the impacts of extreme weather, finding negligible effect. Changes in precipitation, evapo-transpiration, and run-off are more important than possible extreme weather conditions.

Onshore and offshore wind

One respondent answered that increased turbulence and gusts could lead to higher structural loads for onshore wind farms and (inter alia) higher efforts for corrective maintenance.

Solar PV

Extreme weather conditions have only limited impact on design and operation of solar PV plants. In Slovenia, for instance (Pašičko, 2010):

- Higher temperatures and less precipitation will result in more forest fires which may affect PV systems; the risk is hard to quantify, but can be reduced by choosing appropriate locations for PV;
- Expected increase in strong winds and storm events can impact PV panels if not considered in the design.

Concentrating Solar Power

One respondent reported possible damage from (higher) wind loads. In the extreme conditions, this would cause the exposed collector loops to be taken out of the operation, leading to the reduction of the solar field availability and output reduction. At one facility a several meter high pillar reinforced wind breaker wall was designed for the exposed boundaries of the solar field. The original design included a wind fence from wire, but a windbreaker from bricks may be also implemented. Such protection incurs additional investment costs.

More frequent or vehement storms may also damage the support structure of CSP plants. This structure, which is typically made of metal, holds the mirrors in accurate alignment while resisting the effects of the wind. More robust designed can prevent damage from frequent or vehement storms, mostly at limited extra costs.

Biomass-based power

The respondents did not specify any other possible climate change induced extreme weather conditions which could significantly affect their operations. One stated that the current operating range of the plant he operates is more than sufficient to cover even the most pessimistic forecasts for the next decades.

Still the supply of biomass is very much prone to extreme weather effects which are likely to increase with climate change. The lack of concern among stakeholders might reflect the fact that many of these extreme events (floods, pests, storms) tend to increase the supply of biomass suitable for power generation, reducing the cost of feedstock and are thus not seen as real threats.

The main difference between the biomass-based power production cycle and the conventional power plants is the possible high variability of the biomass supply. As mentioned earlier, climate change is expected to have a significant impact on biomass supply, with pronounced regional differences.

This is of course much more relevant for those facilities that rely on biomass as their main input, than for those, which co-fire it with fossil fuels. For the latter, a reduction of biomass supply is not considered a major disruption as the biomass shortfall can simply be replaced by additional coal input. On the other hand, an increase in biomass supply is usually constrained by power plant design which only allows co-firing up to a maximum share of fuel input. Consistently reaching the upper limit of co-firing possibilities would also require additional maintenance and investments in automation and additional biomass intake facilities (including pre-milling), which one of the respondents estimated at €15 million (for intake facilities able to process more than 300.000 tonnes of biomass per year).

5.4.8 Biomass supply

For plants that fully rely on biomass as their feedstock for power generation, the effects of changes in biomass supply are more pronounced. A lower biomass supply means lower output. One of the respondents operating a waste incinerator running on 50 percent biomass and a bio-electricity plant relying exclusively on waste wood as feedstock, reported the following costs of a reduced biomass supply: for the waste incinerator, a 10 percent lower biomass supply means a negative impact of about €3 million per year; for the bio-electricity plant, a 10 percent lower supply means approx. €2.5 million lower income annually. If the opposite situation occurs and biomass supply increases, a certain amount of overload is possible (3-5%) and income effects are similarly proportional (but positive, of course). Accommodating biomass amounts above design capacity would require additional investments, depending on the type of biomass. Dusty biomass feedstocks require a separate, completely closed system, which is estimated to costs ca €1 million for a bio-electricity plant smaller than 30 MW.

Changes in biomass supply are also assessed in terms of their impacts on the price of biomass: higher biomass supply on the market means lower input costs, which improves plant profitability. Having a multi-fuel plants and secure supply of a variety of biomass feedstocks is a concrete strategy to cope with varying biomass supply and costs.

5.4.9 Costs and investments

Hydropower

None of the respondents for hydropower reported an expected increase in generation cost or (additional) investment cost. Only one respondent made notice of a further reduction of hydroelectric generation and availability due to avalanches, soil erosion, landslides and rock fall. Pumped storage plants in the high Alps will be most affected. Storm damage could also trigger power plant shutdown.

For *Switzerland* (Alpine region), Schaefli, Hingray and Musy (2007) report that the hydropower production undergoes a shift of about 7 percent from winter to summer production due to a modification of the prevalent hydrological regime. This regime modification partly explains the decrease in the release reliability, as planned releases during the winter months can no longer be met and production in summer months is sometimes higher than planned.

The worsening of the release vulnerability is accompanied by occasional spillway activation. In the most extreme climate change scenario, stimulated discharge through the spillway is 177.4 m^3/s, whereas the maximum discharge recorded before the dam construction amounted to some 59 m^3/s (45 years of data). In the median climate change scenario (+2.6°C), the maximum spill is 60 m^3/s, similar to the discharge before dam construction.

Another study assesses the impacts on a hydroelectric scheme in the Rhone generating 1.8 TWh/year (~3% of total Swiss hydro generation) (Westaway, 2007). In the Lac des Dix, Westaway (2007), climate change is expected to increase discharge, run-off and evaporation while precipitation remains largely unchanged, assuming a temperature increase of 1.4°C in the period 2031-2060. As a result, total water inputs to the reservoir increase by 35%, while annual water outputs increase by only 2%. This produces an average monthly pattern of reservoir level similar to that at present, but with a steeper rising limb, and more months when Lac des Dix is estimated to be full (June to September). The results indicate that hydroelectric generation might increase by 25.6 percent. However, because the reservoir is nearly full in the summer, most extra water simply 'runs off' without generating additional electricity, unless the reservoir volume would be increased.

The impacts of climate change on hydroelectric generation is likely to be neutral in Central Europe and even positive for the northern part of Europe, but the effects could be negative in Mediterranean countries.

Onshore and offshore wind

For onshore and offshore wind, stakeholders reported no additional generation costs or increased investment costs due to climate change. The only impact that is reported is a possible reduction of the average wind speed for onshore wind farms. For instance, a reduction of the average wind speed of 0.3 m/s may incur a 2 percent decrease of electricity generation. Therefore, it is assumed that the impacts of climate change on wind electricity generation are fairly small.

The main reason why climate change will not significantly affect onshore and offshore wind is that the changes anticipated in average wind speed are small and gradual during the 20 to 25 year lifetime of onshore and offshore wind turbines. The impacts of climate change on e.g. sea level occur at much longer term. For the foundations of offshore wind farms, the economic lifetime may be longer, but even so stakeholders expect no major increase in investment costs.

Solar PV

For solar PV, the cost implications for climate change are small. Even in Scandinavia, the most affected region, ambient temperature increase ranges from 2.5-3.0°C in Trondheim (Norway) to 4.6-4.7°C in Helsinki (Finland). In addition, the solar irradiation is expected to decrease by 2%, due to decreasing snow cover.

The combined effect would entail a reduction of the yield of PV systems of 6 percent at most.

Concentrating Solar Power

For Concentrating Solar Power, the respondents did not report increased generation cost or increased investment cost due to climate change. Literature on CSP gives some indications of the impact of water scarcity (which is already in issue in relevant regions in southern Europe) on the cost of CSP plants.

CSP plants are preferably placed in deserts, where water is too scarce to be used for cooling, and additionally, vapour plumes from cooling towers can shadow the collectors. Instead, dry cooling can be used, using ambient air as cooling medium. Dry cooling will increase the construction costs (3-6%) as well as operation and management costs (1-3%), and decrease the performance (5-9%) of the plant, costs varying widely with site specifications. Even if dry cooling is used, there can still be minor water requirements, for collector washing, boiler make-up in steam cycles etc (Pihl, 2009).

A number of future CSP plants in the Mediterranean region will also be built with dry cooling. Also, the solar dish technology (based on Stirling engines) uses less water than other CSP technologies. This technology, however, is not as well as developed as other CSP technologies. As arid lands are most appropriate for CSP plants, there tend to be few competing land uses, so that the main competition is over water. It may therefore be necessary to apply cooling technology with low cooling water demands, even without considering impacts of climate change. Consequently, climate change impacts on future CSP projects will probably be relatively minor, as the need for low cooling water demands is already factored in at the design of the plan.

Biomass-based power

All respondents had difficulty providing any estimates of direct costs related to climate change adaptation, either because they are expected to unfold too far into the future or are considered to be of marginal importance for the power production process.

Nevertheless, estimates exists for costs related to production disruptions, which can be due to the effects of climate change, and the related adaptation investment needs. The available estimates are plant-specific, though, and too few and far between to calculate representative average costs for the sector. The available estimates are:

- For climate change induced costs:
  - For a small-scale (<30 MW) mainly waste-wood fired installation any 5 °C increase above the normal average temperature of 15 °C represents a reduction in power output of 5 percent. The related monetary cost changes with electricity price;
  - Another waste-wood-fired facility estimates that every 1 °C increase in air temperature above 25 degrees can cause a loss of income of €40 for every operating hour;
  - For the same type of facility, a reduction of biomass supply (possible due to fires etc) of 10 percent means a yearly loss of income of between €2.5-3 million, depending on proportion of biomass feedstock (50% or 100%).
- For adaptation investments:
  - To withstand an increase of air temperature to critical levels, a biomass power plant smaller than 30MW would need to invest in more cooling area, which would cost ca. €5 million for the whole plant;
  - Facing a consistent increase in cooling water temperature, a large-scale plant would need to invest between €10-20 million in cooling towers;
  - A small-scale plant faced with an increase of supply of biomass type with high ash content would require the 100 percent biomass fired plant to invest ca. €1 million in a separate, completely closed system;
  - For large scale coal-based plants which co-fire biomass (>400 MW), the investment needed to increase the intake capacity to accommodate larger supply of biomass, is estimated at ca. €15 million (to handle an access of 300,000 t of biomass).

5.4.10 Conclusions

Wind electricity generation

According to one respondent, increased turbulence due to climate change could lead to higher structural loads and higher efforts for corrective maintenance. Also, the lifetime of wind turbines could be shortened, though no quantitative information was provided. Nevertheless, the respondent does not anticipate investments needed to adapt to a change in wind speed or turbulence. Instead, the wind turbines may be replaced or the wind farm be repowered at the end of the economic lifetime.

Another respondent expects only have minor impacts from climate change on operation of onshore wind farms. For instance, a reduction of the average wind speed of 0.3 m/s may incur a 2 percent decrease of electricity generation.

For wind electricity, the uncertainty in predicted output of wind farms is relatively large. Therefore, utilities developing wind farms are used to making business cases taking into account significant margins with regard to the expected output of a wind farm. This applies to both onshore and offshore wind farms. In that sense, uncertainties due to climate change are not new, and add only a small margin of uncertainty. Therefore, utilities that operate (onshore and offshore) wind farms are not so concerned about impacts from climate change.

Furthermore, the lifetime of onshore wind turbines is not so long that climate change may impact their design or operation significantly in that period. Companies manufacturing onshore wind turbines may anticipate on possible impacts by changing the design when repowering. For offshore wind, investigations with regard to the impacts may be needed if foundations would last longer than the turbines.

Hydropower generation

Changing water availability due to shifting precipitation patterns and glacial melting is the main impact of climate change on hydropower. Hydroelectric generation is highly sensitive to both changes in precipitation and river discharge is high: a 1 percent change in precipitation results in a 1 percent change in generation.

The long timeframe of over which hydropower operators plan their investment is difficult to harmonise with the timeline of other water management issues, complicating planning for climate change. Hydropower companies usually evaluate the economic performance of a large dam over 25 years. However, for such a long period, potential water management conflicts between different users can emerge. Additionally, even in cases of excess water availability, governments hesitate to commit themselves to the 'investors' 25-year period, especially now that there is great uncertainty about the impact of climate change.

Biomass-based power

Similarly to other power generating technologies, biomass-using power producers are only slowly starting to assess any possible impacts of climate change on their operations, starting with the cooling process. How to handle an increase (rather than a decrease) in biomass supply is also considered by some in the sector.

Most plant designs allow for absorption of a certain level of climate impacts. Uncertainties regarding timing and intensity of climate change effects, retrofitting existing plants with adaptation investments are not yet considered. Nevertheless, climate change impacts are constantly monitored and new insights should be incorporated when designing new facilities.

Photovoltaic electricity generation

Table 10 summarises the estimated climate change impacts on PV systems in the Mediterranean and Scandinavia. In the Mediterranean, the aggregate effect is an increase of the yield of 6%, neglecting minor potential impacts from decreased snow cover and storms. In Scandinavia, using the results for a PV panel in Oslo as an example, the electricity output of solar cells will be reduced by about 6 percent if solar irradiance falls 2 percent.

Table 10 Climate change impacts on PV in the Mediterranean and Scandinavia

	Increase	Δ efficiency	Δ yield
Mediterranean	-	-	-
Ambient temperature	+ 2°C	- 0.15%	- 1%
Solar irradiance	+ 7%	-	+ 7%
Aggregate	-	-	+ 6%
Scandinavia	-	-	-
Ambient temperature	+ 2.5°C - + 4.7°C	none	none
Solar irradiance	- 2%	-	- 6%

Concentrating Solar Power

The main impact of climate change on Concentrating Solar Power (CSP) plants is reduced availability or absence of cooling water - more frequent or vehement storms will have only minor impacts for (the design of) CSP plants. .As CSP plants tend to be in arid regions, dry cooling systems are often necessary. Dry cooling has in principle three drawbacks: higher parasitic losses, lower steam-cycle efficiency and higher investment costs. The difference in cost between dry and wet cooling is approximately $200/kWe, increasing the construction costs by 3-6%, and operation and management costs by 1-3%. Plant performance can decline by 5-9%. However, costs varying widely with site specifications.

5.4.11 Summary renewable energy sources

Hydropower generation

With increasing temperature and changing weather patterns, the potential hydroelectric generation is expected to grow in northern countries (by more than 25 percent by 2050 and up to 30 percent by the 2070s) and to decline in southern ones (by around 25 percent by 2050 and up to 50 percent by the 2070s). Therefore, electricity generators in the Mediterranean need to focus on possible impacts and ways to mitigate them.

Onshore and offshore wind generation

The wind resource is largely dictated by the upper percentiles of the wind speed distribution, which is further amplified by the non-linear relationship between incident wind speed and power production from a wind turbine. Given the energy in the wind is the cube of wind speed, a small change in the wind climate can have substantial consequences for the wind electricity resource. However, changes in weather patterns are slow, so changing wind speeds can be addressed when wind farms are at the end of their economic lifetime and are replaced or repowered. Wind energy is therefore little affected by climate change.

Biomass-based generation

Biomass-based electricity generation fully relies on biomass as feedstock, and the effects of changes in biomass supply may be pronounced. Changes in biomass supply are also assessed in terms of their impacts on the price of biomass: higher biomass supply on the market means lower input costs, which improves plant profitability. The opposite holds for a reduction in supply quantities. A concrete strategy to cope with variability of biomass supply is to have multi-fuel plants and secure supply of a variety of biomass feedstocks. Biomass-based power plants also suffer from decreasing availability of cooling water, requiring investment in cooling towers.

Photovoltaic power generation

Impacts of climate change on photovoltaic power generation will generally be small. In the Mediterranean, the aggregate effect is an increase of the yield of 6%, neglecting minor potential impacts from decreased snow cover and storms. In Scandinavia, climate change also reduces snow cover, causing decreased reflection, so that PV generation declines. In Nordic countries, the yield of solar cells may be reduced by about 6 percent if solar irradiance falls by 2 percent.

5.5 Electricity transmission and distribution facilities

5.5.1 Introduction

Research on the impacts of climate change on electricity networks is fairly recent and high-level. Most has focused on two factors: wind conditions and temperature. Flooding has received attention in EU Member States that have recently experienced flood damage.

Fourteen European network operators and related stakeholders have contributed to this research, either through the questionnaire or through discussion of specific topics, depending on their preference. Their input has been combined with information from literature and consultation with academics at universities and research institutes.

5.5.2 Network operators

Lack of certainty makes adaptation low priority for network operators

The impacts of climate change itself on electricity networks are small compared to the impacts of climate change policy. Most European network operators are primarily concerned about the rapid growth of intermittent power supply to their network. They are also preparing to transmit electricity from planned new nuclear power plants to end-users.

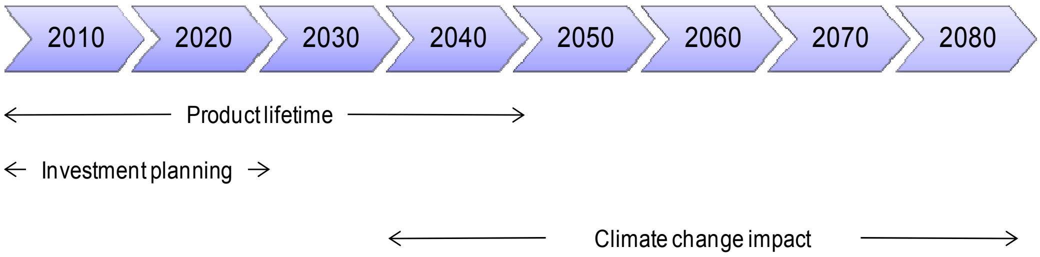
Effects of climate change have been a relatively low priority. Most have identified the impacts of climate change as important in the future, but few assessed them in detail. None of the consulted network operators has a comprehensive strategy in place for dealing with climate change effects.

This low priority is reflected in the Ten Year Network Development Plan of the European Network of Transmission System Operators for Electricity (ENTSO-E), in which climate change adaptation only receives minor attention. The impacts of climate change are addressed more in the ENTSO-E System Adequacy Forecast 2010 – 2025, for which each country has assessed its power sector in the light of wind speed, precipitation and temperature and their impact on power generation and demand. Still, only three network operators mention potential unavailability of thermal power plants due to rising cooling water temperature. Only one envisions a possible reduction in available network capacity at high temperatures.

Several reasons explain the little attention that has been paid to climate change impacts on the electricity networks. Uncertainty in climate change projections is a major obstacle. Most TSOs see weather events causing damage as one-offs, which they address on a case-by-case basis. Developing a systematic strategy based on (perceived) single events is difficult or deemed unnecessary.

A second problem for incorporating climate change effects into network planning is the long timeframe over which these impacts play out – typically 50 years or more. Despite the relatively long lifetimes of network equipment, this is beyond the planning horizon and lifetime of some technologies (Figure 16). Network operators therefore often expect that climatic changes can be addressed when old assets are replaced, using improved or adapted technology.

Figure 16 Time frame of climate change impacts relative to product lifetime and investment planning cycle



Other reasons for the lack of urgency include:

- Network operators expect that the impacts of climate change on electricity networks will be minor in the foreseeable future;
- The impacts are broadly known. Increasing wind speeds can damage overhead lines, and increasing temperatures would raise line resistance and increase losses. Flooding of substations and other network assets can also cause supply disruption;
- Existing technology can often be used for adaptation, for instance replacing overhead lines in sensitive areas by underground cables;
- The costs of using climate-proof technology often outweigh the (perceived) risk. Underground cables, for example, can be 5 to 20 times more expensive than conventional overhead lines, while their benefits are difficult to quantify because of uncertainty in climate change projections;
- Many network operators consider preparing for the integration of renewable electricity and new nuclear power more urgent, because it has larger and more immediate impacts on the grid and its operation.

However, many adaptation measures are win-wins: they have other benefits too, and are being introduced in European grids for those reasons. European electricity networks are therefore becoming more climate-proof already. Such win-win measures include:

- Undergrounding parts of the network reduces both visual and environmental impacts;
- Using flexible AC transmission systems makes networks better controllable;
- Installing monitoring equipment facilitates integrating intermittent supply.

5.5.3 *Leading initiatives driven by past experience or regulatory requirement*

TSOs that have analysed certain weather-related impacts on their grid in detail have generally done so because they have suffered from weather-related damage in the recent past. The UK has progressed furthest to a strategic approach to climate change adaptation. Its government has started a programme for developing adaptation strategies throughout its economy, after adopting the Adaptation Reporting Power in the 2008 Climate Change Act (DEFRA, 2009). All major operators of electricity networks are required to assess the impacts of climate change on their business in detail, evaluating the costs and benefits of adaptation. They are due to provide an initial report in autumn 2010, and the whole process will continue into 2011. The Electricity Network Association is coordinating the work of the network operators, but each company will perform its own analysis.

5.5.4 *Network regulators*

Most European regulators with remit over electricity networks have identified climate change adaptation as a potential future concern, but this has not been translated into regulatory strategy. Again, the UK is at the head of the pack. OFGEM will report about the role of adaptation as part of the government programme. It will primarily consider its own activities, including potential changes in regulatory practice. For example, the calculation of network tariffs could be changed to allow network operators to invest in adaptation. Regulators in most other countries have only considered the vulnerability of the electricity sector in general.

5.5.5 Electricity network technology suppliers

Adaptation needs have made few inroads into the product development strategy of major electricity network technology suppliers. Developing and marketing products for integrating renewable electricity into the grid is their primary focus, because of high demand from network operators.

The technology suppliers consulted stress that their product development is driven by customer interest. They expect that climate change adaptation will influence the purchasing decisions of an increasing number of clients in the future, so they will develop the necessary products then.

5.5.6 Summary electricity transmission and distribution facilities

Evaluating the impacts of climate change and assessing adaptation strategies has been a low priority for network operators in Europe. In the short term, they expect that the changes needed to integrate new (intermittent) electricity sources will outweigh the impacts of climate change. Even the impacts of increasing storms and flooding, which are considered most worrying, are relatively minor and unpredictable. The first in-depth analysis has recently started in countries like Sweden and the UK, primarily driven by legislative requirements and recent experience of weather-related damage.

5.6 Comparison analysis between electricity generation technologies

Climate change assessments

We found that all nuclear facilities have assessed the effects of climate change, because they are part of the mandatory Periodic Safety Review. For fossil-fuelled plants this was the case for only half of them. In the renewable electricity industry the climate change effects are assessed rarely. In the electricity transmission and distribution sector stakeholders have only just started assessing the effects. The results are summarised in Table 11 below.

Table 11 Percentage of climate change effect assessments done per electricity sector

Sector	Percentage of CC effect assessments
Nuclear power	~100%
Fossil-fuelled power	~30%
Renewable electricity	<5%
Electricity transmission and distribution	~0%

Long-term strategies

Half of the nuclear facilities have included climate change effects in such strategies. For the fossil-fuelled power plants only 26 percent has developed long-term strategies regarding climate change effects. Such strategies are rarely found in the renewable electricity industry or electricity transmission and distribution sectors. These results are shown in Table 12 below.

Table 12 Percentage of climate change effects taken-up in long term strategies per electricity sector

Sector	Percentage of long-term strategies including CC
Nuclear power	~50%
Fossil-fuelled power	~26%
Renewable electricity	<5%
Electricity transmission and distribution	~0%

Three most harmful effects of climate change are the same for nuclear and fossil-fuelled power are reduced cooling water availability, increased ambient air temperatures and flooding risks. The same holds true for biomass based power. These three factors affect cooling, which is essential for all thermal facilities. This cooling can be done by water or air, and when these cooling agents are not abundant or cold enough there are efficiency losses. Flooding is a rare extreme even, but can bring operation of all types of power plants to a full stop and potentially damages the plants heavily. For the renewable electricity and power transport sectors, there are varying harmful effects that impact the equipment by damage or lack of 'fuel' (i.e. water for hydropower and irradiance for concentrating solar power). Often, the most harmful climatic effects for the renewable energy sources and electricity transmission and distribution facilities are related to the risk of heavy damage, due to flooding or storm events. Table 13 summarises the most important climatic effects for each technology.

Table 13 showing the most harmful climatic effects per electricity sector in order of importance

Sector	Most harmful climatic effects
Nuclear power	1. Flooding
	2. Water temperature increase and cooling water availability decrease
	3. Ambient air temperature increase
Fossil-fuelled power	1. Water temperature increase and cooling water availability decrease
	2. Flooding
	3. Ambient air temperature increase
Base load renewable energy sources	
• Hydropower	1. Changing water availability
	2. Flooding
• Biomass-based power	1. Flooding
	2. Water temperature increase and cooling water availability decrease
	3. Ambient air temperature increase
Intermittent renewable energy sources	
• Wind power	1. Sea level rise is a serious threat for offshore wind
	2. Heavy storm events
• Photovoltaic power	1. Heat waves
	2. Heavy storm events
• Concentrating solar power	1. Flooding
	2. Heavy storm events
Electricity transmission and distribution	1. Heavy storm events
	2. Ambient air temperature increase
	3. Flooding

6 Cause-Consequence patterns: linking pressures and pre-conditions

This chapter will look into how climate change effects will impact the operation of power plants. This is done by making an inventory of climate change impacts per generation technology. This information is quantified into the so-called Ecorys Risk Assessment Model (RAM), in order to estimate the EU wide adaptation cost of power plant operators under different climate change and energy supply scenarios. The basis of this chapter, in terms of analysis, is concentrated towards the climate change scenarios and the Eurelectric baseline scenario for its electricity supply projections. As an illustration, the same procedures and methodological steps have been performed for the Eurelectric Power Choices scenario, for which the results are shortly presented in section 6.3.2, to show what the potential investment needs can be for a more extreme set of scenario assumptions in terms of the energy supply mix and climate adaptation objectives.

6.1 Cause-consequence relations and risk schemes

The effects of climate change differ as a function of the region, technology, and underlying causes. For this reason, their assessment in the context of this study will be conducted on two levels.

1. The first level will be a graphical overview of the main effects and relationship between climate change and technologies, regions and underlying causes, leading to a qualitative overview;
2. The second level will be a thorough assessment of the identified impacts, and these will be described and analysed in detail, leading to a quantitative estimation of the adaptation costs.

Table 14 shows how generation technologies will be affected by five average increases in climate change indicators and three types of extreme events. Based on literature review, input received from power plant operators and regulators during the stakeholder consultation and internal expertise, the significance of the predefined climate change effects for each electricity generation technology has been determined. In that respect, a categorisation has been made towards the impact significance. When there is no significant impact expected this has been indicated, together with an indication about the severity of the climate change impact when a significant impact can be expected. The darker green the shading in the table, the more severe the impact of the climate change effect on the electricity generation technology. Important to note is that the classification describes qualitatively the potential severity of a climate change effect in terms of classification, but not in terms of level of significance (= the size of the impact).

Table 14 Qualitative link between technologies and climate change effect

Technology	Δ air temp.	Δ water temp.	Δ precip.	Δ wind speeds	Δ sea level	Flood	Heat waves	Storms
Nuclear	1	2		-	-	3	1	-
Hydro	-	-	2	-		3	-	1
Wind (onshore)	-	-	-	1	-	-	-	1
Wind (offshore)	-	-	-	1	3	-	-	1
Biomass	1	2	-	-	-	3	1	-
PV	-	-	-	-	-		1	1
CSP	-	-	-	-	-	1	-	1
Geothermal	-	-	-	-	-	1	-	-

Technology	Δ air temp.	Δ water temp.	Δ precip.	Δ wind speeds	Δ sea level	Flood	Heat waves	Storms
Natural gas	1	2	-	-	-	3	1	-
Coal	1	2	-	-	-	3	1	-
Oil	1	2	-	-	-	3	1	-
Grids	3	-	-	-		1	1	3

Note: 3 = Severe impact, 2 = Medium impact, 1 = Small impact, - - No Significant impact.

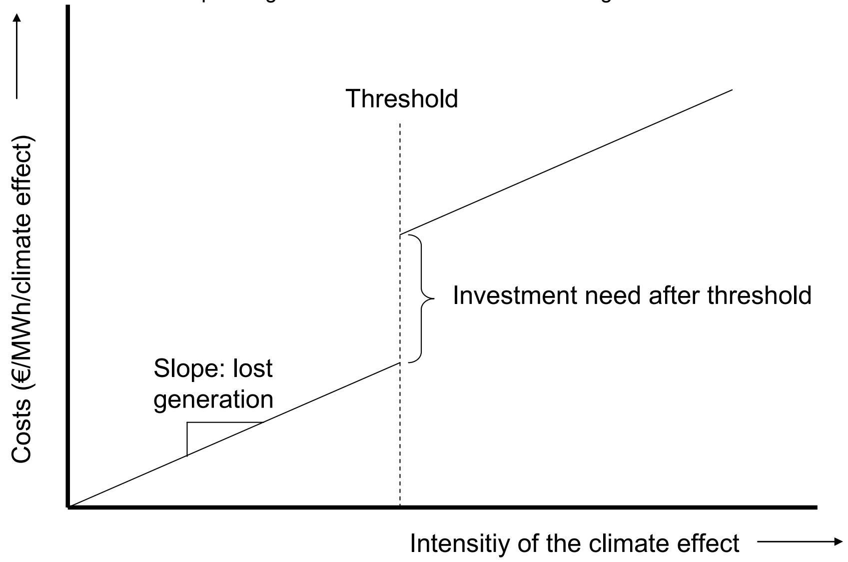
The presentation of Table 14 is already a qualitative result, showing the technology-wise potential vulnerability to various climate change indicators. The table shows that an increased occurrence of floods is assessed as having the most severe impact, influencing nuclear, hydro, biomass and fossil fuel generation technologies. Furthermore, sea level rise will severely affect offshore wind parks, whereas higher temperatures and storms will severely affect grids. Under a scenario of climate change, these impacts will most probably be so severe that preventive investments will be needed in order to be able to cope with the new climatic reality. The other climate change indicator – technology pairs with medium to small impacts – would generally only lead to a loss in generation, whereas preventive investments are generally not needed.

The second step is the quantification through the Ecorys Risk Assessment Model which goes through the following steps:

- Divides EU27 into four climate zones, with maximum difference between the zone and minimal difference within the zones;
- Linking climate change indicators to generation technologies, and identifying the relevant indicator-technology pairs;
- Quantification of climate change indicators using three relevant regional models;
- Estimate climate change adaptation cost functions, namely:
  - Loss of generation (gradual loss);
  - Investment needs after critical threshold.
- Electricity scenarios to estimate the generation volume per technology;
- Estimate total costs to adapt to the situation in 2080.

The following figure shows that climate change can lead to a gradual loss in power generation (slope effect) or lead to an investment need when a certain threshold value of climate change is exceeded.

Figure 17 Investment needs and power generation loss due to climate change



6.1.1 *Risk schemes further elaborated*

This section will further elaborate on the collected data and provide further detail. This section aims to provide an evaluation of the consequences of climate change effects on different technologies as well as indicating their risk of occurrence and their timeframe. The goal of this restructuring is to have, for each impact and technology, a quantification of the intensity of different impacts in the three chosen scenarios and an indication of the level of risk per technology, quantified in monetary terms.

The consequences will be further broken down, according to the different scenarios. This breakdown will help identify the level of risk of an impact of a specific scenario on each technology. Input will be provided through the stakeholders' questionnaire. Respondents were asked in the questionnaire to quantify the potential costs from needed investments and losses according to the same impacts and intensities outlined in an overview table.

Table 15 provides the overview for 2080 (and serves as an example) in terms of assessed costs due to climate change impacts. For this particular table the aggregated result for the EU-27 for the three regional climate change scenarios have been studied. Based on the inputs received from interviews, questionnaires, analysis reports and generic literature a threshold value has been determined for each of the technologies that can potentially significantly be impacted by certain climate change effects. More details about the threshold calculations and the threshold values per electricity generating technology and climate change effect will be provided in section 6.2. The threshold values determine to what extent a change in the climate variables will have an impact on the efficiency of the generating operations by power plants. In other words, the larger the surpassing of the threshold value of a predefined climate change effect, the more significant the impact will be on potential efficiency losses of daily operations. Based on conversion factors, per electricity generation technology, to express percentage efficiency losses into operational costs (= the opportunity costs for not having the best efficiency ratio in daily operations). This will be further elaborated in the next sections.

In the table below, the operational costs have been aggregated towards the different climate change scenarios and the predefined climate change effects per technology. In the next section the same will be done, but then towards the determined climatic zones instead of the climate change scenarios. In the table the cells with 'values' indicate that the critical threshold has been crossed and investments are undertaken in order to adjust to the expected new climate reality in 2080. The cells with 'small stripes' mean that the climate change effect for that electricity generating technology has not been assessed as significant, however, that does not mean that there is no impact at all but rather it is small and as such not taken into account.

Table 15 Cost assessment of climate change impacts in 2080

(In million €'s)		Nuclear	Hydro	Wind (onshore)	Wind (offshore)	Bio mass	PV	Natural gas	Coal	Oil	Grids	Total
Δ water temperature	Wind	448	-	-	-	106	-	288	390	15	-	**1245**
	Temp	659	-	-	-	156	-	431	584	22	-	**1851**
	Rain	343	-	-	-	83	-	231	298	12	-	**966**
Δ air temperature	Wind	228	-	-	-	-	-	152	-	8	1739	**2126**
	Temp	119	-	-	-	-	-	78	-	4	906	**1107**
	Rain	223	-	-	-	-	-	150	-	8	1707	**2088**
Δ precipitation	Wind	-	2046	-	-	-	-	-	-	-	-	**2046**
	Temp	-	499	-	-	-	-	-	-	-	-	**499**
	Rain	-	275	-	-	-	-	-	-	-	-	**275**
Δ average wind speeds	Wind	-	-	40	32	-	-	-	-	-	-	**72**
	Temp	-	-	52	42	-	-	-	-	-	-	**93**
	Rain	-	-	20	16	-	-	-	-	-	-	**37**
Δ sea level	Wind	-	-	-	4260	-	-	-	-	-	-	**4260**
	Temp	-	-	-	4260	-	-	-	-	-	-	**4260**
	Rain	-	-	-	4260	-	-	-	-	-	-	**4260**
Occurrence of floods	Wind	560	488	-	-	291	-	661	1101	111	86	**3297**
	Temp	1502	838	-	-	541	-	987	1514	167	125	**5674**
	Rain	712	686	-	-	421	-	697	1153	119	85	**3872**
Occurrence of heat waves	Wind	226	-	-	-	51	22	152	192	8	86	**737**
	Temp	327	-	-	-	77	31	213	285	11	125	**1070**
	Rain	221	-	-	-	52	22	150	187	8	85	**726**
Occurrence of storms	Wind	-	-	75	60	-	-	-	-	-	2135	**2270**
	Temp	-	-	108	87	-	-	-	-	-	3704	**3899**
	Rain	-	-	74	59	-	-	-	-	-	2431	**2564**
Total	Wind	**1462**	**2534**	**115**	**4352**	**448**	**22**	**1253**	**1682**	**141**	**4046**	**16054**
	Temp	**2607**	**1337**	**160**	**4388**	**774**	**31**	**1709**	**2383**	**203**	**4861**	**18453**
	Rain	**1499**	**961**	**94**	**4335**	**556**	**22**	**1227**	**1638**	**146**	**4309**	**14787**

6.1.2 Risk index scheme for electricity generating technologies and scenarios

The following table shows three main climate change impacts and their extreme event equivalents. While the data on average effects is well-documented and available, the derivation of estimates for the likelihood of extreme events to occur is more difficult and very complex. This issue can be overcome, since the incidence of extreme events mainly goes hand in hand with (increases in) the level of temperature for which good data is available, also with sufficient regional variation. Here we will assume this link to be 1:1. Precipitation will decrease particularly in Mediterranean countries, whereas wind speeds generally show a slight decrease. Floods, drought and storm events are projected to increase in frequency and intensity (assumed to be proportional to the overall pattern of temperature increase).

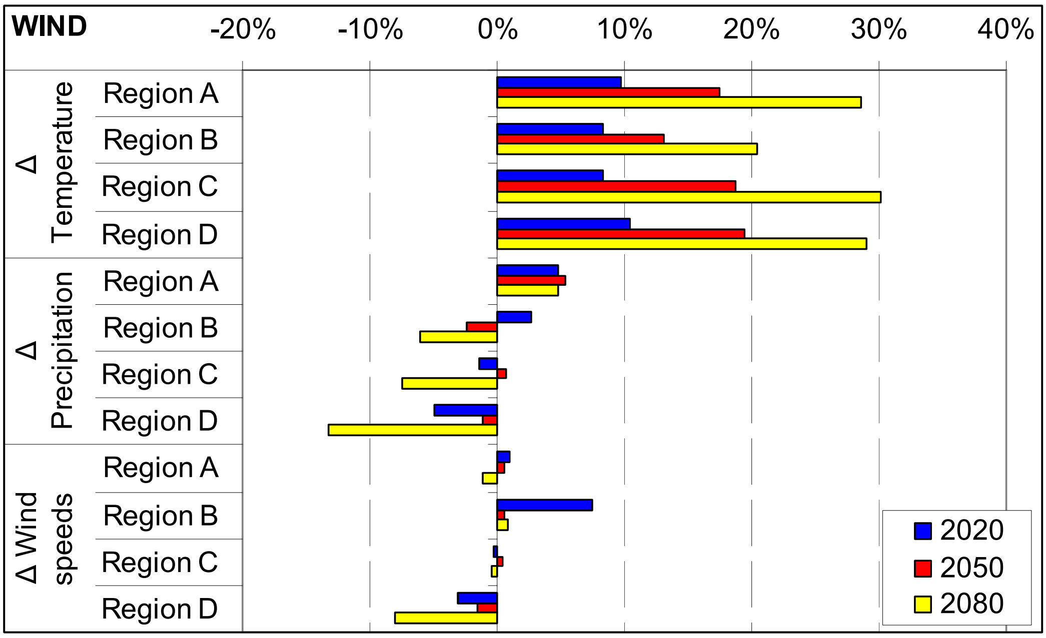
Table 16 Climate change scenarios: average effects versus extreme events

	Average effects		Extreme events	
Temperature	Δ water/air temp Δ Sea level	Good data Formula on temperature	Heat waves	Formula on temperature
Precipitation	Δ precipitation	Good data	Floods/ Droughts	Formula on temperature
Wind	Δ wind speeds	Good data	Storms	Formula on temperature

The following figure shows the values from three selected regional climate change models, namely:

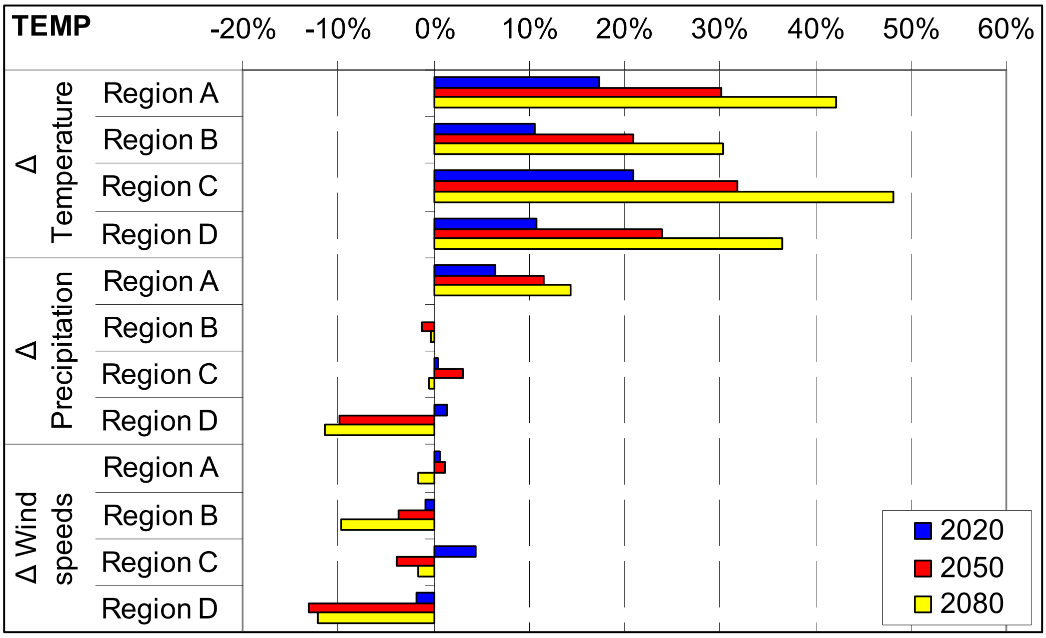
- WIND – Based on a regional model with a focus on wind variability;
- TEMP – Based on a regional model with a focus on temperature variability;
- RAIN – Based on a regional model with a focus on precipitation variability.

Figure 18 Climate change impacts quantified at a regional level – WIND scenario



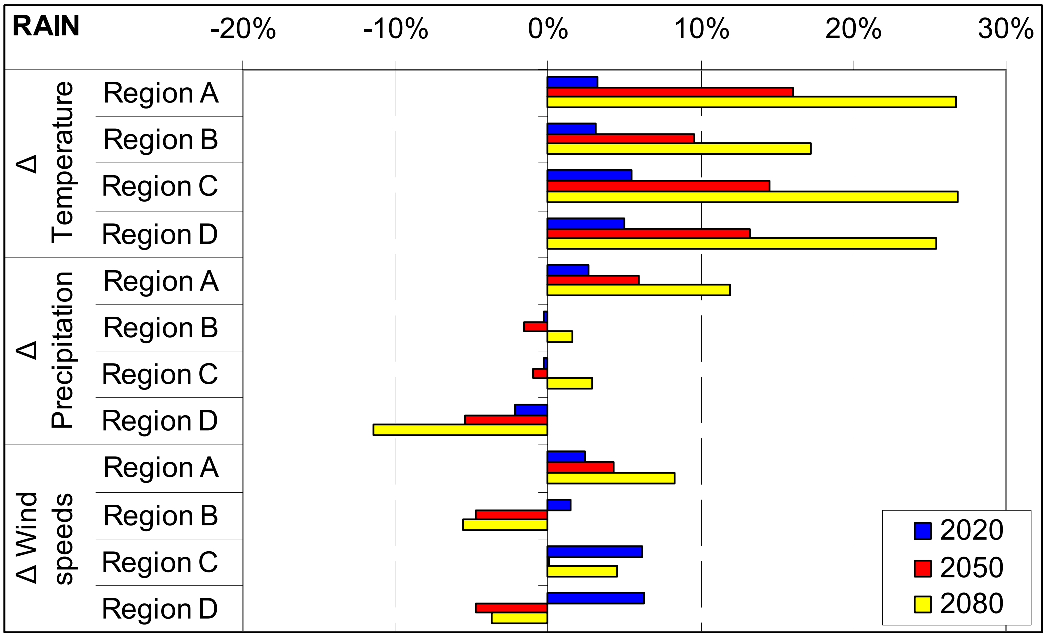
Note: Δ Temperature = % change in temperature with respect to 10 °C (or Δ Temp/10), Δ Precipitation = % change in precipitation, Δ Wind speeds = % change in average wind speeds. Here the difference with respect to 1950-2000 is considered for 2020 (2010-2030), 2050 (2030-2060), 2080 (2060-2100).

Figure 19 Climate change impacts quantified at a regional level – TEMP scenario



Note: Δ Temperature = % change in temperature with respect to 10 °C (or Δ Temp/10), Δ Precipitation = % change in precipitation, Δ Wind speeds = % change in average wind speeds. Here the difference with respect to 1950-2000 is considered for 2020 (2010-2030), 2050 (2030-2060), 2080 (2060-2100).

Figure 20 Climate change impacts quantified at a regional level – RAIN scenario



Note: Δ Temperature = % change in temperature with respect to 10 °C (or Δ Temp/10), Δ Precipitation = % change in precipitation, Δ Wind speeds = % change in average wind speeds. Here the difference with respect to 1950-2000 is considered for 2020 (2010-2030), 2050 (2030-2060), 2080 (2060-2100).

Perhaps the most important impact of climate change is an increase in the average world surface temperature varying between 2–5 °C until 2100. The projected changes in precipitation patterns show an interesting regional variation. Depending on the scenario, but on average, the level of precipitation is projected to increase in the Baltic region (Region A); it will decrease in the Mediterranean region (Region D) whereas the change is undecided in the North Sea (Region B) and Central and Eastern European (Region C) regions. The change in wind speed is variable and relatively minor, with a tendency towards a slight decrease.

6.2 Risk analysis of stakeholder consultation

6.2.1 Quantifying the costs of climate change on power generation in the EU

The following major climate change impacts and their financial consequences for power plants came forward from the interviews:

Higher air temperature

The main effect is that if the air temperature becomes too high (generally during summer heat wave, which will be longer and more frequent under average higher temperatures) the **fuel burning efficiency** will decrease due to a lower oxygen concentration in the air, caused by a lower atmospheric pressure under higher temperatures. [18] Another reason for lower efficiency due to an increase in average outside temperature is a lower difference between outside and turbine temperature. This is mainly relevant for NG, oil and nuclear, but negligible for coal and biomass where the outside temperature would only affect demand but not power plant operation. Furthermore, the losses of electricity networks increases with rising temperatures due to increased resistance. A too low air temperature could lead to icing problems, but under a temperature increase scenario such events are projected to become less frequent. There are also indirect effects of higher temperatures in the day to day demand patterns, where the level of demand in summer grows most quickly, which is also the period when the power plants are most vulnerable, leading to new challenges in balancing the power system:

- This effect can roughly be quantified as 0.1% lower efficiency for every increase in temperature by 1 ^{o}C for NG and oil fired power plants, which translates into more expensive power generation costs, due to higher fuel consumption, which would translate into 2 ‰/^{o}C loss in power generation;
- For nuclear an estimate was made for 3 MW lower capacity availability per ^{o}C, and after comparing this to an average size of 3000 MW translates into a 1 ‰/^{o}C loss in power generation.[19];
- During heat waves operational costs may go up with more people in service (increase by 50-100%) and more material in stock (increase by 10-20%).

Investment needs could be:

- Preventive investment is possible by constructing a cooling tower. This is often a standard equipment of new CCGT NG, which is often designed to quickly ramp up and down during the day to follow price incentives in the power spot market due to real time demand and supply changes. Cooling towers are already quite common for coal fired power plants;
- 2.5 M€ (≈ 2.5 €/kW) is the cost to refurbish 4 existing cooling towers leading to 2-3 ^{o}C cooler water. Four new cooling towers would cost around 80 M€ (≈ 80 €/kW), where the benefits do not weigh up to the costs;
- To avoid “thermal inversion” (rare but possible at around 45 ^{o}C) walls can be constructed around the chimney which would cost around 1 M€ (≈ 1 €/kW), which is a relatively low cost, but also with relatively low benefit;
- High-temperature transformers, gas-insulated lines and real-time temperature rating can help reduce the temperature impacts on network capacity.

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[18] Off course, the generating efficiency is higher when the process temperature is higher (e.g. 1200°C for a gas-fired combined cycle plant, 600+°C for the maximum steam temperature of a coal-fired power plant).

[19] Linnerud, Kristin, Torben Kenea Mideksa and Gunnar S. Eskeland, 2011. The impact of climate change on nuclear power supply. *Electricity Journal*, 32 (1): pp. 149-168. (In Press) has a particular focus on nuclear electricity and estimates the overall reduction in output at 0.5% per 1 ^{o}C increase in average temperature. This estimate is in line with our estimates, which break this further up in climate change specific effects.

Higher water temperature

The main effect is that if the water temperature at the cool-water inlet becomes too high for cooling the turbines (generally during summer heat wave, which will be longer and more frequent under higher average temperatures) the ability to generate will reduce due to **cooling constraints**. This is relevant for all fossil fuels, but also for biomass and nuclear, due to regulatory requirements concerning cooling water and discharge water temperatures. Hence, this is mainly a regulatory risk. Cooling is technically possible, but is not (and probably rightly should not be) allowed for due to considerations for negative impact on nature (aqua life and bio-organisms) of an increased water temperature. Also a distinction is needed between river/lake and sea water, where the latter has much less temperature variation and could only pose a problem in the Mediterranean region:

- Preventive investment may be needed to pre-cool the water with a water cooling mechanism;
- Another investment need could be an algae cleaning system to purify sea water, with an estimated cost of 1.5 m€ (≈ 1.5 €/kW). This is relevant for coastal power plants, where algae blooming will intensify with higher temperatures.

Precipitation changes

This is mainly a regional shift, where precipitation is expected to increase in the Baltic and decrease in the Mediterranean. In total the hydro output in Europe would be about equal, where a higher output in the north would compensate a lower output in the south. An increase (decrease) would lead to a higher (lower) output of hydro power. Indirectly, power plants that are cooled with river water could also be affected when the amount of available cooling water drops or if the amount of flow increases, leading to a higher flooding risk. This can disrupt both power generation facilities and transmission network infrastructure. An increased frequency of storms could also lead to a higher intensity of lightning, which would in particular affect networks. As a regulatory constraint the flux of water can be constrained as well, which will also lead to a loss in power generation:

- The availability of cooling water could be controlled by constructing a dam and reservoir to regulate the level of water in the river (but this solution would not always be possible, for instance in relatively flat regions). Construction of a dam and reservoir is often part of the initial investment cost, but longer and more frequent droughts would need larger reservoirs to guarantee power generation. Watershed management should therefore take a comprehensive approach to harmonizing competing uses of water;
- The possibility of a flood is a serious risk that certainly needs to be avoided, for instance by constructing a protection wall for power plants exposed to river flows and by placing critical equipment at a sufficient height. Alternatively a dike could be built or discharge pumps would need to be installed and on stand-by.

The following table shows indicated per climate change effect and electricity generating technology the:

1. the lost power generation (in %);
2. the investment needs (in €/kW);
3. the threshold value for which a climate change effect will have an investment need.

As such the table provides preliminary estimates of the lost power generation and a preventive investment including a threshold value for the climate change effect after which such an investment would be needed. As has been discussed in the previous section, the determination of the threshold values has been done based on inputs from interviews, questionnaire, internal resources, generic literature and studies reporting about the level of power generation efficiency and the impact of climate change.

Table 17 Quantifying climate change effects: lost generation per unit and investment need after a critical threshold is crossed

Climate change effect	Technology	Lost power generation	Investment Need €/kW	Threshold value	Remark
Δ air temperature	Nuclear	0.10%	50	5	0.1% less per 1 °C increase from NRG
Δ air temperature	Biomass		150	5	Like coal
Δ air temperature	Natural gas	0.10%	75	5	0.1% efficiency decrease per 1 °C
Δ air temperature	Coal		100	5	Negligible impact
Δ air temperature	Oil	0.10%	85	5	0.1% efficiency decrease per 1 °C
Δ air temperature	**Grids**	**0.20%**	**40**	**5**	**0.2% extra transmission losses per 1 °C**
Δ water temperature	Nuclear	0.20%	50	5	0.2% per 1 °C increase from NRG
Δ water temperature	Biomass	0.20%	150	5	Small plants larger cost per unit
Δ water temperature	Natural gas	0.20%	75	5	Low investment costs
Δ water temperature	Coal	0.20%	100	5	Investment cost figure from interview #13
Δ water temperature	Oil	0.20%	85	5	Bit higher than NG
Δ precipitation	Hydro	-100.00%	250	10%	In the Mediterranean, to maintain the same reliability for yield, reservoir storage must increase by between 12% and 38% in 2050. High loss value taken due to unit measurement in %.
Δ average wind speeds	Wind (onshore)	-6.67%	350	1	1% lower yield for 0.15 m/s lower average wind speed according to stakeholder Need for more sensitive rotor
Δ average wind speeds	Wind (offshore)	-6.67%	500	1	
Δ sea level	**Wind (offshore)**		**500**	**0.25**	**Need for alternative foundation (*current 20-year return period wave* in the North Atlantic may occur every 4–12 years by 2080).**
Occurrence of floods	**Nuclear**		**100**	**25%**	
Occurrence of floods	**Hydro**		**100**	**25%**	
Occurrence of floods	**Biomass**		**150**	**25%**	

Climate change effect	Technology	Lost power generation	Investment Need €/kW	Threshold value	Remark
Occurrence of floods	CSP		200	50%	CSP plants are in arid areas
Occurrence of floods	Geothermal		200	50%	
Occurrence of floods	**Natural gas**		**100**	**25%**	
Occurrence of floods	**Coal**		**150**	**25%**	
Occurrence of floods	**Oil**		**110**	**25%**	
Occurrence of floods	Grids	0.10%	40	50%	
Occurrence of heat waves	Nuclear	1.00%	50	100%	
Occurrence of heat waves	Biomass	1.00%	150	100%	Occurrence of heat waves is an issue in the Mediterranean area
Occurrence of heat waves	PV	1.00%	250	100%	
Occurrence of heat waves	Natural gas	1.00%	75	100%	
Occurrence of heat waves	Coal	1.00%	100	100%	
Occurrence of heat waves	Oil	1.00%	85	100%	
Occurrence of heat waves	Grids	0.10%	40	100%	
Occurrence of storms	Hydro		250	100%	Other issues due to more extreme weather affect hydropower, e.g. avalanches, soil erosion, landslides and rock fall.
Occurrence of storms	Wind (onshore)	1.00%		100%	Loss of power generation due to storms
Occurrence of storms	Wind (offshore)	1.00%		100%	Loss of power generation due to storms
Occurrence of storms	PV		250	100%	Extreme events would have only minor effects on PV
Occurrence of storms	**CSP**		**250**	**100%**	**Extreme events would have only minor effects on CSP**

Note: The green shading indicated the high(-est) severe impacts. The empty cells flag that the possible climate change effects are not shown or it is unlikely that these will have a significant impact.

Table 18 shows the assumed capacity factors for each of the electricity generation technologies. The multiplier to convert investment needs from €/kW to €/MWh follow an interest rate of 5% and an economic life of 20 years. The capacity factors have been determined based on desk study and internal resources.

Table 18 Technology-wise capacity factor and the resulting multiplier to convert investment needs from €/kW to €/MWh

	Capacity factor	Multiplier
Nuclear	80%	0.0114501
Hydro	40%	0.0229003
Wind (onshore)	30%	0.0305337
Wind (offshore)	35%	0.0261718
Biomass	70%	0.0130859
PV	18%	0.0508895
CSP	25%	0.0366405
Geothermal	70%	0.0130859
Natural gas	75%	0.0122135
Coal	75%	0.0122135
Oil	25%	0.0366405
Grids	60%	0.0152669

The cost of generation loss is based on an average wholesale power price of 70 €/MWh. For instance, if the loss in generation is 1% per 1°C, then the cost per 1 °C is 0.7 €/MWh.

6.2.2 Risk analysis and investments needed for nuclear electricity generation

As shown in Table 14, there are four climate change indicators relevant for nuclear electricity generation. Based on the investment need determined per technology (in EUR/kW) in Table 17, this would mean per significant climate change indicator:

1. 0.1%/°C loss in generation due to change in air temperature. 50 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
2. 0.2%/°C loss in generation due to change in water temperature. 50 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
3. No loss in generation due to floods, but 100 €/kW preventive investments needed if floods would become 25% more intensive;
4. 1.0%/°C loss in generation due to more heat waves. 50 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

6.2.3 Risk analysis and investments needed of electricity generation from fossil fuels

As shown inTable 14, there are four climate change indicators relevant for electricity generation from fossil fuels. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change indicator:

1. 0.3%/°C loss in generation for oil and natural gas, but not for coal, due to change in air temperature. 75–100 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
2. 0.2%/°C loss in generation due to change in water temperature. 75-100 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
3. No loss in generation due to floods, but 100–125 €/kW preventive investments needed if floods would become 25% more intensive;
4. 1.0%/°C loss in generation due to more heat waves. 75–100 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

6.2.4 Risk analysis and investments needed for electricity generation from renewable electricity sources

Wind electricity generation

As shown inTable 14, there are three climate change indicators relevant for electricity generation by wind offshore (onshore). Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change indicator:

1. 1% lower yield for 0.15 m/s lower average wind speed. Need for more sensitive rotor, leading to 500 (350) €/kW preventive investments for offshore (onshore) wind are not needed, as threshold will not be surpassed;
2. Need for alternative foundation for offshore wind (current 20-year return period wave in the North Atlantic may occur every 4–12 years by 2080). 500 €/kW preventive investments, with threshold value of 0.25 m sea level rise;
3. 1% loss in generation per 1% increase in storms, but no preventive investments needed.

Hydropower generation

As shown inTable 14, there are three climate change indicators relevant for hydro power. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change indicator:

1. The gain or loss in generation is quite sensitive to the average amount of rainfall output would reduce 1:1 to the average level of rainfall. In the Mediterranean, to maintain the same reliability for yield, reservoir storage must increase by between 12% and 38% in 2050, leading to 250 €/kW preventive investments;
2. No loss in generation due to floods, but 100 €/kW preventive investments will be needed if floods would become 25% more intensive;
3. No loss in generation due to storms. 250 €/kW preventive investments not will not be needed as the threshold value will not be surpassed.

Biomass electricity generation

As shown inTable 14, there are four climate change indicators relevant for electricity generation from biomass. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change indicator:

1. No loss in generation due to change in air temperature. 150 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
2. 0.2%/^{o}C loss in generation due to change in water temperature. 150 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
3. No loss in generation due to floods, but 150 €/kW preventive investments will be needed if floods would become 25% more intensive;
4. 1.0%/^{o}C loss in generation due to more heat waves. 150 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

Photovoltaic (PV) electricity generation

As shown inTable 14, there are two extreme events relevant for PV electricity generation. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change event:

1. 1.0%/^{o}C loss in generation due to more heat waves. 250 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
2. No loss in generation due to storms. 250 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

Concentrated Solar Power (CSP)

As shown inTable 14, there are two extreme events relevant for CSP electricity generation. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean per significant climate change event:

1. No loss in generation due to more heat waves. 200 €/kW preventive investments will not be needed as the threshold value will not be surpassed;
2. No loss in generation due to storms. 250 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

Geothermal

As shown inTable 14, there is one extreme event relevant for geothermal electricity generation. Based on the investment need determined per technology (in €/kW) in Table 17, this would mean:

1. No loss in generation due to floods. 200 €/kW preventive investments will not be needed as the threshold value will not be surpassed.

6.2.5 Risk analysis and investments needed for electricity transmission and distribution facilities

Dealing with uncertainty

Adapting to climate change is all about dealing with uncertainty – i.e. risk management. Network companies have experience with this, as their business strategy must already account for potential future developments that are difficult to predict. For example, the number and location of new intermittent electricity sources that will connect to the network is uncertain, yet they must still ensure that their network can accommodate them. Uncertainty about the effects of climate change is, in that sense, nothing new, but the timeframe and uncertainties are larger.

Business strategy

In its guidance to companies for adapting to climate change, the UK Department of Food, Environment and Rural Affairs recommends three approaches to dealing with uncertainty (DEFRA, 2009):

- Incorporate flexibility to allow for adjusting to changing conditions;
- Increase resilience by designing facilities to allow for a large range of climatic conditions;
- Identify low-regrets and win-win. Low regrets have low costs and relatively large benefits, while win-wins deliver other benefits in addition to climate change adaptation.

These strategic choices should be incorporated in the long-term planning of network operators, which would, in turn, support effective individual measures.

Insurance costs

Network operators can take out insurance policies for damages from extreme weather, but as the frequency of extreme events rises, so will the insurance cost. In extreme cases, insurance may no longer be available in vulnerable areas, as in Florida following the damage caused by hurricane Andrew in 1992. Florida Power and Light Company, the local utility, subsequently established a fund to build up reserves for future storms, financed by a levy on consumer prices (Peters et al, 2006).

Product procurement

Climate change could also become a factor in procuring systems for expanding and upgrading networks, For example, a regulatory requirement to increase efficiency combined with rising ambient temperatures could make network operators select technologies that can operate efficiently at high temperatures. Network technology suppliers would respond to such a demand by developing the necessary products.

Daily operations

Daily operations of network companies should also incorporate adaptation. Often, this requires only minor changes to regular procedures. Monitoring networks for signs of climatic impacts can save money by allowing companies to identify potential problems before they occur, and take measure to prevent them[20]. It also helps network operators improve grid management during normal conditions – a clear win-win.

Emergency response

Adaptation also includes strategies to respond quickly in case of disruption. These describe procedures to limit the impacts to a small area, for instance by islanding parts of the grid and re-routing supply around the fault, as well as the necessary repair procedures.

Wind speed and storms

Current activity

An increasing share of the European distribution grids (up to 150 kV) are being placed underground:

- In the Netherlands, Tennet is undergrounding part of its 150 kV grid expansion in the Randstad conurbation to limit visual impact in the built environment;
- Energinet in Denmark expects all its lines under 100 kV will underground by 2030, and it is already undergrounding new 132 to 150 kV lines. The 400 kV grid will remain predominantly overhead, as placing this underground is technically not yet feasible (Energinet, 2008).

Climate-proofing is only a minor driver for undergrounding distribution grids. Social acceptance and/or environmental impact tend to be the primary consideration. Potential electromagnetic interference of underground cables is also lower.

Adaptation measures

Placing network assets underground is the most obvious structural adaptation to wind and storm damage (Table 19), but this has three limitations:

- It is not technically feasible for AC cables above 150 kV, due to risk of overvoltage[21];
- Costs are a major drawback of underground cabling: it can be 4 to 5 times more expensive than using overhead lines at low voltage, rising to 10 to 20 times for high voltages (ENTSO-E, 2010; Energinet, 2008). By comparison, strengthening pylons and lines to raise resilience to high winds is usually feasible at less than twice the costs of the conventional approach (Energinet, 2008);
- Underground cables are difficult to inspect, so that faults are hard to anticipate and repairs usually take days instead of hours if faults do occur (Martikainen et al, 2007). So while increasing climate-resilience, under grounding reduces response capability.

Overhead lines are therefore still dominant in transmission networks, accounting for 75% of the planned 42,100 km new and refurbished lines in ENTSO-E's Ten-year Network Development Plan (ENTSO-E, 2010). However, network operators may choose to strengthen a critical backbone grid to a higher level than surrounding networks, as EdF and RTE are doing in France[22].

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20 In France, for example, RTE is completing its ROSE infrastructure project, installing telecommunication terminals at 300 sites and 15.000 km optical fibre cabling to allow for monitoring, operating and protecting the grid remotely. It expects that the various benefits will pay for the EUR 300 million investment by 2016.

21 Overvoltage can be avoided by additional protection, but this has not been proven commercially for stretches longer than 40 km (Energinet, 2008).

22 In this 'Survivability Design Concept', the maximum design wind velocity for critical lines is now 170 to 180 km/h in coastal areas, and 160 to 170 km/h in inland regions. (Peters et al, 2006).

Table 19 Adaptation measures for high winds and storms

Impact	Adaptation measure	Benefit	Costs
Wind / storm damage	Use underground cables	Unaffected by wind	5 – 20 times overhead line cost, depending on voltage level[23]
	Strengthen overhead lines and pylons	Higher threshold wind speed causing damage	Approx. €1,000,000 / km
	(Re)-orientate assets	Higher threshold wind speed causing damage	+10% design cost
Heat convection	(Re)-orientate assets	Largest effect when wind at 90° angle with lines	+10% design cost

As an alternative to undergrounding, network operators can plan for increasing wind speeds and storm events during design of new lines or replacement of existing assets by (re-)locating and (re-) orientating overhead lines such that they are sheltered from the prevailing wind/storm direction. Depending on the scale of the (re)location, design costs will rise, typically by 10% or more (Parsons Brinkerhoff, 2009).

Temperature

Current activity

Network operators still plan new network assets based on current ambient temperature and regulation, without anticipating rising average temperatures in the future.

Adaptation measures

Electricity networks can be adapted to rising temperatures by using new technologies, but also by changing network operation and network planning procedures.

Technological adaptation

Technological adaptation differs by network component (Table 20). **Transformers** can be made less vulnerable to rising temperature through advanced cooling systems or by using conductors other than copper that are less susceptible to temperature. However, the efficiency benefits are small, and new conducting materials are expensive. Conventional transformers using copper windings are therefore likely to remain the dominant technology in the next 10 to 20 years.

For **lines and cables** several options exist. AC Gas Insulated Lines (GILs) are coated with an insulation layer filled with SF_6 and/or N_2[24]. Due to the gas insulation, GIL capacity and efficiency are largely unaffected by temperature. At €9 million per km, GILs are 9 to 12 times more expensive than conventional high-voltage lines (IRENE-40, 2010). As with transformers, high-temperature conductors also reduce the impacts of rising temperatures. The safe load increases by a factor 1.6 to 2 (ENTSO-E, 2010; Pink, 2010), and sagging decreases by 50%, as they extend less with rising temperature (Pink, 2010). Currently, these are only commercially applied for short distances in dense urban areas, because costs are still three to four times higher than for conventional technology (Fischer, 2010), and losses increase rapidly with distance.

Gas-insulation is the main measure for reducing temperature impacts on **substations**, but not yet used for that purpose, although they are used in harsh environments near the arctic, on salty

[23] Costs are approximately €4 million - €20 million/km for 400 kV (technology not yet available), €450,000/km for 132 to 150 kV, €170,000/km for 30 to 60 kV, and €50,000/km for 6 – 20 kV (Energienet, 2008).

[24] GILs also reduce the magnetic flux induced by transmission lines so that they can safely pass close to buildings (12-15 m in Germany). Reactive power losses also decrease by up to 50%. These benefits have been the major drivers for their application to date.

coastlines, close to chemical exhausts and in sandstorm regions. Their small size also makes such systems attractive in dense urban areas.

Table 20 Adaptation measures for increasing temperature

Impact	Adaptation measure	Benefit	Costs
Transformer de-rating, decreased line conductivity	Flexible line management	Up to 20% additional capacity	Varies with local conditions and technology.
	High-temperature transformers	Marginal increase in efficiency at high temperature	Not yet competitive (emerging technology)
	High temperature low-sag conductors	1.6 – 2x nominal capacity[25]	Installed cost 3 – 4x conventional technology
	Gas-insulated lines	Greater line capacity Lower magnetic flux Reactive power losses approx. 50% lower	Approx. €9 million per km (9 – 12x conventional technology)
	Gas-insulated substations	Resilient to extreme (climate) conditions	
Sag	Higher pylons	Ground clearance greater to avoid sagging problems	Approx. €100,000 / km
	High temperature low-sag conductors	Sag approx. 50% less	Installed cost 3 – 4x conventional technology

Network operation can help increase capacity of electricity networks. Using flexible line management for instance, the maximum load on lines is adjusted dynamically according to environmental conditions,[26] increasing line capacity by up to 20% (ENTSO-E, 2010).

Network planning allows for comprehensive adaptation when designing new transmission assets. Capacity loss at high temperature can be anticipated by installing a higher capacity to start with. Building higher pylons can help address sagging problems, but can cost around €100,000 per km.

Drought

Current activity

Network operators already check local soil conditions when laying underground cables, calculating how much heat can safely be dissipated into the ground. This helps them establish the safe capacity of cables in the soil.

Adaptation measures

The simplest measure for reducing the potential vulnerability of underground cables to temperature rise is through improving soil properties by backfilling cables with soil types of high conductivity and good water retention properties, such as loam (Gouda et al, 1997). This usually increases installation costs only marginally (Table 21). Improving insulation around cables, for instance with GILs, also reduces temperature impacts but is expensive.

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25 Conductivity of conventional conductors is 60% up to 80°C. Gap-type high-temperature conductors achieve the same conductivity up to 150°C, and Invar-core conductors up to 210°C (Pink, 2010).

26 Usually, the maximum line load is set by a fixed outside temperature limit, reflecting the typical highest temperature of the year (35°C for central Europe). At lower temperatures, though, the line could carry a higher load while staying below the temperature limit.

Adaptation to prevent damage from movement of dry soils is hard, but the risks can be evaluated when laying the cable, and conditions can be monitored during dry spells by installing sensors measuring temperature, sag, strain and vibration are available, but their use is still relatively new. Costs and benefits vary with network size, structure, and local conditions[27].

Table 21 Adaptation measures for drought

Impact	Adaptation measure	Benefit	Costs
Moisture migration	Backfilling with sandy and loamy soils	Better heat dissipation in the surrounding soils	Marginal increase of new design costs
	Gas Insulated Lines	Less heat dissipation to soil	Approx. €9 million per km (9 – 12x conventional technology)
Dry soil movement	Monitoring soil conditions	Anticipate and possibly prevent damage	Depends on the size of the area and length of drought

Flooding

Current activity

Adaptation to flooding risks has progressed furthers in Europe, primarily because several network operators have experienced flood damage in the recent past, as in the UK in 2007. Network operators therefore tend to evaluate flood risk regularly and have a strategy in place to respond when flooding threatens to occur.

Adaptation measures

Flood defences are the primary adaptation measure for reducing flood risk (Table 22). If flood frequency increase, flood defences must be strengthened if the same level of protection is to be maintained. Upgrading flood defences for assets that have become extremely vulnerable may be excessively expensive. Investing in mobile flood defences for protecting vital elements of the network during extreme flooding can then be a cheaper option. As a last resort, network assets may have to be relocated away from flood plains.

Table 22 Adaptation measures for flooding

Impact	Adaptation measure	Benefit	Costs
Inundation	Increase local flood protection	Increases threshold causing flood damage	Variable
	Stand-by mobile flood defences	Allows protection of low-risk assets or during highly unlikely events	Variable
	(Re)locate assets away from floodplain	Assets at lower risk	Up to 100% new design cost
Damage due to soil movement	Evaluating / monitoring soil conditions	Anticipates and possibly prevents damage	Depends on the size of the area at risk

[27] Parsons Brinkerhoff estimates the costs of adding remote monitoring equipment in Australia at AUS$400,000 per network operator (approx. €275,000) (Parson Brinkerhoff, 2009).

6.3 Comparison analysis between electricity generation technologies

6.3.1 Investment needs under the Eurelectric baseline scenario

The cost functions as presented in Table 17 are transformed into costs in €/MWh using the quantified climate change indicators for three regional climate change scenarios. These costs are then aggregated into EU-wide cost estimates using the electricity scenarios (with the Eurelectric baseline scenario assumptions) in which the investment need per technology is quantified. The results of these are presented and discussed below.

Figure 21 presents the investment needs in the EU-27 in 2080 following the electricity projections in the Eurelectric baseline scenario. The figure presents the aggregated (investment needs) results over the three regional climate change scenarios, expressed per generation technology (including grids) and the predefined climatic zones. The bars indicate the significance and size of the investment needs, however, a distinction has to be made between 'necessary' investment needs and 'potential' investment needs. The striped bars indicate that there is a 'necessary' investment need as the critical climate change threshold value for that technology and region has been crossed. In other words, investments for that technology in that region are critical for the continuation of successful electricity generation as operations otherwise have to be shutdown. The 'normal' bars indicate that there are 'potential' investments needed as the electricity generation technology in that climatic zone faces efficiency losses, however, the critical climate change threshold value for that technology and climatic zone are not surpassed and are as such not critical for the successful continuation of electricity generation operations.

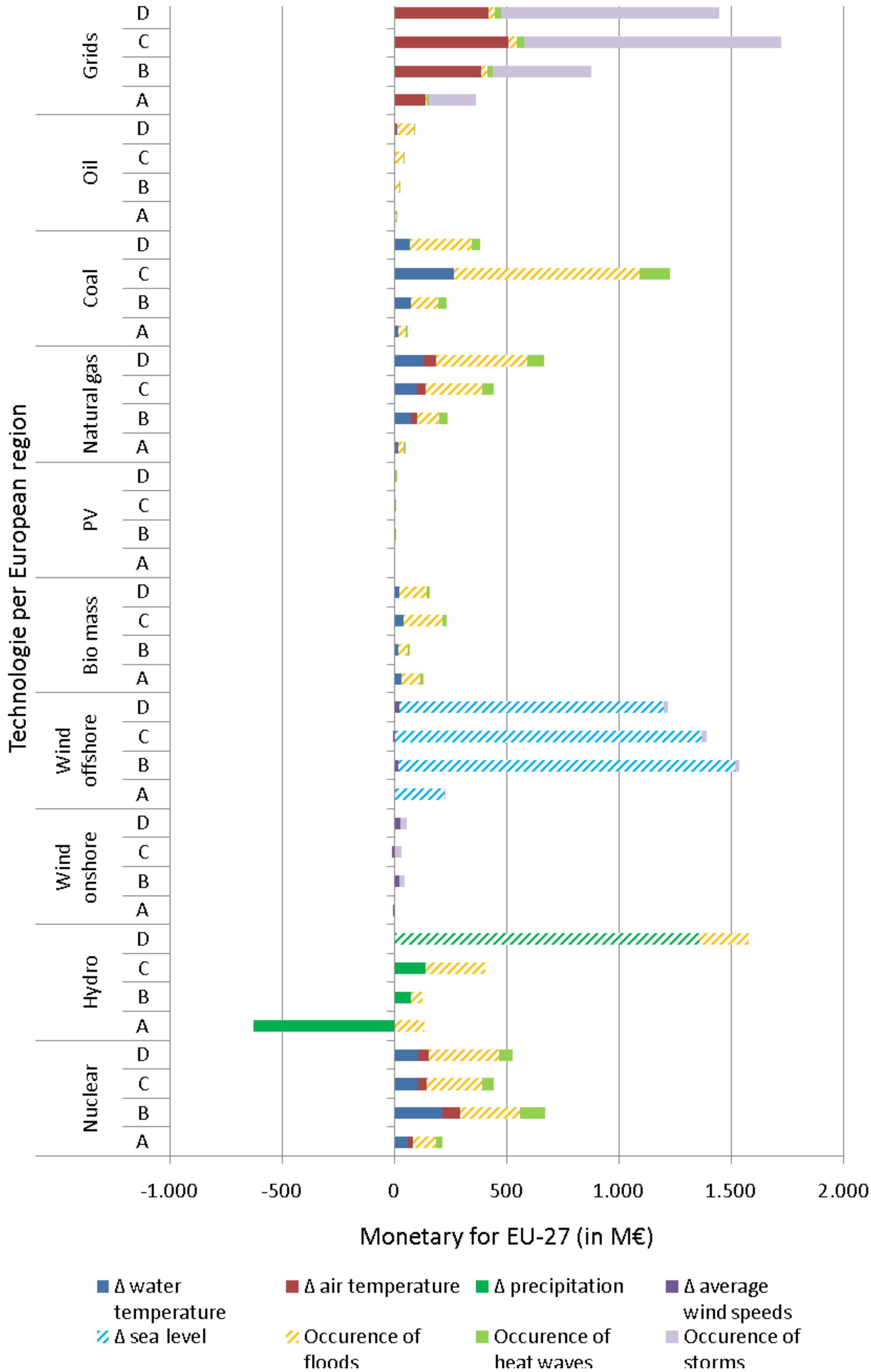
In Figure 22 the investment needs under the Eurelectric baseline scenario are the same as in the above figure, but are presented in a different way. In this figure the aggregated (investment needs) results over the three climatic regions are expressed per climate change indicator (see Table 15 for the exact threshold values assumed in the analysis) and the climate change scenarios (WIND, TEMP, RAIN).

The main results, in summary, in terms of climate change adaptation costs by power plants in the EU-27 in the year 2080:

- The average or gradual increases due to climate change, will reduce output, but do not require investments, except for:
  - lower precipitation severely affecting hydro in the South;
  - Sea level rise affecting off-shore wind.
- Changes in precipitation benefits the North, but the cost to the South is at least two times higher;
- Extreme events pose the greatest adaptation challenge:
  - Floods would affect nuclear, hydro & biomass and fossil fuel fired power plants;
  - Storms would mainly affect networks;

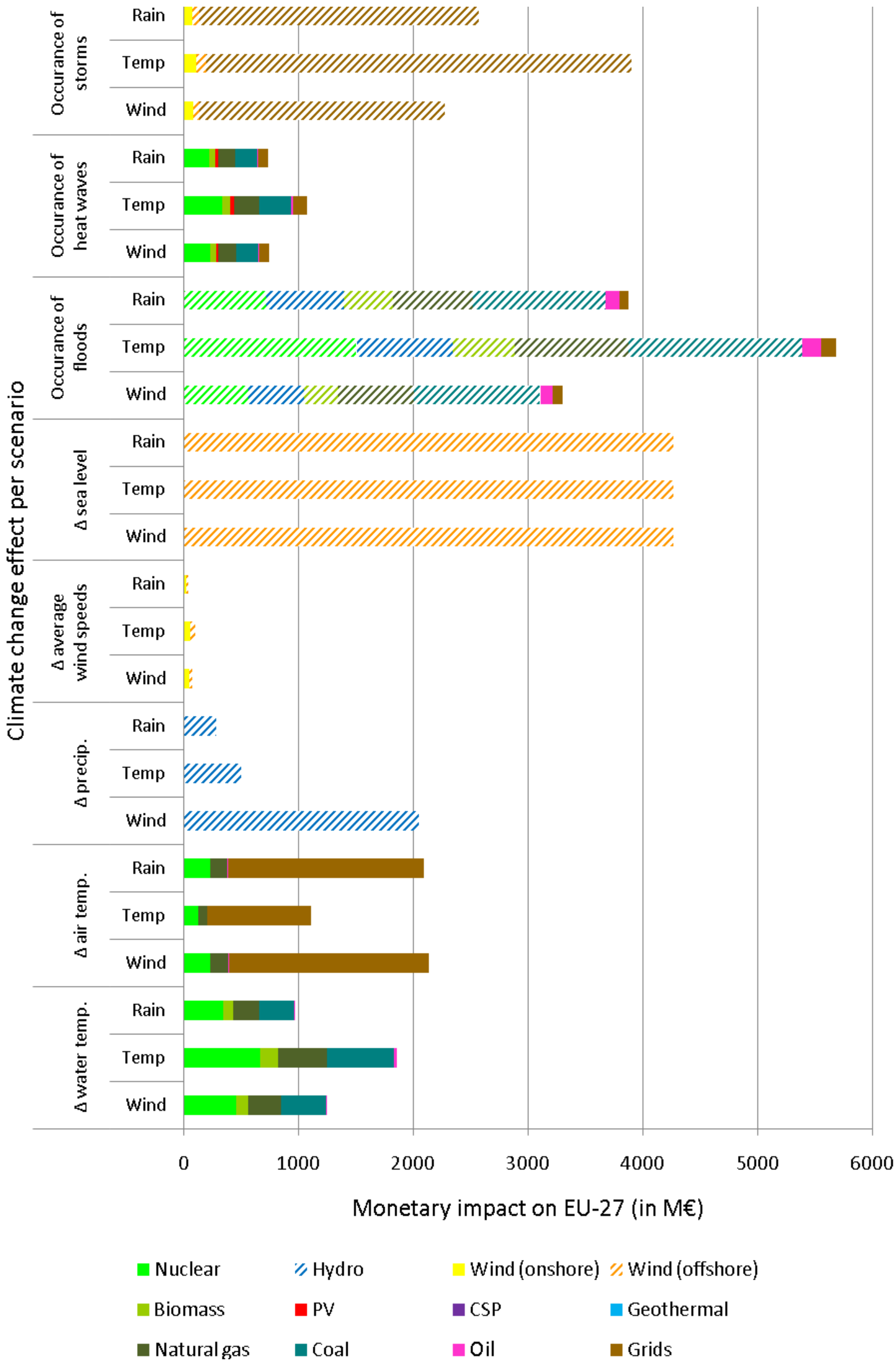
Extreme events cost most to Central Europe and the South, whereas only the North Sea region needs no investments

Figure 21 EU wide monetary impacts of climate change on electricity generation, per region and technology



Note: On the vertical axis the climate change indicators are listed, including the climatic change scenario definitions: RAIN = Precipitation scenario, TEMP = Temperature scenario, WIND = Wind scenario. On the horizontal axis the investment needs in monetary terms are flagged, where a 'positive' investment need means an increase in operational.

Figure 22 EU wide monetary impacts of climate change on electricity generation, per climate change effect and climate change scenario



Note: On the vertical axis the climate change indicators are listed, including the climatic change scenario definitions: RAIN = Precipitation scenario, TEMP = Temperature scenario, WIND = Wind scenario. On the horizontal axis the investment needs in monetary terms are flagged, where a 'positive' investment need means an increase in operational.

Figure 21 and Figure 22 graphically show that the total yearly cost (annuities; yearly costs to finance the investment needs over time) to be incurred in the power sector (generation, transmission and distribution) to adapt to the average climate situation in 2080. It has been assumed that the current state of technology is estimated at € 15–19 billion. In the presented figures the averages of the three regional scenarios have been taken. This is an acceptable approach as the results of the three regional scenarios (jointly the climate change and electricity supply scenarios) are relatively close to each other. Therefore, showing the results for the four climatic distinct regions in Europe provides us with some additional insights.

Table 23 presents the actual regional costs (in terms of yearly annuities) for the different climate change indicators, electricity generation technologies and climatic zones. The marked green cells in this table highlight the most significant investment needs towards 2080, with a critical threshold value (in terms of significance) of € 400 million. The largest investment will be needed for electricity generation from off-shore wind, due to sea level rise (over € 4 billion), followed by grids to adjust to more intense storms (EUR 2–4 billion). The increased incidence of floods impacts on all thermal generation technologies including nuclear and biomass (total cost € 3–6 billion). The change in precipitation patterns only leads to a significant cost for the WIND scenario (met cost over € 2 billion). Finally, although below the investment threshold, coping with an average temperature increase will be a challenge for grids (€ 1–2 billion). All other cost estimates are relatively minor and not significant. Especially, the impact of average wind speeds would hardly affect the operation of power plants.

The total costs are the lowest in the Baltic region (A) simply because the share of EU-27 generation is relatively low here. The cost of adjusting to precipitation is varied, where there is a benefit in region A, due to more precipitation, whereas the costs are much higher, especially in region D where additional costs are needed to make up for lost generation capacity, which is about twice as high as the benefits in region A.

The occurrence of floods for thermal generation and storms for grids are not marked as investment for region B, because in the North Sea region only in one of the three scenarios the critical threshold is crossed, namely TEMP.

As a final remark, the effect on wind speed is varied, leading to benefits in region A and C, whereas there are costs in region B and D. The costs, though small and amount to € 89 million, are about four times higher than the benefits.

The main results, in summary, in terms of climate change adaptation costs by power plants in the EU-27 in the year 2080:

- The average or gradual increases due to climate change, will reduce output, but do not require investments, except for:
  - lower precipitation severely affecting hydro in the South;
  - Sea level rise affecting off-shore wind.
- Changes in precipitation benefits the North, but the cost to the South is at least two times higher;
- Extreme events pose the greatest adaptation challenge:
  - Floods would affect nuclear, hydro & biomass and fossil fuel fired power plants;
  - Storms would mainly affect networks;

Extreme events cost most to Central Europe and the South, whereas only the North Sea region needs no investments

Table 23 Quantified regional costs for power plants in the EU to adapt to climate change in 2080

		Nuclear	Hydro	Wind (onshore)	Wind (offshore)	Bio-mass	PV	Natural gas	Coal	Oil	Grids	Total
Δ water temperature	A	60	-	-	-	30	-	13	15	1	-	**119**
	B	212	-	-	-	19	-	73	73	4	-	**381**
	C	106	-	-	-	43	-	102	267	4	-	**522**
	D	105	-	-	-	24	-	128	69	7	-	**333**
Δ air temperature	A	23	-	-	-	-	-	5	-	-	137	**166**
	B	82	-	-	-	-	-	28	-	1	386	**498**
	C	38	-	-	-	-	-	36	-	1	**508**	**583**
	D	47	-	-	-	-	-	57	-	3	**421**	**527**
Δ precipitation	A	-	-628	-	-	-	-	-	-	-	-	**-628**
	B	-	74	-	-	-	-	-	-	-	-	**74**
	C	-	138	-	-	-	-	-	-	-	-	**138**
	D	-	**1,356**	-	-	-	-	-	-	-	-	**1,356**
Δ average wind speeds	A	-	-	-4	-3	-	-	-	-	-	-	**-7**
	B	-	-	21	17	-	-	-	-	-	-	**38**
	C	-	-	-8	-7	-	-	-	-	-	-	**-15**
	D	-	-	28	23	-	-	-	-	-	-	**51**
Δ sea level	A	-	-	-	221	-	-	-	-	-	-	**221**
	B	-	-	-	**1,499**	-	-	-	-	-	-	**1,499**
	C	-	-	-	**1,366**	-	-	-	-	-	-	**1,366**
	D	-	-	-	**1,174**	-	-	-	-	-	-	**1,174**
Occurance of floods	A	101	132	-	-	87	-	24	35	5	9	**393**
	B	263	51	-	-	40	-	97	120	16	27	**614**
	C	247	268	-	-	170	-	253	**826**	34	36	**1,834**
	D	313	219	-	-	121	-	**408**	275	77	28	**1,441**
Occurance of heat waves	A	29	-	-	-	15	-	6	7	-	9	**67**
	B	114	-	-	-	10	6	39	39	2	27	**237**
	C	54	-	-	-	22	8	52	135	2	36	**308**
	D	61	-	-	-	14	11	75	40	4	28	**233**
Occurance of storms	A	-	-	5	4	-	-	-	-	-	207	**215**
	B	-	-	24	19	-	-	-	-	-	**438**	**480**
	C	-	-	32	26	-	-	-	-	-	**1,141**	**1,199**
	D	-	-	25	20	-	-	-	-	-	**971**	**1,016**
Total		**1,856**	**1,610**	**123**	**4,358**	**592**	**25**	**1,396**	**1,901**	**163**	**4,405**	**16,431**

Note: The dark green marked fields mean that in that region, for that technology and for that climate change indicator the impact is more significant. The critical threshold value for marking the investment need is EUR 400 million per year (annuity).

6.3.2 Investment needs under the Eurelectric Power Choices scenario

In this section the analysis has been performed as in the former section, but now for the Eurelectric Power Choices scenario (including its assumptions towards climate adaptation). These costs are here aggregated as well into EU-wide cost estimates using the electricity scenarios (with the Eurelectric Power Choices scenario assumptions) in which the investment need per technology is quantified.

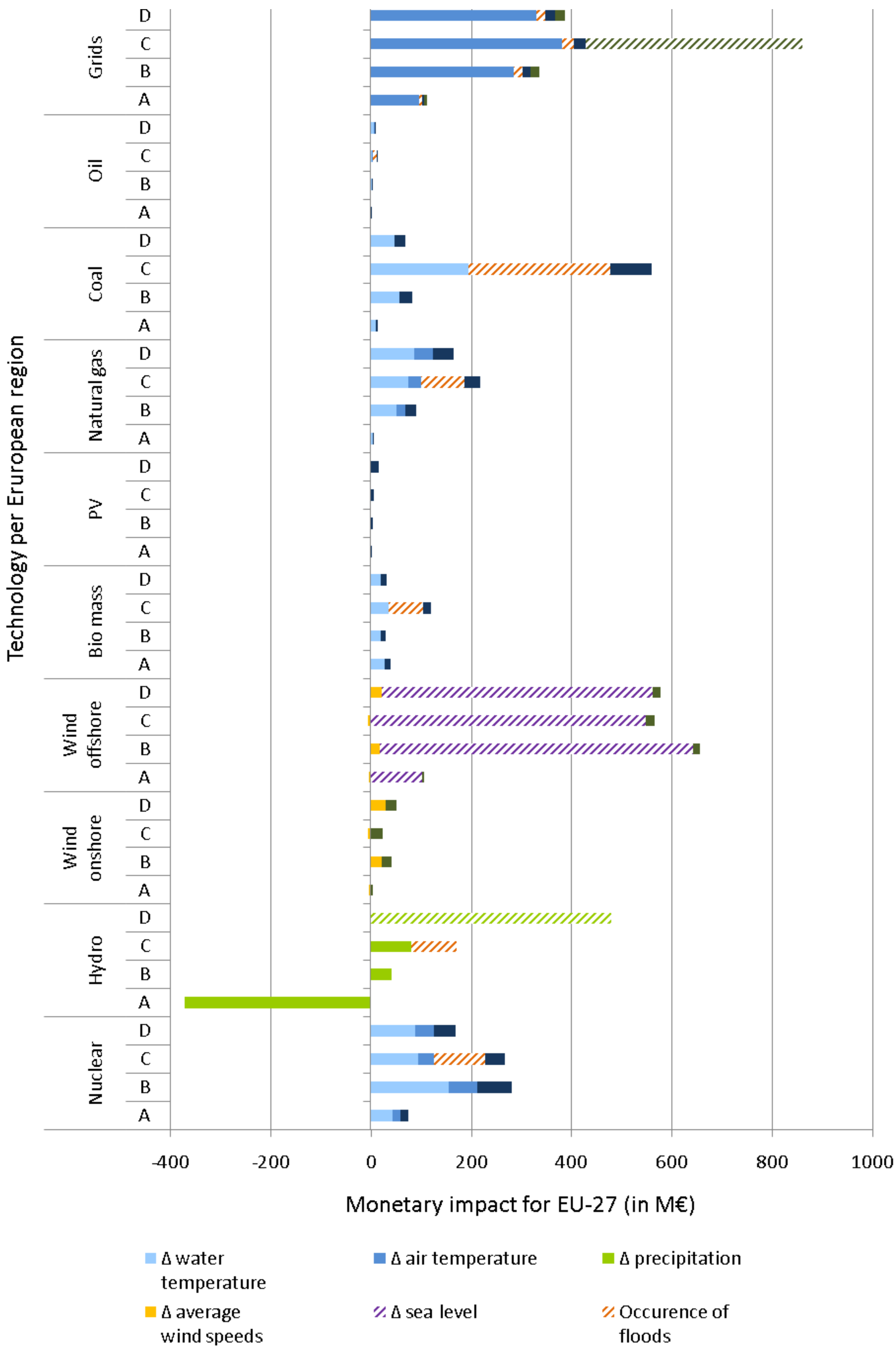
For conducting a consistent risk assessment, there is needed coherency between the climate change indicators (in terms of climate change scenarios) and the electricity supply projections. Since the assumptions and projections under the Eurelectric Power Choices scenario are way more radical and extreme (i.e. this scenario assumes a 75% reduction in CO_2 emissions by 2080) compared to the Eurelectric baseline scenario, the indicators in the climate change scenarios also needed to be adapted as the IPCC A1B scenario principles follow a more moderate changing behavior of the climatic system. In other words, in the Power Choices scenario it is assumed that the climate adaptation (and mitigation) measures are more stringent and successful than in the baseline scenario (meaning lower CO_2 emissions and more moderate impact of climate change effects). Therefore, as a rule of thumb, the climate change impacts have been accounted for 59% of their initial indicator values. The reasoning for this is that under the Eurelectric Power Choices assumptions, there will be a maximum increase in air temperature of 2 ^{o}C, where in the Eurelectric baseline scenario the increase in air temperature is assumed to be 3.4 ^{o}C. As such, the ratio between both factors is 2/34 = 59%.

Figure 23 presents the investment needs in the EU-27 in 2080 following the electricity projections in the Eurelectric Power Choices scenario. The figure presents the aggregated (investment needs) results over the three regional climate change scenarios, expressed per generation technology (including grids) and the predefined climatic zones. The results, in terms of investment needs, have been aggregated over three climate change scenarios, however, the differences in results between the climate change scenarios are more profound than under the Eurelectric baseline scenario, particularly for the TEMP scenario. For compatibility reasons the aggregated results are presented here; more detailed data and regional investment need figures can be found in the Annex to this report.

Figure 24 presents the same investment needs under the Eurelectric Power Choices scenario but presented in a different way. Also here, the aggregated (investment needs) results over the three climatic regions are expressed per climate change indicators and the climate change scenarios (WIND, TEMP, RAIN).

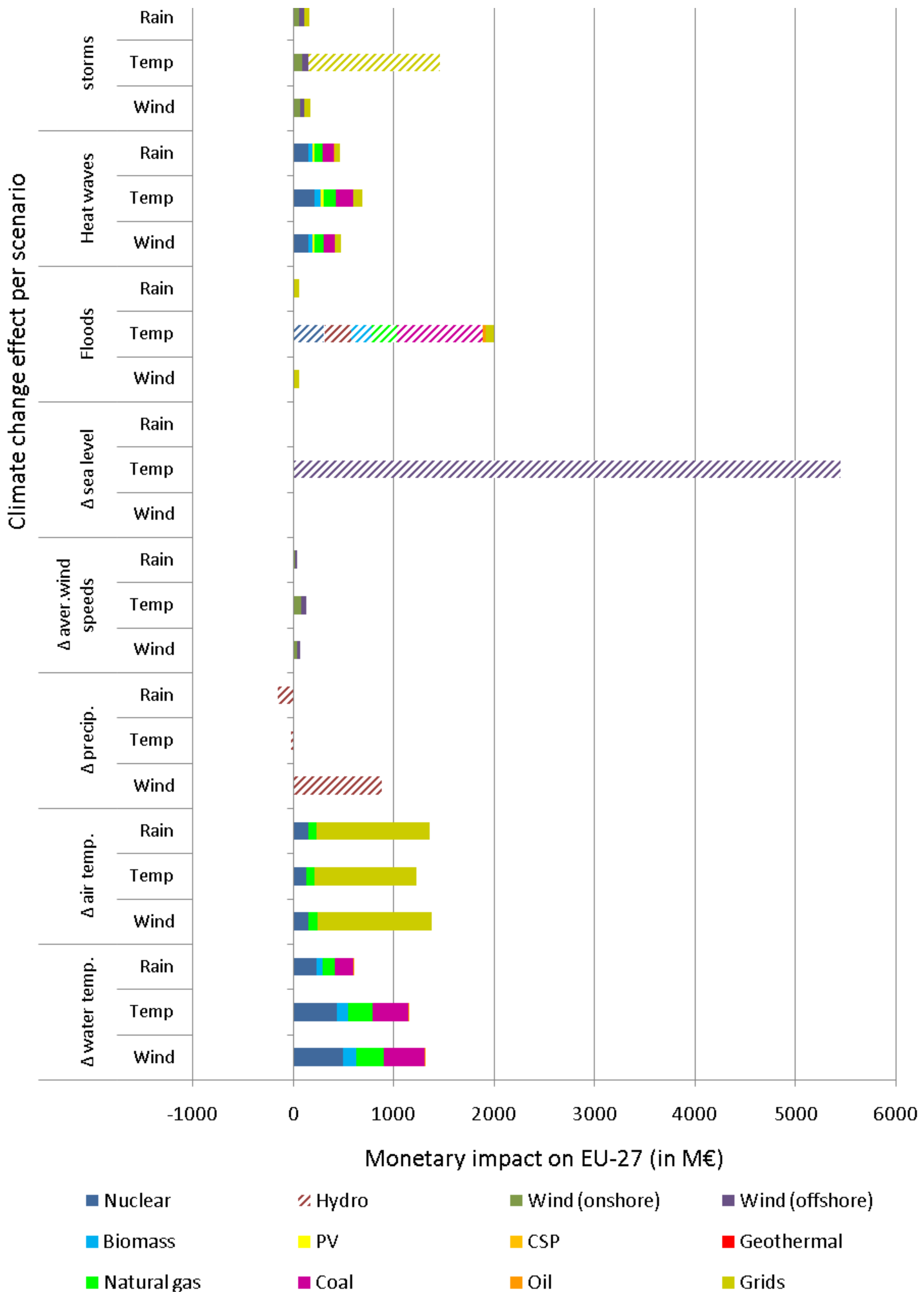
The observed trends and patterns in investment needs under the Eurelectric Power Choices scenario are more or less the same as in the Eurelectric baseline scenario, however, the results are, in general, less profound.

Figure 23 EU wide monetary impacts of climate change on electricity generation, per region and technology (Eurelectric Power Choices)



Note: On the vertical axis the electricity generation technologies are listed, including the climatic zones classification: A = Baltic region, B = North Sea region, C = Central and Eastern European region, D = Mediterranean region. On the horizontal axis the investment needs in monetary terms are flagged, where a 'positive' investment need means an increase in operational costs and a 'negative' investment need means an increase in operational benefits.

Figure 24	EU wide monetary impacts of climate change on electricity generation, per climate change effect and climate change scenario (Eurelectric Power Choices)



Note: On the vertical axis the climate change indicators are listed, including the climatic change scenario definitions: RAIN = Precipitation scenario, TEMP = Temperature scenario, WIND = Wind scenario. On the horizontal axis the investment needs in monetary terms are flagged, where a 'positive' investment need means an increase in operational.

7 Synthesis

This final chapter is a brief recap of the outputs obtained during the project cycle and links the results to provide overall findings. Furthermore, the chapter puts the results obtained into perspective and concludes with some recommendations relating to future investment needs.

7.1 Overview : Power Technologies in Europe

The analysis in this report has mainly focused on potential vulnerability to climate change of power generation technologies in Europe.

Table 24 shows the distribution of generation technologies across the four climatic zones in the EU-27. This shows for instance that nuclear is mainly concentrated in the North Sea region, whereas hydro has the highest concentration in the Baltic region (even though Norway is excluded).

Table 24 Share of generation technology per climatic zone in 2050

	Region A	Region B	Region C	Region D	EU-27	(M€) Costs	(M€) Costs/ EU-27
Nuclear	34%	43%	15%	22%	28%	1,856	6,600
Fossil	17%	30%	52%	43%	39%	3,461	8,800
Hydro	22%	4%	8%	8%	8%	1,610	20,600
Other RES	27%	23%	25%	27%	25%	5,099	20,400
Thermal total	68%	77%	73%	70%	73%	5,909	8,100
Share in generation in EU-27	8%	34%	31%	26%	100%		

Note: According to Eurelectric baseline scenario.

The table shows that in spite of regional differences from 68% in the Baltic region to 77% in the North Sea region, thermal generation will still be the dominating technology in 2050. In addition, the table also shows the adaptation costs per technology group, whereas the last column divides these costs by the share of the EU-27. The results is that the ratio is the lowest for nuclear, closely followed by fossil, whereas the ratio is equally high for hydro and other RES. This means that the actual adaptation costs are the highest for renewable energy generation technologies and these are about three times higher than for nuclear.

Planning of new generation technologies is a dynamic process. Ideally, older power plants will ultimately be retired and replaced – in time – with the latest technologies, which are intentionally more resistant to climate change. This will be true both for thermal and renewable generation technologies. The generation technologies with a relatively short lifetime, like wind, will have the capability to adjust as time progresses. The challenge will be greater for technologies with relatively long lifetimes, like nuclear and coal. Here all possible climate change impacts will have to be anticipated in the long lifetime ahead and there are uncertainties about the rate at which climate change impacts will materialize. Hence, it can be considered that the expected lifetime of a power plant is an important aspect to consider in deciding upon undertaking a climate change impact risk assessment for the planned power plant.

7.2 Investment needs in electricity generating technologies

An overall conclusion of the analysis is that a risk assessment for possible climate change effects is rarely done for existing capacity. However it is more and more becoming an integral part of the planning for new power plants, especially considering those climate change impacts that are likely to occur in the life time of the power plant. As a result, new capacity is often equipped with adapted technologies so as to be sufficiently resilient against floods and to meet cooling needs by including cooling towers into the investment plans. This conclusion holds mainly for thermal generation technologies including biomass, whereas nuclear already has a long history of risk assessment, including the possible impacts of climate change, which ensures that operations will be done under acceptable safety standards.

The same conclusion can be drawn for renewable generation technologies, where a risk assessment for possible climate change effects is even rarer. It is difficult to consider renewable generation technologies as one homogenous group. On the one hand, there is hydro which has a long history of experience and operation and where the risks are relatively well-known. On the other hand, there are relatively new mostly intermittent technologies, which have not yet been employed on a large scale and where learning is still actively ongoing, but these also have relatively short life-times. Here the assessment of climate change risk is generally not yet a point of concern.

The analysis in this report has identified investment needs up to the year 2080, given the state of technology as of 2010, relating to four of the eight considered climate change impacts:
- A decrease in precipitation will require preventive investments for hydro power plants in the Mediterranean region;
- An increase in the sea level will require preventive investments for off-shore wind power plants in all European Seas;
- An increase in the occurrence of floods will require preventive investments for thermal generation technologies all over Europe, except for the North Sea region;
- An increase in the occurrence of storms will require preventive investments for networks all over Europe, except for the North Sea region.

All other climate change impacts, such as changes in water and air temperature, changes in wind speeds and heat waves, can be compensated within current technology without making investments, possibly at the cost of a marginal loss of output.

In practice hardly any investment needs to adapt to climate change have been identified. However, climate change, though gradual, has an impact on the operation of power plants, which need to be compensated with some limited additional investment together with better harmonization of supply and demand so that less reserve capacity will be needed.

7.3 Conclusions and Recommendations for future investment needs

The main conclusions and recommendations from this study are:
- Planning of new generation technologies is needed which could prepare the power plant operator for the possible impacts of climate change and avoid unexpected disruption of generation;
- The adaptation costs to climate change for renewable energy technologies are much higher in comparison with thermal generation;
- Thermal generation will be the dominant technology in Europe to generate electricity for the coming decades;

- Nuclear and fossil facilities have incorporated climate change risks and formulated long term strategies more than renewable technologies;
- Most attention is needed for renewable energy technologies to cope with climate change effects.

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Annex A Background on electricity generation technologies

A.1 General approach

In this chapter we introduce the different power sectors, viz:

- Fossil-fuelled power;
- Nuclear power;
- Renewable energy, namely:
  - Hydropower;
  - Wind power, on- and offshore;
  - Photo Voltaic (PV) power;
  - Concentrating Solar Power (CSP);
  - Biomass-based power.
- Electricity transmission and distribution.

All these sectors are described in terms of their current status and role in Europe, physical and technical characteristics and sensitivity to weather and climatic effects. These descriptions are based on our own experience and expertise, supplemented with scientific literature.

From this information we have formulated questionnaires, different for each type of stakeholder per energy sector. These can be found in Annex D.

A.2 Electricity generation from fossil fuels

Introduction

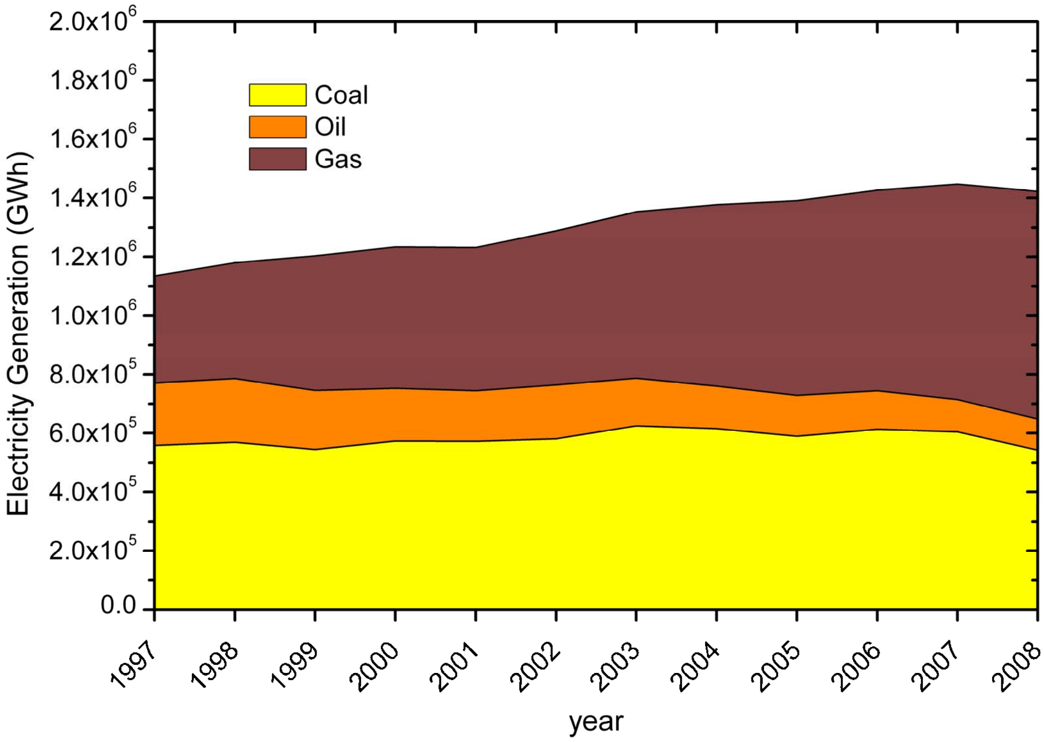
Fossil fuels have remained the primary source of electricity generation in the world. To generate electricity these fuels are burned in order to create steam or combustion gases that make the blades of a turbine spin. Fossil fuels can be categorized into three main groups:

- Coal;
- Natural gas;
- Petroleum products (oil).

Role of fossil fuels in electricity generation in Europe

In Europe, as in the rest of the world, fossil fuels still play a major role in the generation of electricity. Over the past decennium, the percentage of electricity generated by means of fossil fuels has remained more or less stable around 55 percent of the total electricity generation. Although the use of fossil fuels has stayed relatively the same, the share of the individual categories coal, petroleum products, and natural gas has changed remarkably. As can be seen in the figure below there has been a tendency towards the use of natural gas, at the expense of both coal and petroleum products. The most predominant reasons are the increasing oil prices and of all fossil fuels natural gas is the cleanest in terms of air pollution and CO_2 emissions.

Figure 25 Electricity generation in the EU-27



Source: Eurostat, 2010.

Electricity generation from coal

In a conventional coal-fired plant water under high pressure is pumped into a boiler. By burning finely grounding the coal (pulverised coal) the water is heated. There are also coal-fired plants that operate via an Integrated Gasification Combined Cycle (IGCC) procedure. During this procedure, the coal will first be gasified. Subsequently, the gas is burned in a gas turbine and the remaining heat is again used to generate steam heat.

The water in many parts of the boiler is heated until it becomes superheated steam with a temperature of about 550 °C and a pressure of 180 bar. When the steam from the boiler is drawn in a steam turbine the energy in the steam is converted into rotational energy. The pressure and temperature of the steam below are considerably reduced. With rotational energy of the steam turbine a generator is driven that generates the electricity.

The steam from the high-pressure steam turbine is being led again by the boiler to increase the energy content, and then in the medium and low pressure steam turbines to further expand thereby driving the generator further. When the steam is fully expanded, it will be condensed into water and can be used again. During this condensation process, a lot of heat is produced. To cool the condenser, often cooling water is used, and possibly even aided by cooling towers. In a few cases, the facility is cooled-down by air. The cooling agent ultimately depends on the type of plant, surrounding water temperature or ambient air temperature, and the availability of abundant water supply.

A modern coal plant can achieve an efficiency of 46 percent using (ultra) super critical technology with temperatures going up to 566–593 °C. This means that 46 percent of the energy content of the coal is converted into electricity. The efficiency of older plants is often about 35 percent. The remaining part is transferred into heat losses that cannot be converted into electricity.

Electricity generation from natural gas

In conventional gas-fired power plants, water under a high pressure (about 180 bar) is fed into the boiler and heated by burning the natural gas. The water converts into steam and will be heated further to approximately 550 °C. The energy content of the steam is converted into mechanical rotational energy by a turbine to drive the generator that generates electricity in its turn. The steam from the high pressure steam turbine is reheated and used again. When the steam is fully expanded a condenser is employed, where the condensed steam turn into water and reused. For cooling the condenser often cooling water or cooling towers are used. The most common technology for gas-fired plants is to operate via a Combined Cycle Gas Turbine (CCGT) procedure. In this way an efficiency of over 60% is possible for the most modern plants.

Electricity generation from oil

An oil-fired power plant operates on different types of oil, and works similar as a natural-gas fired power plant. The oil is heated with steam and mixed with air after which the mixture is combusted to heat the water in the boiler.

Climate change impacts on fossil-fuelled electricity generation

In this section we have described the potential climate (change) effects upon normal operation of fossil-fuelled power plants. We focussed on impacts that are specific for these types of plants, thereby omitting obvious extreme climatic impacts such as hurricanes, floodings, etc. The issues under scrutiny are the effects of water temperature and availability, coal supply and air temperature.

Cooling water temperature and availability

As explained above, most fossil-fuelled power plants need water to cool their equipment. However, the waste water produced during this cooling process is potentially harmful for the water temperature and the local ecosystem. To overcome these harmful effects on the environment governments or water boards impose legal constraints on the power plants on cooling water usage. These regulations can be restrictions of water usage by stipulating the inlet capacity. Another example is that there is a maximum tolerated difference between the inlet and outlet temperature or the power plant' cooling water temperature output has to be within specified ranges, so to prevent warming of the water body (Rothstein and Halbig, 2010).

Although depending on the geographical location, climate change can have a serious impact on the operation of the fossil-fuelled power plants through the effects on cooling water. These effects can be of a legal nature when the inlet water is too warm. In that case, the power plants need additional water to cool their equipment, or have to discharge cooling water of a higher temperature. In order to comply with the legal constraints, the power plants have to reduce the electricity generation or come to a full stop. Thereby, the plants reduce their revenues and make costs (Rothstein and Parey, 2009).

The effect of climate change on cooling water can also be a physical constraint when due to dry periods the water level of the water bodies decreases. In that case, the water availability is not enough to cool the equipment down sufficiently and the plants need stop electricity generation to prevent overheating. This can be especially the case for fossil-fuelled power plants that are cooled by river water (Rothstein and Halbig, 2010).

An additional problem climate change induced cooling water issues is the combined effect of the legal and physical constraints. For example, during the hot summer of 2003 in west and central Europe, high water temperatures and low river levels occurred simultaneously. This resulted at the restriction that only fossil-fuelled power plants could stay in operation that had cooling towers (Eyster, 2004).

Water level for coal supply

An additional problem can arise for the supply of coal for coal-fired plants due to climate change. Coal-fired plants can only operate economically if they are constructed closely to a coal mine or when the coal can be transported in via waterways. In case the water level of the water ways drops too low the coal-fired plants risk that their coal supply is delayed or hindered. In that case, coal must be supplied via train or truck which brings high costs with it (Rothstein and Halbig, 2010).

Ambient air temperature

Higher ambient air temperatures affect fossil-fuelled power plants – especially natural gas-fired facilities – in a negative way. There a basically two effects. Firstly, the power needed to drive the compressor that compresses the inlet fuel mixture is based on the difference between the inlet and outlet pressure of the gas. Since warmer air is harder to compress than colder air, the compressor needs additional power. This will ultimately affect the efficiency of the whole plant, since more of the electricity generated is needed for additional power for the compressor, thereby producing less net electricity output.

Secondly, all fossil-fuelled power stations need air (oxygen) to burn the fuel and release the heat to warm the boilers. Since warm air contains less oxygen as the same volume of cold air, additional air, and thus compressing and pumping power, is needed to produce the same amount of electricity, thereby affecting the efficiency of the fossil-fuelled power plants negatively.

As in general it can be expected that the air temperatures will rise due to climate change over the coming years, the costs can theoretically increase dramatically. It has been mentioned that increases of ambient air temperature of 10 °C can lead to several percentages of efficiency losses (Leopold, 1984). These effects are already observed for the differences between winters and summers.

A.3 Nuclear electricity generation

Principles of nuclear power production and reactor designs

The pressurized water reactor (PRW) is the most commonly used reactor design in the world; also in Europe. The design of this type of reactors, abbreviated with PWR is based on the original U.S. reactor that was designed for powering submarines and surface ships. Another variant of this design was developed in the former Soviet Union (Water-cooled Water-moderated Energy Reactor, abbreviated to VVER).

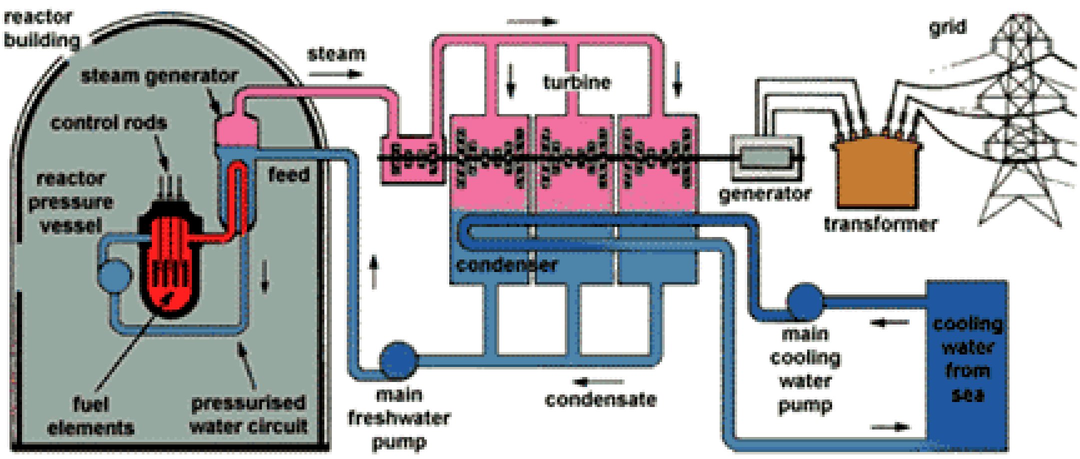
In a PWR, the reactor core (fuel and control rods to regulate the nuclear chain reaction) is enclosed in a steel pressure vessel and cooled by water (primary coolant). The pressure of this coolant is about 15 MPa and has a temperature of about 300 ^{o}C during operation of the reactor. The concept of a PWR is shown in Figure 26. The “cold” primary coolant is pumped into the reactor vessel. After passing the core where it is heated by the nuclear fission process, the heated primary coolant leaves the pressure vessel and flows through a vertically positioned heat exchanger (steam generator). Here the heat is transferred from the primary coolant to the secondary coolant that evaporates into hot steam at a pressure of about 7 MPa. This hot steam drives the electric generator and after expansion it is collected in a condenser where the steam condenses into water (secondary coolant). From the condenser the coolant is pumped back to the steam generator. The condenser is externally cooled by water extracted from surface water (river or sea). Cooling towers may be used to cool down the warm water before release into the surface water. Water inlet and outlet are well separated to prevent recirculation.

The VVER design is designed similar to the PWR but the steam generators are horizontally rather than vertically positioned.

PWRs may have two (Doel -1, 2), three (Doel-3, Emsland, Gravelines) or four (Siemens –Konvoi, Areva-EPR) large steam generators. The VVER-440 has six small (horizontal) steam generators. The larger type VVER-1000 has vertical steam generators. In addition to the Westinghouse PWR design, built in Spain and Sweden and Slovenia, Electrabel and Framatome further developed this design (Electrabel: Doel-1,2), Electrabel/Framatome Doel 3,4 Tihange 1,2 3). During 1970 -1990 Framatome developed the REP-900 series (presently called CP0, CP1 and CP2), the REP-1300 series (presently called CP4 and CP'4) and the N4 designs, Together with Siemens, Framatome (Areva) has developed the EPR. In Germany the PWR concept has been developed by Kraft Werk Union/Siemens to PWR category 2, 3 and 4. Category 4 is also called the Konvoi design.

A particular variant of the PWR design is the so called pressurized heavy water reactor. Here the primary coolant is heavy water (D_2O) that is pumped through pressure tubes that contain the fuel elements. Inside the pressure tubes heat is transferred from the fission process to the heavy water. The pressure tubes are enclosed in a pressure vessel that also contains heavy water which is used to moderate the chain reaction process in the pressure tubes. The hot heavy water from the pressure tubes is collected and flows through steam generators and is pumped back to the pressure tubes. Inside the steam generator, the heat is transferred from the heavy water to normal (light) water that evaporates into steam. This steam is used to drive the generator. Refuelling takes place during operation. Presently in Europe there are only two reactors (CANDU) of this design, built at Cernavoda by AECL.

Figure 26 Generic schematic diagram of Sizewell B[28]



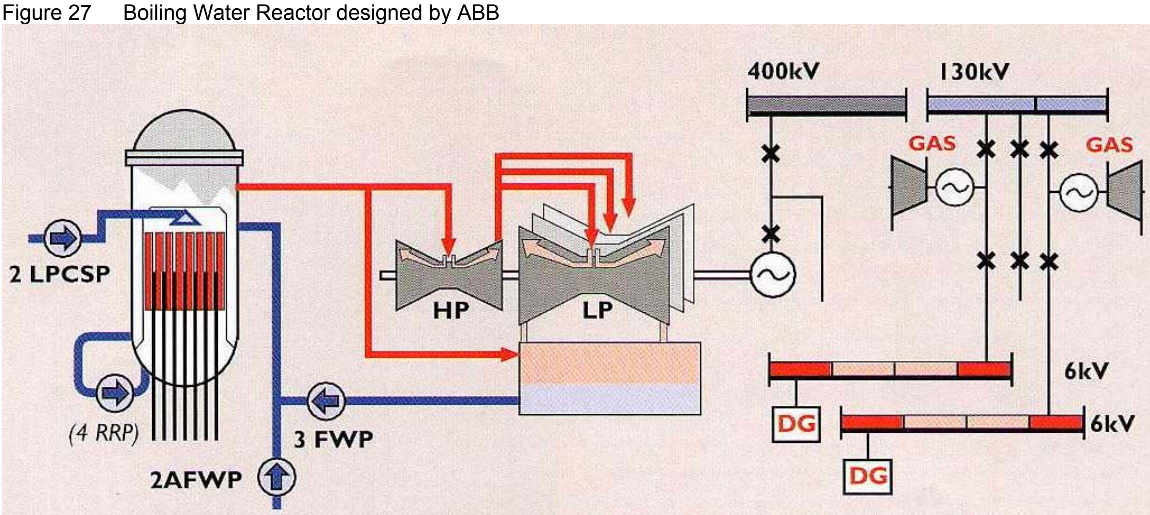
Similar in concept to the PWR and VVER is the Boiling Water Reactor (BWR) where again the reactor core is enclosed in a steel pressure vessel and is cooled by water (coolant) that circulates through the core at a temperature of about 290 ^{o}C. The circulation is driven by internal or external pumps or could also be gravity driven (natural circulation), see Figure 27. The water layer above the core is 'boiling'. The steam generated from this layer leaves the pressure vessel at a pressure of about 7 MPa. The steam flows directly from the pressure vessel, passing an adjustable valve, to the turbine. After expansion in the turbine the steam is condensed inside the condenser that is

[28] See reference http://www.british-energy.co.uk in Report for the European Commission, contract: ENV.C.2/ETU/2000/0020, 2001.

cooled by water extracted from surface water. The water resulting from condensation is pumped back to the reactor vessel.

There have been fewer boiling water reactors built than PWR or VVER. In the European Union, Germany, Sweden, Finland and Spain have installed BWR's. Diverse types of BWR are built in the EU, for example the Siemens/KWU SWR , category 69 and 72 (Gundremmingen) and reactors built by Asea (ABB) in Sweden. In addition, Spain has BWR's of type Mark II (Garoña) and Mark III (Cofrentes) designed by General Electric.

Figure 27 Boiling Water Reactor designed by ABB

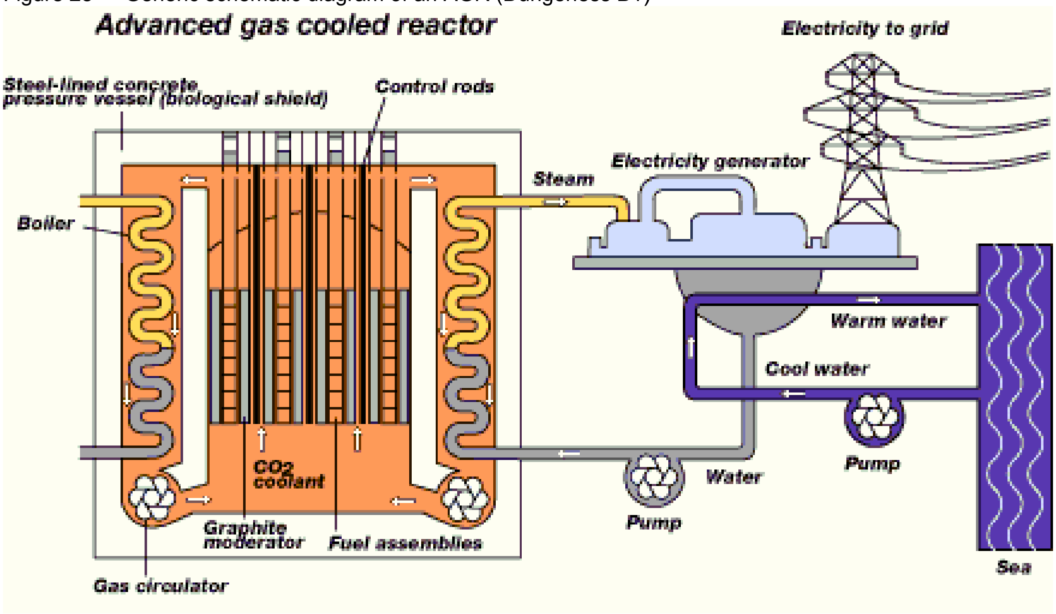


Note: In the pressure vessel (at the left side0, water circulates through the core by four external pumps (4 RRP),. The steam generated in the pressure vessel is passed (by the red line) to the high pressure (HP) and low pressure turbine. (LP). The condensate collected in the condenser (vessel below the LP turbine) is pumped back by 3 feed water pumps (3FWP) to the pressure vessel. In case of a loss of coolant incident additional water is supplied by AFWP (auxiliary feed water pump) or by LPCSP (low pressure coolant supply pump).

In the U.K. two types of gas cooled reactors have been built - Magnox and Advanced Gas Cooled Reactors (AGR). Almost all gas cooled reactors of older Magnox design, have been decommissioned and all the Advanced Gas Reactors (AGR) are operating.

IN the AGRs and the later Magnox plant, the coolant (CO_2) is heated to almost 700 ^oC when passing through the graphite blocks that contain steel tubes with fuel elements. The graphite blocks are inside a pressure vessel made of pre-stressed concrete with a steel liner, see Figure 28. Inside the steam generators, the heat is transferred from the CO_2 to water to produce super heated steam (more than 550 ^oC and at a pressure of about 16 MPa) that drives the turbine. The cooled CO_2 is pumped back to the pressure vessel. Refuelling takes place during operation. The thermal efficiency of AGRs is fairly high (41%) when compared to PWRs and BWRs.

Figure 28 Generic schematic diagram of an AGR (Dungeness B1)[29]



For more details on the nuclear reactors in EU-Member States we refer to the National Reports of the EU Member States to comply to on the Convention of Nuclear Safety.

Nuclear power plants

For the climate change effects analyses, the nuclear power plants are arranged in four regions for which the climate change effects will be rather similar. This approach is also used for the other electric power generation facilities, such as fossil plants and wind turbines. For each region the preconditions to generate nuclear energy are summarized.

Baltic region

In the Baltic region only Sweden and Finland have operational nuclear plants and other nuclear fuel cycle facilities. Presently, mainly three utilities are operating these nuclear plants: Vattenfall, Fortum and TVO. The Utility E.ON is also participating at Oskarhamn. In addition to the four operational units in Finland, a new unit is being built and two other units are approved to be built. The political situation in Sweden is not clear now. According to the proposal approved by the former Government, Sweden will replace its existing plants, and is keeping options open for expanding its fleet in the future. However, the new Government could easily reject this proposal and to proceed with the decommissioning of the plants.

Table 25 Current installed capacity and (proposed) new capacity in the Baltic region

Country	Capacity 2010 [GW_e]	No. of operational units	Capacity being built [GW_e]	Capacity be planned [GW_e]
Finland	2,7	4	1.7	Max. 3.6 approved
Lithuania	0	0 (2 decommissioned)	0	(1)
Sweden	9.0	10	0	(similar capacity)

In Finland, the maximum permitted cooling water inlet temperature of the NPP is 25 ºC for safety reasons and a maximum cooling water outlet temperature of 32 ºC mainly for protection of the environment. The existing sites are protected against flooding from sea and from high intensity

[29] See reference http://www.british-energy.co.uk in Report for the European Commission, contract: ENV.C.2/ETU/2000/0020, 2001.

rainfalls that are predicted by climate change effects scenarios. Till the year 2100, TVO and Fortum foresee no large investments for measures related to impacts of climate changes. Fortum has installed a sophisticated lightning protection system. No further improvement needs for the Loviisa site have been identified.

In Sweden, the permitted maximum cooling water inlet temperature is 27 ºC for safety reasons and the permitted outlet temperature is below 32 ºC because of the protection of the environment.

Sites located at the Baltic and Finland Sea, have no experiences with very high surface water temperatures during summer. Also for the future (> 2100) no drastic changes are foreseen.

At the west coast of Sweden, the NPP sites have been confronted in the past by obstruction of inlet by marine life (redesigned inlet). Presently, surface water temperatures at the Swedish coast that exceed 26 ºC are unusual. During summertime it is likely that the sea water temperatures at the coast are high (up to 25 degrees Celsius). There is a risk that cooling capacity in water cooling systems is reached its maximum and a production capacity decrease is needed. Water cooling systems may be needed to adapted/updated.

Future problems with water inlet temperature (due to the shallow west coast) may be avoided by deep-water intake (large investments (ca. 200 M€).

Present ambient air temperatures during summers are such that no measures are needed. During outages during the autumn, one even has to heat the buildings and also the cooling water. In case the temperatures during the winter period would be lower, the tanks with borated water could be frozen. In would require a minor investment to solve that problem.

In general, the utilities indicate that there are no operational problems when the ambient air temperatures will be in the range between - 40 ºC and + 40 ºC.

In conclusion the preconditions at the nuclear sites in the Baltic reason are such that no major problems with nuclear power generation are foreseen due to climate change effects during the next 40, and 70 years. Even predictions beyond 2100 do not envisage large problems either on safety or production efficiency.

North Sea region

In the North Sea region, Belgium, France, the Netherlands and the UK have operational nuclear plants and other fuel cycle facilities. Presently, three utilities are operating these nuclear plants: EdF, Electrabel (Suez) and EPZ. In addition to the sixty operational units, one new unit is being built in France and one other is approved to be built, also in France. In the U.K EdF but also the utilities E.ON and RWE have firm plans to build new units on existing sites. Hence, there would be an expansion of nuclear power over the next 20 years in this region. Due to the long time-to-market of nuclear power plants, the increase is unlikely to start before 2020.

In Belgium all the present power plants are older than 25 years. No building of power plants (for replacement) is foreseen. Life-time extension is most probable. In the Netherlands, the only NPP will operate till 2033. Presently, there are two requests for building a new unit at Borssele.

Presently, this region has the largest impact on the nuclear production in the EU. Total nuclear power production in the North Sea region is about 500 TWh(e).

Table 26 Current installed capacity and (proposed) new capacity in the North Sea region

Country	Capacity 2010 [GW_e]	No. of operational units	Capacity being built [GW_e]	Capacity be planned [GW_e]
Belgium	5.8	7	0	0
France	63.4	58	1.7	1.7
Netherlands	0.49	1	Lifetime extension	(2.5)
UK	10	17	NA	16

In Belgium, At Doel, the maximum permitted cooling water outlet temperature is 33 ºC to protect the environment. Measures to protect the Doel site against flooding till the next 10 to 20 years have already been taken. A long term strategy has been developed to protect also Doel to impacts envisage during a longer period. Because the Western Scheldt is an economical important water way (harbours of Antwerp) frequent improvements (deepening) of this water way will be undertaken.

At Tihange, maximum cooling water outlet is 28 ºC. The delta T is 4 to 5 °C depending also on river flow. Present annual average outlet is about 17.5 ºC. Measures to protect site against flooding have been taken. Adequacy of these measures is reviewed in the Periodic Safety Reviews.

The predicted loss of efficiency due to higher ambient air temperature is 0.1 percent per 1 °C temperature increase. According to the Utility, only when the maximum ambient air temperature would be in the range 40 to 42 ºC, (present average 27 °C during summer), investments to implement measures will be done.

Although, France is part of the North Sea region, most of the nuclear power plants in France are located inland at river sites. Impacts of climate change effects on these sites are similar to those on the sites in Spain (southern part of France) and in Germany (region middle and south Germany).

The nuclear power plants are operated by EdF in load-following mode. Through a combination of units at the beginning of their cycle (power variation is easily done) and units that are at the end of their model (constant power), France is able to provide sufficiently back-up of the other energy sources. EdF has an upgrading program for all of its nuclear power plants if safety issues are concerned and for almost all of these plants as far as adaptation is concerned. For example 1455 to 1500 MWe for the N4 designs. Also the other designs are planned to be upgraded: the 900 series (CP0, CP1 and CP2) in 2008. Also the 1300 series (P4 and P'4) are to be upgraded by 7 percent, starting in 2015. (Source: World Nuclear Association, country report, updated September 2010). Weighted average of regulated tariffs for nuclear energy by EdF for 2009 has been 4.3 €ct/kWh. Expected costs of the new EPR will be ca. 6 € ct/kWh.

Most nuclear power plants situated at the 15 inland sites are using cooling towers (cooling of the outlet). At Civaux, a closed cooling circuit has been use in combination of the cooling towers together with supplementary cooling devices for purge. Here only make-up water is provided by the river (Vienne). The cooling towers are in general based on natural draft and are rather high, more than 100 m. Because of amenity, forced draft is chosen for the cooling towers at Chinon (25 m). Four of the inland sites (Blayais, Fessenheim , Tricastin, St Alban) extract river or lake water directly for cooling).

Cooling water availability

During hot summers, the water flow at the river Loire can be better regulated than the rivers Rhone and Garonne due to the relative small variation in height of the river bed. Reservoirs at the Central Massive are used to regulate the river flow.

French policy to protect biodiversity relies on the new European Directive on biodiversity. Research is performed to find the right indicator for the water quality. Changes of biodiversity have been observed mostly in the rivers in south of France (Rhone and Garonne), probably due to the natural increase of river water temperature due to climate changes. These effects have to be accounted for when setting the cooling water limits. Relaxation of the cooling water outlet temperature limit is sometimes approved during hot summers, when the security of supply is threatened (limit normally is 28 °C but in summer time also relaxation to 29 °C or 30 °C is allowed). These special limits depend on the site (river and water region) and were occasionally used during the summer of 2003.

Already during the nineties, EdF has studied the impact of climate changes on river water temperature and has developed models to predict water temperature resulting from ambient air temperature and other changes such as variation of precipitation (for example the Rhone). For example, real-time models have been developed by which predictions by Meteo de France could be translated in changes of river water temperatures.

After 2003 all sites have been investigated using these models and the experiences developed during the nineties. As a result of these investigations measures were implemented to improve the sites.

Cooling water studies have been developed before 2003. Based on these modelling (real time-model) and the experiences of 2003 have been used as a good approximation of what could happen to the nuclear plants in the future because of the predicted climate changes. As a result measures were implemented to improve the operations of all nuclear power plants. Measures will be incorporated in the newly designed plants to protect these plants against the impacts of climate change effects that are expected during the next 60 years. These studies and similar studies for the UK have been published.

Based on these studies also the existing plants in France will be adapted before 2014, to be protected against extreme weather conditions that may occur during at least the next 30 years.

Protection against impacts of climate changes is part of the periodic safety review. France learnt their lessons very well during the events of 1999 and heat waves in 2003. Due to the incident at Blayais, all sites have been assessed within two years after the incident. All sites have been reinforced (higher protection dikes in Blayais and complementary protection at some other sites) to prevent future flooding (based on analyses of water height prognoses for the next 30 years). Except the Tricastin site where the combined effects of all other industries located at this site and the hydro dams, are analysed before measures will be taken. Costs of these reinforcements of the NPP sites have been integrated in the normal maintenance costs. Impacts of heavy rain fall on the sites located at the lower Rhone (Cruas and Tricastin) have been studied to reassess the protection of these sites. The action of reinforcing the sites has been taken independent of the actions followed from the 10-year Periodic Safety Reviews.

Rise of ambient air temperature

Also measures have been taken to protect the installations against high ambient temperatures during heat waves, such as occurred during the summer of 2003. Safety of the electronic equipment and other safety related systems was affected. EdF has assessed these problems and has implemented urgent modifications during the next 3 to 4 years. It is expected, that there will be no need for further modifications due to the large margins that have been accounted for in the design changes. These design changes have been based on expected extreme air temperatures for at least the next 30 years which are diagnosed through climate change studies.

No special measures have been taken in France to protect the NPP against higher wind speeds and more frequent and more powerful lightings. Only measures to protect the grids against higher wind speeds (storms).

Presently, there are no plans of EdF to abandon the present river sites. Investments are made to enable operating the NPPs at these sites also in the future. There are now good financial conditions for developing strategies to keep these sites open. There is an adaptation program going on to keep these sites open during the lifetime of the units on these sites.

Locations at sea shore

For the sites located on the coast, less impact of any climate change effects is expected also during a long time period. For this reason the next new NPPs will probably be built at these coastal sites.

Of course there are problems and may be future problems when concentrations of marine life are changing and will hamper the inlet or outlet of cooling water. These obstructions occurred at the inlet filters of Gravelines and Paluel. The costs of measures that have been implemented to solve these problems are minor.

Presently in the Netherlands, the only nuclear power plant at Borssele will be operating till 2033. Measures have been taken to protect this site against flooding during the next 20 years. In the event that new plants will be built, impacts over longer periods (over a period up to 100 years) will be assessed to judge the adequacy of the present protective measures.

The present site has a problem with the cooling water inlet that has been clogged by marine life. Now adequate measures have been taken. The average water temperature has to increase about +5 ºC to have a decrease of efficiency of 1.2 percent. Two applications for new plants have been made. In addition to the Borssele site The Government has a reserved site for nuclear power operations at the northern part of the Netherlands.

In the United Kingdom, two of the Magnox nuclear power plants (Wylfa and Oldbury) and all nuclear power plants with advanced gas cooled reactors (AGR) are operating. All these plants have two reactors and are located near the sea shore. The Magnox plants operated by Magnox North Ltd. will all be closed before 2015. The last AGRs were commissioned in the 1980’s and by 2023 only the Sizewell B nuclear power plant (PWR) will be operated. British Energy, now part of EdF, the utility that operates these AGR’s and PWR, has started a life-time extension program for these AGR’s The British Government by its Department of Trade & Industry has commissioned an energy review and discussion report[30] In this report all existing nuclear sites (also inland) have been assessed. There are 9 coastal sites suitable for building a nuclear power unit (1100 MWe – 1600 MWe) and 2 of these sites are even suitable for dual units (2200 MWe – 3200MWe).

Several companies have proposed to build in total at least 16 GWe new nuclear (6.4 GWe by EdF, at least 6 GWe by RWE/E.ON and 3.6 GWe by a consortium led by GDF Suez.

According to the environmental report issued by British Energy in 2007[31], the present sea shore locations are still suitable at the end of this century. That has been the result of an assessment by the British Met Office and the Halcrow company of these sites, in which the worst credible impact of

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30 Siting New Nuclear Power Stations: Availability and Options for Government, published by Jackson Consulting Limited on 26th April 2006.

31 Climate Change and replacement nuclear build, a report which has been prepared and issued in November 2007 by British Electricity.

climate change on these coastal sites has been assessed. They assumed sea levels increase of 1.7 m over the century. Also the impacts of more severe storms and higher ambient air temperature on installations at these sites have been assessed. The conclusion of British Energy has been that they have 8 coastal sites that are suitable for new nuclear plants that could be built, operate and be decommissioned during a period extending from 2010 to around 2100. Also the infrastructure and the grid connections have been considered. Other sites considered for new nuclear are Wyfla and Oldbury (by RWE/E.ON) and Sellafield (GDF Suez).

Measures shall be taken to protect the nuclear plant against clogging of inlets with marine life (other CW pumps and filters). There are maximum temperature limits on the outlet for each station which vary from site to site. This can be anything from 11-18 degree ºC above the inlet temperature. Further additional measures may be required to protect the site against flooding. Also there is a need to protect the infrastructure near the plants (against surface flooding).

Presently coastal erosion was seen as the major threat on existing sites. The situation has been analysed and reported. All sites can be protected but one site (Dungeness) has been taken off the list of possible future sites.

For currently operating plant the variations attributable to climate change are within design conditions, but additional protective measures needed could be identified from the PSRs.

The environmental agencies prescribe the following cooling water limits: an upper limit of 10 ºC or 12CºC is set for the temperature increase of cooling water between inlet and outlet. For new NPPs the agency will set a limit at the edge of the cooling water discharge mixing zone of not exceeding on an annual basis a 98 percentile of 23 ºC. Outside the mixing zone temperature uplift in the thermal plume above ambient background shall not exceed 3 °C. In waters of high ecological status the uplift shall not exceed 2 ºC. In addition to the above standards, other temperature standards may need to be considered in relation to specific conservation objectives. In case the permitted temperature rise has been exceeded the Regulator would require the operator to reduce or cease power in order to stay within the temperature limits. In conclusion: the present sites are sufficiently protected.

Central and Eastern region

Bulgaria, the Czech Republic, Hungary, Poland, Romania and the Slovak Republic are all planning to build new nuclear power plants in the next 10 years, but developments in the Central and Eastern region hinge on the future of nuclear power in Germany, which has the largest installed capacity by far in this region. The German government has expressed a preference for extending the lifetime of the existing plants by around 15 years, and the possibility to build reactors has not been ruled out. Opponents of nuclear power exist in all major parties, though, so a nuclear renaissance is by no means secured. With the expected lifetime extension, though, capacity in this region will increase to beyond 2030 at least.

Table 27 Current installed capacity and (proposed) new capacity in the Central/East region

Country	Capacity 2010 [GW_e]	No. of operational units	Capacity being built [GW_e]	Capacity Planned [GW_e]
Bulgaria	1.9	2	0	2.0, in Belene
Czech Rep.	3,7	6		To add new units to replace units that will be decommissioned
Germany	20.5	17	0	Lifetime extension until 2020 -2030
Hungary	1.9	4		Lifetime extension & new units
Poland	0	0	0	Several new units planned
Romania	1.3	2	0	1.4 at Cernavoda site 2.4 in Transsylvania, after 2020
Slovak Rep.	1.8	4	0.94 at Mochovce	1.0 - 1.6 at Bohunice

In Bulgaria, the present nuclear site is located near Kozloduy at the Danube River. The utility is the Kozloduy NPP Plc which is a subsidiary of Bulgarian Energy Holding EAD. There are two VVER-1000 at the site which are operating since 1987 and 1991. In addition there are 4 VVER-440 reactors which are decommissioned.

The location has sufficient coolant water. Engineering tools have to be used for removing algae from the cooling water. In the NPP Technical Specifications the cooling water temperature has to be in the range of +5 ºC - +33 ºC. The following temperature bandwidth is agreed with the Regulator: During summer the water outlet temperature may vary between 31 and 37 ºC. During winter, the outlet temperature may vary between 15 and 21.5 ºC. According to the license, the water temperature of the inlet from the Danube at the point of complete mixing should not exceed its temperature at the point upstream the hot channel outlet with more than 3˚C. When inlet or outlet temperature is close to its limits, the plant has to reduce power. Higher ambient air temperature has limited impact on the safety of the plant. The plant is protected against lightning. However the impact of flooding of the site due to heavy precipitation has not been analysed yet. Life time extension is foreseen for the present plant. To make up for the closed units at Kozloduy, the Bulgarian Energy Holding EAD is planned to build two VVER-1000s at the Belene site. Part of the constructions and infrastructure is already available at this site.

Presently there are two sites in the Czech Republic, at Dukovany and at Temelin. During the period of 2005-2010, the efficiency of Dukovany NPP is 88 percent. During the 2005-2010 the efficiency of Temelin NPP is 75 percent.

Generally: the Czech national regulation set the permissible temperature of the surface waters. The NPP's at Dukovany and Temelin use closed cooling systems. The thermal heat load of the cooling water is transferred to the ambient air in the cooling towers and only the evaporated water in cooling towers is made up from river water (the river Jihlava at Dukovany and the river Vltava at Temelin). For this reason, the outlet/inlet water temperature from NPP does not practically affect the temperature of river water. Regulations have set maximum inlet water volume from river and maximum outlet water volume to river. In case of insufficient inlet water, the plant operation could continue at lower power.

According to the Czech Nuclear Regulator (SUJB) impact of climate change effects and weather conditions generally on the safety of the operation of NPPs have to be assessed. It is necessary to take into account all effects in the safety review, e.g. it will be necessary to analyse possibilities of fast changes of electrical output of NPPs depending on situation in electrical grids (e.g. impact of wind power stations etc).

There are 17 operating nuclear power units in Germany. Presently, there are 4 utilities that operate the NPPs in German: E.ON, RWE, EnBW and Vattenfall. E.ON owns the plants at: Brokdorf, Isar (1+2), Grohnde, Unterweser, and Grafenrheinfeld. RWE owns the plants at: Biblis (A+B), Gundremmingen (B+C) and Emsland. It also owns the NPP at Mühlheim Kärlich, which is under decommissioning regime. EnBW owns the plants at Phillipsburg and at Neckarwestheim.

The German NPP´s are designed and maintained to withstand a variety of meteorological hazards (e.g. flash of lightning, storm and flooding). Presently, no measures are foreseen. Review of the adequacy of the existing measures to protect the NPP against impact of climate changes is part of the periodic safety review. Investments to implement measures will be part of the normal maintenance costs.

The working group (standing division) of BMU which is dealing with Nuclear Legislation, Länder Committee for Nuclear Energy, and Technical Supervision of the Federal Office for Radiation Protection envisages doing some studies on questions of climate changes effects in the near future. Criteria for cooling water are prescribed in the licensed by the Federal Environmental Protection Agency.

Intakes temperature in the range of 22 – 30 °C were used to proof the efficiencies of the emergency core cooling systems and residual heat removal pumps. In 2003 NPP operation were reduced due to heat waves. There is a minimum and maximum level (temperature) of intake of cooling water established in the NPP license. Specific licence is required to change upper limit of water level. Protection of NPP against flooding is implemented according to KTA 2007 (protection against extreme water levels).

The economic life time of the operating NPP has been limited to 32 year, but presently the German Government proposes to extend the life time of these plants.

Presently there is only one site in Hungary at Paks at the river Danube. Water from the Danube River is used, at a rate of 100 – 110 m^3/s, which is 5 percent of the average flow in the river. No cooling tower needed. Power generation shall be reduced or discontinued in case of insufficient cooling capacity due to high river temperatures. The allowed difference of the intake and outlet temperatures of the cooling water is 11 ºC in general, and is 14 ºC in case when the inlet temperature is below +4 ºC. These values are valid for all power outputs. The maximum water temperature shall not be higher than 30 ºC at the distance of 500 m from the outlet cross section.

It is possible to relax the temperature limits, when the temperature values can't be lowered by increasing the quantity of cooling water intake, the production shall be decreased or stopped. In case of energy deficiency and on the basis of the request from the Hungarian Energy Office, and with consent from the environmental supervision, the HAEA may and probably would give permission to deviate temporarily from the values contained in the license.

Utility is the Hungarian Power Companies Ltd. (MVM Rt). Life time extension is foreseen. The plant at Paks will be in operation till about 2030. Impacts from climate changes are accounted for in the periodic safety review.

Presently there is one nuclear site in Romania at the Danube River near Cernavoda. In the late 80ies 5 NPP's of the Candu type have been planned. At the end of the Ceaucescu regime only one unit was almost finished. The first unit has been completed and commissioned. Recently, unit 2 is competed and commissioned. There are also worked out plans to complete units 3 and 4 and put them in operation.

The present lifetime of units 1 and 2 of the Cernavoda NPP is 30 years for each unit, with the possibility of extending lifetime with about 20 to 30 years by performing refurbisment .The margin depend on the intake water temperature. The maximum outlet water temperature shall not exceed 35 degree C. The utility is S.N. Nuclearelectrica S.A.

Presently there are two sites in the Slovak Republic, at Jaslovské Bohunice (EBO 1-4, called NPP V1 and NPP V2) and at Mochovce (SE-EMO 1-2). EBO 1 and 2 are decommissioned. The utility is ENEL. Both site using closed cooling system in combination with cooling towers. Make-up water is extracted from the river. Presently, the units 3 and 4 at Mochovce are being completed.

Mediterranean region

Spain is the only country with substantial nuclear capacity in the Mediterranean region, but the country has maintained its opposition to renewing or expanding its installed base, focusing on renewable energy sources instead (see the table below). Italy may well fill the gap in the future, as its government has called to overturn its nuclear moratorium to reduce its reliance on imported gas and electricity, and the consequent high electricity prices. The country has sufficient technical and engineering expertise to achieve this, but political uncertainty and complex planning procedures could hamper the construction of new nuclear power plants. In the long term, nuclear capacity in the Mediterranean could grow strongly.

Table 28 Current installed capacity and nuclear policy in the Mediterranean region

Country	Capacity 2010 [GW_e]	No. of reactors	Policy
Italy	0	0	Plans for new units
Slovenia	0.67	1	Lifetime extension & new
Spain	7.5	8	Life time extension. No nuclear build at present

Presently there only one nuclear power plant in Slovenia at Krsko. Owner ship is shared with Croatia. There is an upgrading and lifetime extension planned.

There are 8 nuclear units in operation. The policy of the Government is to build no nuclear. In the mean time, the plants may operate longer. The lifetime of the existing plants have been extended by another 10 years. The utilities foresee a life time of 60 years of the plants.

According to the nuclear regulator they consider impact of climate changes effects on the NPP. If the current limits established in the license conditions (Safety Analysis Report and Technical Specifications) need to be changed, the new values have to be justified. In some cases a power reduction could be necessary and plant modifications may be needed to restore the full power operation. Currently those effects are not foreseen to occur in the near future.

Fuel cycle operations

Compared to fossil-fuelled power plants, operation of a nuclear power plant requires additional pre- and post processes. This sequence of processes, including the nuclear power generation is the so-called nuclear fuel cycle. This cycle starts with the mining and milling of the uranium ore, followed by the extraction of uranium (compounds) from the ore. Presently these processes take mostly place outside the European Union[32]. Most nuclear power plants in the EU Member States use enriched uranium. Natural uranium compounds from outside the EU will be processed in enrichment facilities in France, U.K. Germany and the Netherlands. The next process is the fuel fabrication that takes place in several EU Member States. After the fuel has been ‘used’ in a nuclear power plant, the irradiated fuel is temporary stored at the plant. In addition to the fission products, the used (irradiated) uranium fuel contains actinides such as the element plutonium. In case no direct storage of the used fuel is foreseen, the used fuel is reprocessed into fission products and some actinides that will be conditioned for long-term storage and reprocessed uranium and plutonium. Both fissile elements are used to fabricate fuel (REPU and MOX). There are reprocessing facilities in France and the UK. As result of the nuclear fuel cycle processes, operational radioactive waste is generated in EU Member States. This waste is to be stored to decay (short-living radioactive substances) or to be stored (long-living radioactive substances) for disposal in deep geologic formations or isolated (uranium mines). Presently, two facilities for disposal of long-living radioactive material are being built.

Protection against external events such as occurrence of more extreme weather conditions due to climate changes, such as heavy rainfall resulting in flooding, is part of safety requirements when designing and building the fuel cycle facilities. In EU Member States a ten-year Periodic Safety Review of the nuclear power plants by the national Authorities it is mandatory. During this review the impacts of climate changes on the existing sites and installations have to be assessed on the basis of expected climate change effects during the next 20 years. In case impacts are expected mitigating measures have to be implemented before the next periodic review. For new NPP, potential impacts of climate change effects to the NPP site and installations during a longer period in the future, more than 60 years, have to be assessed.

For the climate change effects analyses, also climate change impacts on other fuel cycle facilities than nuclear power plants have to be assessed. Similar to the method used earlier, these facilities are arranged in four regions for which the climate change effects will be rather similar. Fuel cycle facilities not related to nuclear power production are not discussed in this study.

Baltic region

In the Baltic region only Sweden and Finland have operational nuclear plants. In addition Lithuania has two RMBK-1500 units which are decommissioned.

Sweden and Finland are building permanent disposal facilities for high level waste in deep geological formations (near Forsmark site and near the Olkiluoto site). The safety cases prepared for these underground facilities include assessment for a period of millions of years. Also impacts of future Ice-ages have been incorporated in these safety cases.

Intermediate spent fuel storage facilities and final disposal facilities for low and medium level waste at Oikiluoto and Loviisa sites and an interim spent fuel storage (CLAB) near Oskarhams site. Sweden also has a fuel fabrication facility (Westinghouse).

Protection of these fuel cycle facilities against climate change effects is periodically reviewed and measures will be taken when safety is affected (low costs investments).

[32] The two CANDU reactors at Cernavoda (Romania) uses natural uranium fuel elements made from locally mined uranium.

North Sea region

In the North Sea region, Belgium, France, the Netherlands and the UK have operational nuclear plants and other fuel cycle facilities.

Other nuclear facilities in Belgium

Belgium has in addition to power stations, 2 research reactors at SCK-CEN at Mol. Waste from the NPP is collected and stored at Dessel. NIRAS is the national radioactive waste organisation. At Dessel there are facilities to store the vitrified waste and low/ intermediate level waste. A subsurface disposal facility is prepared at Dessel for short-living low- and intermediate-level waste. Investigation is going on to dispose the high-level waste and the long living waste in geological formations (clay).The fuel fabrication factory is decommissioned.

Other nuclear facilities in France

France has no operational uranium mine but all other facilities of the fuel cycle are present at France. Conversion facilities at Pierelatte and Malvesi, both near Tricastin. Also the enrichment facilities (George Besse plants) are located near Tricastin. At the large reprocessing facility at Cap la Hague, uranium and plutonium is extracted from the used fuel (850 tonnes spent fuel → 810 tonnes reprocessed uranium and 8.5 tonnes of plutonium). MOX fuel is produced at the Melox plant near Marcoule.

Nuclear waste from the French NPP are collected and stored by ANDRA. Disposal of low-level and short-lived intermediate level waste at Soulaines and Morvilliers facility.(near Troyes) for low-level waste from NPP dismantling activities. Facility for disposal of long-lived waste will be developed (underground laboratories at Bure). In addition to the nuclear power plants, France has several research reactors (14) and other research facilities, located near Paris (Orsay and Saclay) and at an industrial site located at the Rhone near Tricastin site (Pierrelatte, Marcoule).

Protection against impacts of climate change effects is covered in the periodic safety reviews of these installations.

Other nuclear facilities in the Netherlands

In addition to the Borssele, there are research reactors at Petten and Delft and an enrichment facility (Almelo). Waste is collected and stored by the National Agency (COVRA) at their facility near Borssele. Also the vitrified waste returned from reprocessing abroad is stored here. Also the research reactors and waste storage facilities are periodically be assessed (also for external impacts, such as flooding from sea and heavy rains).

Other nuclear facilities in the U.K.

In addition to the nuclear power plants there is an enrichment facility (Capenhurst) and a reprocessing facility at Sellafield. Fuel fabrication facilities (Springfields). A disposal facility for low-level waste has been developed at Drigg.

Central and Eastern region

Bulgaria, the Czech Republic, Hungary, Romania and the Slovak Republic have all nuclear fuel cycle facilities.

Other nuclear facilities in Bulgaria

At the Kozloduy site a dry storage facility for spent fuel has been built. Also treatment and storage facilities of radioactive waste are present. Safety of these facilities against impacts of climate changes are addressed in the periodic safety reviews.

Other nuclear facilities in the Czech Republic

At Temelin and at UJV Rez facilities for storage of spent fuel have been built. At UJV there isalso a storage facility for high level radioactive waste.The national waste orgniation SURAO has 4 depositories for radioactive waste.

In the design of these facilities external impacts such as flooding has been taken into account. The situation and adequacy of these protective measures are periodical reviewed.

Other nuclear facilities in Hungary

A storage facility has been built at the site, near the NPP at Paks for storing the spent fuel elements during 50 years. A final disposal site is foreseen in the clay formation at the Mecsek Mountains.

Other nuclear facilities in Germany

All previously exploited uranium mines in Saxon and Thuringen (former parts of the German Democratic Republic) are decommissioned. There is an enrichment plant at Gronau. Fuel is fabricated at Lingen (Siemens).Spent fuel will now be stored at the site of the NPP. In the past, spent fuel was sent abroad (France). The returned vitrified waster is stored at Gorleben in casks. At Ahaus intermediate level waste is stored and fuel from research reactors. The major part of the vitrified waste will be returned by 2022. A repository for radioactive waste (low and intermediate level waste) is operated in Konrad (former iron mine) and in Morsleben (salt mine, now to be decommissioned). In addition there are several research reactors and facilities to treat radioactive waste.

Other nuclear facilities in Romania

In Romania there is mining of uranium, a conversion facility and a facility for a fuel fabrication (natural uranium). There is storage facility for spent fuel at Cernavoda site, at SCN Pitesti and at IFIN-HH. On these sites are also waste treatment and storage facilities. The national waste organization is ANDRAD. Romania has a disposal facility at Bihor.

Other nuclear facilities in the Slovak Republic

At both power plants there are facilities to condition the operation waste. There is an additional (experimental) waste treatment centre near Jaslovské Bohunice. The National Repository of low and intermediate level radioactive waste (RÚ RAW) is in operation since 1999 in the locality near Mochovce. The interim spent fuel storage is in operation in Jaslovské Bohunice since 1987, where the project of seismic resistance and storage capacity increase has been implemented. (MSVP – JAVYS).

Mediterranean region

Spain and Slovenia have fuel cycle facilities. Italy has 4 decommissioned reactors and facilities for treatment and storage of radioactive waste.

Other nuclear facilities in Slovenia

At Slovenia there is a Central Interim Storage for Radioactive Waste in Brinje. There are decommissioned sites at the Boršt mill tailings site and the Jazbec mine waste pile at the Žirovski vrh Uranium Mine. Low and intermediate operational radioactive waste and the spent fuel are stored at the Krško NPP site. Non fuel cycle waste is stored at the Central Interim Storage for radioactive waste in Brinje. This facility is operated by the ARAO (national radioactive waste organization).

Other nuclear facilities in Spain

In Spain the low and intermediate level waste is stored and disposed (including the very low level waste) at the “El Cabril” facilities (Córdoba). The spent fuel is stored at the nuclear sites of the national radioactive waste organization of ENRESA.

Existing European projections

Various studies have projected the deployment of nuclear energy in Europe to 2050, including analysis by the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA) and the E3M Lab of NTUA, Athens.

A.4 Electricity generation from renewable energy sources

Introduction

Renewable energy sources currently meet approximately 14 percent of the global electricity demand and are poised to play an even greater role in the future. These technologies provide a key component of efforts to mitigate climate change and environmental protection measures. Given the great variety of renewable-based generating technologies, a choice has been made regarding the scope of study in close consultation withDG ENER. In this study the following renewable generation technologies will be considered:

- wind power (onshore and offshore);
- hydro power;
- biomass-based electricity generation;
- PV (photovoltaic);
- CSP (concentrating solar power).

Wind electricity generation (onshore and offshore)

Of the renewable energy technologies applied to electricity generation, wind energy ranks second only to hydroelectric in terms of installed capacity and is experiencing rapid growth. The EU has set a binding target of a 20 percent renewable energy contribution to the final energy demand by 2020. This roughly equates to a 34 percent share of renewable energy sources in electricity generation in 2020. It is estimated that wind energy could contribute one-third of this production (Pryor and Barthelmie, 2010).

Aside from its role in mitigation, wind energy will also experience effects of climate change itself.

(Long-term) climate change impacts on wind energy

Wind energy, like many of the renewable technologies, is susceptible to climate change because the ‘fuel’ is related to the global energy balance and resulting atmospheric motion. Atmospheric conditions enter into the design and operation of wind turbines and wind farms largely under the rubric of ‘external conditions’. The wind climate governs the energy density in the wind and hence the power that can potentially be harnessed.

The wind resource is largely dictated by the upper percentiles of the wind speed distribution, which is further amplified by the non-linear relationship between incident wind speed and power production from a wind turbine (Pryor and Barthelmie, 2010). Given the energy in the wind is the cube of wind speed, a small change in the wind climate can have substantial consequences for the wind electricity resource. For a change in wind speed at turbine hub-height from 5.0 to 5.5 m/s (i.e. a 10 percent change), the energy density increases by over 30 percent.

The wind climate also governs aspects of the wind turbine design, via its governing role in wind turbine loading through, for example, turbulence intensity, wind shear across the turbine blades, and transient wind conditions such as the occurrence of extreme wind speeds and directional changes. Other atmospheric conditions that are of importance to the design, operation or power production from wind turbines include operational temperatures, air density, icing and corrosion and abrasion due to airborne particles.

Pryor and Barthelmie (2010) review literature about impacts of climate change in several parts of the world:

- Research using 'downscaling' of Atmosphere-Ocean General Circulation Models (AOGCMs) suggests that wintertime energy density in the wind may increase in the North of Europe by the end of the 21st century, but decrease in the south. The changes are small, though, and the findings not significant within natural variability;
- Empirical downscaling research in the USA shows modest declines (<3%) in mean wind speeds in the next 50 years, and less than 5 percent over the next 100 years;
- The wind resource in Brazil may experience much larger effects, showing a decline by up to 60 percent by 2100 under two SRES climate change trajectories. The result may partly stem from simplified assumptions for this study, though;
- No conclusive findings about changes in the variability of wind speeds exist.

Altogether, the findings point to a medium level of uncertainty, and suggest that the impact on wind energy will be less than for other electricity generation technologies. Moreover, the timeframe over which changes may occur is likely to be long (50+ years).

Geographical differences in impacts

Despite caveats signalled by Pryor and Barthelmie (2010), some generalisations may be drawn from research applying 'downscaling' of Atmosphere-Ocean General Circulation Models (AOGCMs) in the context of wind speeds and energy density over Europe. By the end of the 21st century there may be an increase in wintertime energy density in the north and a decline in southeast. This also appears to be true for annual mean wind speeds. This finding is consistent with a continued tendency toward the positive phase of the North Atlantic Oscillation, which is known to be a strong determinant of winter wind speeds in *northern Europe*, and poleward displacement of storm tracks. When the downscaling approach based on downscaling of the Weibull distribution parameters was applied to stations in northern Europe using a suite of Global Climate Models (GCMs) the results indicate an absence of significant changes in wind energy density to the middle of the 21st century, and that changes by the end of the century in the mean and 90th percentile wind speeds and energy density are small (<±10%) and comparable to the current variability manifest in downscaling from different AOGCMs, and natural variability within the climate system.

So-called empirical downscaling for *the USA* using linear techniques applied to output from two AOGCMs suggested modest declines (<3%) in mean wind speeds in the next 50 years, and less than 5 percent over the next 100 years. Research conducted in the northwest states of the USA using classification and regression trees methods in the transfer functions also indicate a decline in wind energy density during the summer, but little or no change in the winter under two climate change emission scenarios and output from four AOGCMs.

Pryor and Barthelmie (2010) also review impacts of climate change on wind energy in *Brazil*. This country has a large wind resource, which was shown to substantially decline by 2100 under two SRES climate trajectories in an analysis using the PRECIS model. The magnitude of the changes (a decline of up to 60 percent in the national resource), greatly exceeds changes reported for other regions of the world, and may derive partly from the simplifying assumptions employed in that study.

Variability of the wind resource

With regard to *variability of the wind resource*, Pryor and Barthelmie (2010) indicate that in light of evidence of changing storm tracks it seems probable that at least in some locations a change in inter- and intra-annual variability of the wind resource is likely, although one study of European wind indices based on output from a single GCM found no evidence of substantial changes in the intra- or inter-annual variability during the 21st century.

Impact on operation and maintenance and turbine design

With regard to the *impact on operation and maintenance of wind farms and turbine design*, Pryor and Barthelmie (2010) present the following main issues and possible impacts:

- Preliminary analyses from both dynamical and empirical downscaling over northern Europe exhibit some evidence for *increased magnitude of wind speed extremes*, and the same holds for central Europe. These findings are consistent with a tendency towards poleward displacement of storm tracks and fewer but more intense mid-latitude cyclones, though caution should be used in interpreting such analyses due to the difficulty in quantifying the occurrence of inherently rare events;
- *Icing on wind turbines* represents a major challenge to installation and operation of wind turbines in high altitudes and arctic latitudes. Data from turbines operating in Sweden and Finland indicate that severe icing can lead to turbine stoppages, and even modest accumulation of ice substantially reduces electrical power production, and significantly degrade annual power production. Indications are that between 9 and 45 percent of turbine downtimes in Finland may be attributable to icing events. Tendencies towards reduced icing frequency may mean sites previously deemed unsuitable for wind turbine deployment due to icing probabilities may become available for development. Also, recommendations have been formulated in the framework of IEA Wind Task 19 for constructing, operating and maintaining wind farms in cold climates (IEA, 2009);
- *Sea ice (drifting sea ice)* potentially greatly enhances turbine foundation loading and thus also represents a critical issue in deployment of wind turbines offshore. Studies of projected changes in sea ice days in the Gulf of Bothnia in the north Baltic Sea indicate a decrease from 130–170 days to 0–90 days in 2071–2100, with many areas becoming ice-free. A study conducted for the entire Baltic Sea indicated large changes in sea ice extent by the middle to end of the twenty-first century under two SRES climate change scenarios.

Other factors

Other factors addressed more briefly by Pryor and Barthelmie (2010) are:

- *Increasing air temperature*, e.g. an increase in air temperature of 5 °C, from 5 to 10 °C leads to a decrease in air density of 1–2 percent with a commensurate decline in energy density;
- *Extreme low and high temperatures* need to be considered in turbine selection and operation due to their ability to alter the physical properties of component materials;
- Other meteorological drivers of turbine loading such as v*ertical wind shear, directional distribution and turbulence intensity* may also be influenced by climate change but changes in these parameters are difficult to quantify;
- *Changes in land cover/land use* (and thus surface roughness length) may impact the future wind resource in some regions, although seasonal variability in surface roughness length were found to have a minor impact on wind resources in one study in northern Europe;
- Wind turbines are frequently in coastal locations and are being increasingly deployed offshore, particularly in Europe. Thus *changes in sea-level and/or salinity* may also be of importance. Sea level rise largely due to thermal expansion of 4.2 mm/year reported in the 4th Assessment

Report of the IPCC may have implications for wind turbines deployed in low-lying coastal areas in terms of foundation loading if flooding becomes more frequent. Corrosion is expected to decrease as the fresh water loading to the oceans increases;

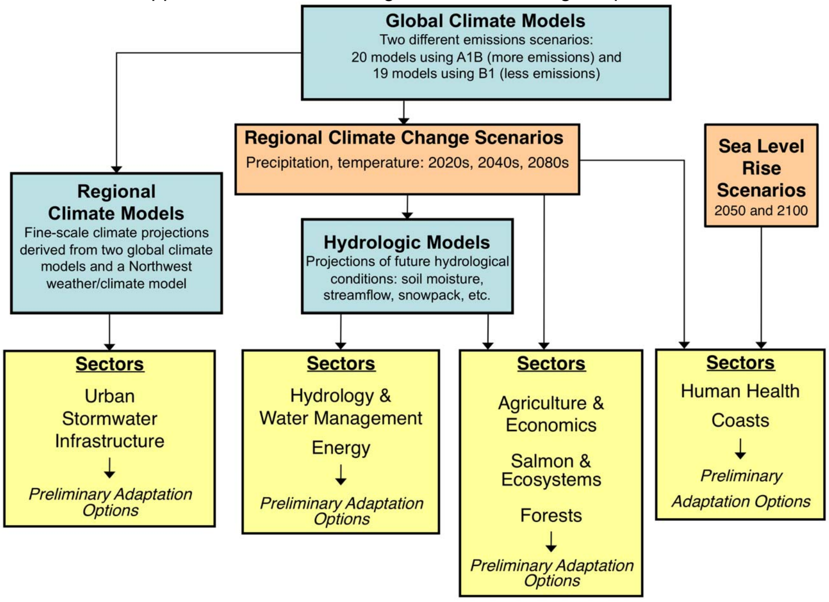
- An offshore wind turbine foundation is subject to the combined action of wind and wave loads, which in turn are a function of the wind speed and significant wave height. The wave state is in turn dictated in part by coupled wind-wave interactions, and thus may be modified by changing atmospheric circulation patterns. One study indicates that the *current 20-year return period wave* in the North Atlantic may occur every 4–12 years by 2080.

Hydropower generation

Introduction

Impacts from climate change on hydropower are related to glacier cover, precipitation patterns, and resulting changes in (annual) discharge and river run-off. Impacts are estimated using models, as exemplified by the figure below (Littell et al, 2009). The sensitivity of hydroelectric generation to changes in precipitation and river discharge is high: a 1 percent change in precipitation or river discharge typically results in 1 percent change in generation (ORNL, 2007). Due to climate change, *Northern Europe* may benefit from an increase in discharge and river run-off. Additional precipitation may benefit Belgium, the Netherlands, and the UK, as well as the Baltic and Nordic states. The potential for hydroelectric generation is hence expected to grow by more than 25 percent by 2050 and up to 30 percent by the 2070s (Alcamo, Moreno, and Nováky, 2007; Lehner, Czisch, and Vassolo, 2005), with the largest increases in Scandinavia (EEA, 2008).

Figure 29 Assessment approach for ‘The Washington Climate Change Impacts Assessment’



Source: Littell et al, 2009.

In contrast, the *Mediterranean* and even *Central and Eastern Europe* may experience a decrease in hydroelectric generation of around 25 percent by 2050 (Jochem & Schade, 2009) and up to 50 percent by the 2070s (Alcamo, Moreno, and Nováky, 2007). Hydropower is likely to suffer from reduced annual precipitation, especially in winter, due to changing climate patterns, except in the Alps and in Portugal where run-off water may raise hydroelectric generation. At the same time, Alpine run-off would become subject to greater intra-annual variability as summers grow hotter (Jochem & Schade, 2009).

Climate change impacts for various EU regions

Observations and projections based on Global Circulation Models (GCMs) show that water flow is decreasing in some regions of Europe and will further decrease in the future (Wolf and Menne, 2007). Studies show a decrease in summer flows in the Alps. The volume of summer low flow may decrease by up to 50 percent in central Europe, and by up to 80 percent around the Mediterranean. Therefore, regions most prone to an increase in water stress are the Mediterranean (Portugal, Spain) and some parts of central and eastern Europe, where the deficit volumes that occur once in a century may increase by 25 percent (Lehner et al., 2005) and the highest increase in irrigation water demand is forecast. Irrigation requirements are likely to become substantial in countries where they now hardly exist, partly influenced by changes in the amount and distribution of agricultural land as affected by the EU Common Agricultural Policy (CAP).

First climate change related effects on water status are to be expected from adding to the burden of existing anthropogenic pressures on water bodies, such as increased water abstraction because of higher summer temperatures, or increasing diffuse pollution due to increasing rainfall intensities (EU, 2009). It is expected that climate change will be fully integrated into the 2nd and 3rd river basin management (RBM) cycles of the EU's Water Framework Directive (WFD; EC, 2000). Specifically with regard to hydropower, the study (EU, 2009) gives the following recommendations:

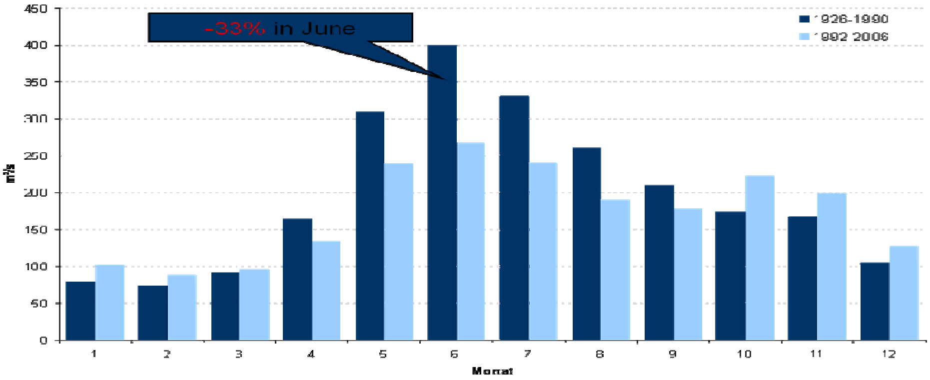
- Existing dams can also contribute to flood risk management. This should be recognised in flood risk assessment and management;
- Dams and reservoirs, if properly planned and managed, can be considered as an important part of integrated water management schemes under climate change conditions. Such dams are subject to operation licenses. The WFD requires that such permitting regimes of impoundments are regularly reviewed;
- Storage power plants have an important effect in reducing local floods, but run-of-river power plants can also have a positive effect, especially on smaller and medium flood events. The way the water flows are regulated in such rivers should take potential changed flood patterns into account, to make sure flood risk isn't increased, but rather decreased in the way the flow is managed.

Alpine region

The total installed hydro capacity of Verbund Austrian Hydro Power AG (Verbund-AHP) amounts to 6180 MW_e. Following reduced production of run-of-river-plants in the southern part of *Austria* compared to expectations, Verbund-AHP has analysed the causes (Verbund-AHP, 2008), and evaluated potential future changes, and the implications for its assets.

Verbund-AHP's observations during the last decades suggest that the average temperature is rising, precipitation patterns are changing – increasing in winter and decreasing in summer – and extreme weather events (strong rainfall, strong winds) are becoming more frequent. Verbund-AHP did not (yet) identifies an overall trend in hydropower generation in Austria, but in regions like Carinthia and Friuli (southern Austria) river discharge fell sharply and showed large seasonal variation. The discharge of the river Drau in Carinthia, for example, has decreased by 33 percent in June in the period 1992-2006, compared to 1926-1990 (see figure below showing the average discharges in Rosegg per month). No significant changes occurred in rivers north of the Alps. These observations match other documented climate trends in the Alps. Verbund expects that climate change will lead to further reduction of hydroelectric generation and availability due to avalanches, soil erosion, landslides and rock fall. Pumped storage plants in the high Alps will be most affected. Storm damage could also trigger power plant shutdown.

Figure 30 Discharge of Drau in run-of-river plant Rosegg, 1992-2006 vis-à-Vis 1926-1990



Source: Verbund-AHP.

According to Pašičko (2010), climate change will reduce hydropower generation in *Slovenia*:

- Lower precipitation means less water inflow to hydro reservoirs;
- Macro-scale hydrological models predict that production from Southern European hydropower will decrease between 20-50 percent by the 2070s (Lehner et al, 2005);
- Recent experience from new small hydro in Bosnia and Herzegovina show in some cases 20-30 percent lower power generation than planned (water flow data used mostly from 1970s).

The annual cost for replacement of a 35 percent loss of hydroelectric generation would be €65 million/a, if replaced by coal-fired power (€ 50/MWh) and € 117 million/a, if replaced by imported electricity (€ 84/MWh).

The installed hydropower capacity in *Switzerland* exceeds 11,000 MW. Switzerland's Fifth National Communication under the UNFCCC (FOEN, 2009) assumes that until 2050, warming will be similar on the northern and on the southern side of the Alps, with a median value for the temperature increase of +1.8 °C in winter and +2.7-2.8 °C in summer. And according to (ETH, 2009), no big changes concerning overall amounts of precipitation are expected within the near future. However, this does not affect the probability of regional differences.

Schaefli, Hingray and Musy (2007) assess climate change impacts on water resources in detail, incorporating a range of potential climate change scenarios, and quantifying related modelling uncertainties. Their analysis pertains to the hydropower plant of Mauvoisin in the Southern Swiss Alps, which generates about 1 TWh/a (1.5 percent of total Swiss hydro generation). Their results show that an increase in temperature over the whole year and a decrease in annual precipitation leads to significant reductions of the ice-covered area and available water in the system, see the table below.

Table 29 Median and 5% / 95% confidence limits of indicators in periods 1961-1990 and 2070-2099

		Control period			Future period		
Indicator name		5%	50%	95%	5%	50%	95%
Reliability	[%]	87.3	88.2	89.2	47.3	64.2	74.3
Resilience	[%]	31.3	33.2	35.2	11.7	13.3	17.7
Vulnerability	[%]	2.4	2.6	2.8	6.8	9.9	14.4
Efficiency	[%]	99.5	99.6	99.7	98.3	99.0	99.0
Production - Absolute	[GWh]	246.2	246.5	246.8	102.7	158.5	188.2
Production - Relative	[-]				0.417	0.643	0.763
WinterProd	[%]	62.7	63.0	63.4	56.1	58.6	60.2
Spill	[%]	0.00	0.00	0.00	0.00	0.06	0.25
Overtopping	[%]	0.00	0.00	0.00	0.00	0.00	0.00

Source: Schaefli, Hingray and Musy, 2007.

Compared to the median hydropower production for the control period (1961-1990), the median future production (2070-2099) corresponds to a decrease of 36 percent. The water use efficiency, however, remains more or less constant for the future period; the loss of hydropower production is exclusively due to the significant decrease in available water through the decrease in precipitation and ice melt and the increase in evapo-transpiration.

The hydropower production undergoes a shift of about 7 percent from winter to summer production due to a modification of the prevalent hydrological regime. This regime modification partly explains the decrease in the release reliability, as planned releases during the winter months can no longer be met and production in summer months is sometimes higher than planned. There is significant increase in the release vulnerability, the average difference between planned and actual release through the turbines. The control median value of 2.6 percent corresponds to around 70 MWh production difference between planned and actual production whereas the future median value of 9.9 percent equals around 269 MWh.

The worsening of the release vulnerability is accompanied by occasional spillway activation. In the most extreme climate change scenario, stimulated discharge through the spillway is 177.4 m^3/s, whereas the maximum discharge recorded before the dam construction amounted to some 59 m^3/s (45 years of data). In the median climate change scenario (+2.6°C), the maximum spill is 60 m^3/s, similar to the discharge before dam construction.

Another study focuses on a hydroelectric scheme in the Rhone generating 1.8 TWh/year (~3% of total Swiss hydro generation) (Westaway, 2007). Based on a model of the Lac des Dix, Westaway (2007) shows that climate change – incurring a temperature increase of 1.4°C in the period 2031-2060 – will have the greatest effect on the discharge and run-off. Both experience an increase and are predicted to occur for a greater part of the year. Evaporation is predicted to show a slight year-round increase, while no clear change is found for precipitation. As a result, total water inputs to the reservoir increase significantly (by 35%), while annual water outputs experience little change (an increase of 2 percent). This produces an average monthly pattern of reservoir level similar to that at present, but with a steeper rising limb, and more months when Lac des Dix is estimated to be full (June to September). The results indicate that hydroelectric generation might increase by 25.6 percent, based on the aforementioned temperature increase of 1.4°C and an increase of annual precipitation of 2.6 percent. However, because the reservoir is nearly full in the summer, most extra water simply ‘runs off’ without generating additional energy, unless the reservoir volume would be increased.

Mediterranean region

Mimikou and Baltas (1997) present an assessment of climate change impacts on critical water management issues such as reservoir storage and hydroelectric production for *Greece*. Two equilibrium scenarios referring to the years 2020, 2050 and 2100 and one transient scenario referring to the years 2032 and 2080 were applied to present both 'greenhouse gas' warming and induced changes in precipitation and potential evapo-transpiration. By using these scenarios, the sensitivity of the risk associated with the hydroelectric generation of a large multipurpose reservoir in northern Greece has been evaluated under conditions of altered runoff. They observe increasing risks associated with the annual quantities of electricity production. To maintain the same reliability for the minimum and average yields, reservoir storage must increase by 12 percent and 38 percent in 2050, respectively in the so-called 'equilibrium scenarios'. In the 'transient scenario', the required increases are 25 percent and 50 percent in 2080, respectively.

Furthermore, climate change will have significant impacts on hydroelectric generation in *Turkey*. Since the beginning of the 1960s, the North Atlantic Oscillation (NAO) has shown a steadily rising trend in the 1990s. This trend accounts for a significant portion of wintertime temperature increase and recent warming over the northern Eurasia and cooling in the Mediterranean and Black Sea regions. In winters affected by a strong NAO, Turkey receives less rain and reduced volume of stream flows. For example, the spring stream flow in the Euphrates River varies by about two-folds with the NAO index. Global warming will likely cause a steady decline in water supply and concomitant hydroelectricity in southern Europe (including Turkey).

Biomass electricity generation

A number of feedstock and conversion technology combinations exist to produce electricity from biomass. Biomass can be combusted in stand-alone applications in dedicated biomass-based power plants where the heat produced by combusting biomass in a boiler can be used to generate electricity via a steam turbine or engine or in combined heat and power (CHP) plants, where the waste heat is recovered and used in an economic application (IEA Bioelectricity, 2009). Biomass can also be co-fired at different proportions (usually up to 25-30 percent) with fossil fuels in standard thermal power plants, solid biomass (mainly wood and agricultural residues) with coal and vegetable oils in gas-fired stations. Other emerging options for producing biomass-based power include waste-to-energy plants, anaerobic digestion and gasification (IEA Bioelectricity, 2009).

The most common biomass-to-power conversion routes are thus thermal processes similar to conventional coal-based power production. Hence, most of the preconditions for successful power production are the same, especially in the case of biomass co-firing (please refer to section 2.2.2 for more details). The main specific preconditions for all of the above mentioned conversion routes are a steady supply stream of biomass feedstock of consistent quality.

Biomass supply differs fundamentally from the supply of fossil fuels in that it is subject to the same factors that affect the supply of agricultural and forestry commodities, including meteorological phenomena, advances in plant yields, pests, forest management practices etc. Furthermore, biomass has many competing uses. In Europe, energy use already accounts for almost half of total wood use (mainly for heat production in private households and heat and/or power production in industries), with this trend projected to increase (Mantau et al., 2007). Meanwhile, several other growing industries (fibre board, paper, construction etc) require forest-based biomass as raw material leading to demand for wood outstripping domestic supply and increasing imports. Several competing sectors also represent a constant pressure on wood prices.

Securing a steady supply of sufficient biomass feedstock, including significant logistical issues, is therefore one of the biggest challenges for biomass-based power production.

Climate change is expected to have a manifold influence on the supply of biomass. It will influence the potential for bioelectricity through its effects on land use patterns and biological productivity (Mideksa & Kallbekken, 2010). Of all the types of biomass used for energy, wood contributes the majority and therefore should be monitored closest in terms of climate change impacts (on power production). With regard to forest-biomass, most modelling experiments project that moderate temperature growth as projected by climate models, will positively impact the global forest sector, increasing timber supply and flattening or reducing the prices (Kirilenko & Sedjo, 2007). However, the reliability of such predictions is limited by factors such as pests, weeds, competition for resources, soil water, air quality, etc., which are still not well implemented in leading models (Kirilenko & Sedjo, 2007).

In any case, large differences between regions are expected, whereby some regions are likely to experience an increase in biomass supply, while others, especially regions projected to become hotter and drier can face a reduction. Kellomaki (2007) estimates that in Finland, the availability of biomass-for-energy from logging residues alone may increase more than 200 percent as a result of climate change.

Besides climate change, forest management is also likely to increase the production of wood for energy. Karjalainen et al (2003) assume that active forest management will increase felling across Europe (for a number of different reasons) by 0.3 percent per annum until 2020-2030 and stabilize afterwards. An increase in felling means a proportional increase in wood residues, which is one of the preferred biomass feedstocks in power production.

Photovoltaic electricity generation

Introduction

Only few studies assess the climate change impacts on photovoltaic power (PV). This may be related to the characteristics of PV, i.e. a relatively fast growing renewable energy source (as compared to mature renewable energy sources like hydropower). For PV panels mounted on roofs or building integrated PV negative impacts, e.g. due to increased wind speeds during storms, may be relatively small. Large PV plants built in Southern Europe on land without agricultural use may be vulnerable to strong winds, but this can be accommodated by slight design changes for the mounting structure.

Here, projections are used based on (Pašičko, 2010) for Slovenia (which is assumed to *be* representative of the Mediterranean) and by (Fidje and Martinsen, 2006) for Scandinavia (which is assumed to be representative of Nordic and Baltic countries). Furthermore, Contreras-Lisperguer de Cuba (2008) in an analysis of climate change impacts on e.g. renewable energy in the Caribbean region refers to research on the potential change in solar irradiance in the USA due to increases of atmospheric greenhouse gases (Pan et al, 2004). Indeed, the latter authors find significant changes in solar irradiance in 2050 due to climate change over the entire country. Most parts of the US have reduced solar irradiance with decreases typically 0-20 percent. The most noticeable decreases are in fall, winter and spring in the mountainous region of the western US. In the winter, spring, and summer, increases in solar irradiance of up to 15 percent are simulated in the southern US. An increase in solar irradiance of up to 8 percent in summer was simulated in the northern US. These results may be a yardstick for changes in solar irradiance to be expected on our continent. In addition, the results of scoping analysis by (Pašičko, 2010) for Slovenia and by (Fidje and Martinsen, 2006) for Scandinavia are presented.

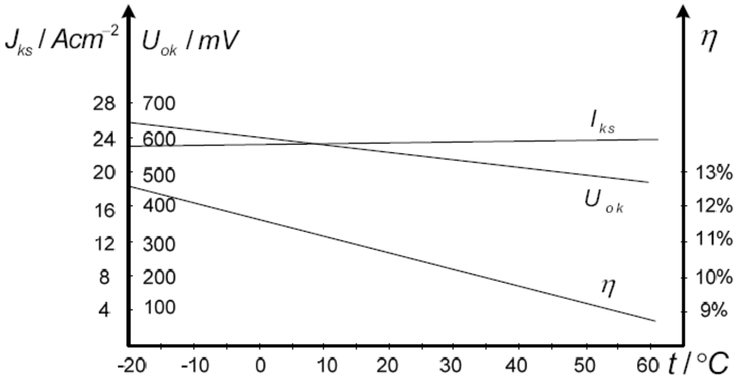
Scoping analysis for PV systems in Slovenia

(Pašičko, 2010) presents a scoping analysis of climate change impacts on (operation of) PV systems in Slovenia. According to (Pašičko, 2010), the impacts of climate change on PV are fourfold:

- Ambient temperature;
- Number of days under snow cover;
- Solar irradiance;
- Extreme events.

The figure below shows the relationship between efficiency of a PV cell and the ambient temperature. Pašičko (2010) concludes that for crystalline silicon based cells, for each 1°C temperature raise the cell efficiency decreases by 0.4-0.5 percent in relative terms. The ‘cell temperature coefficients’ differ according to technology and producer (efficiency, power, current, voltage), though.

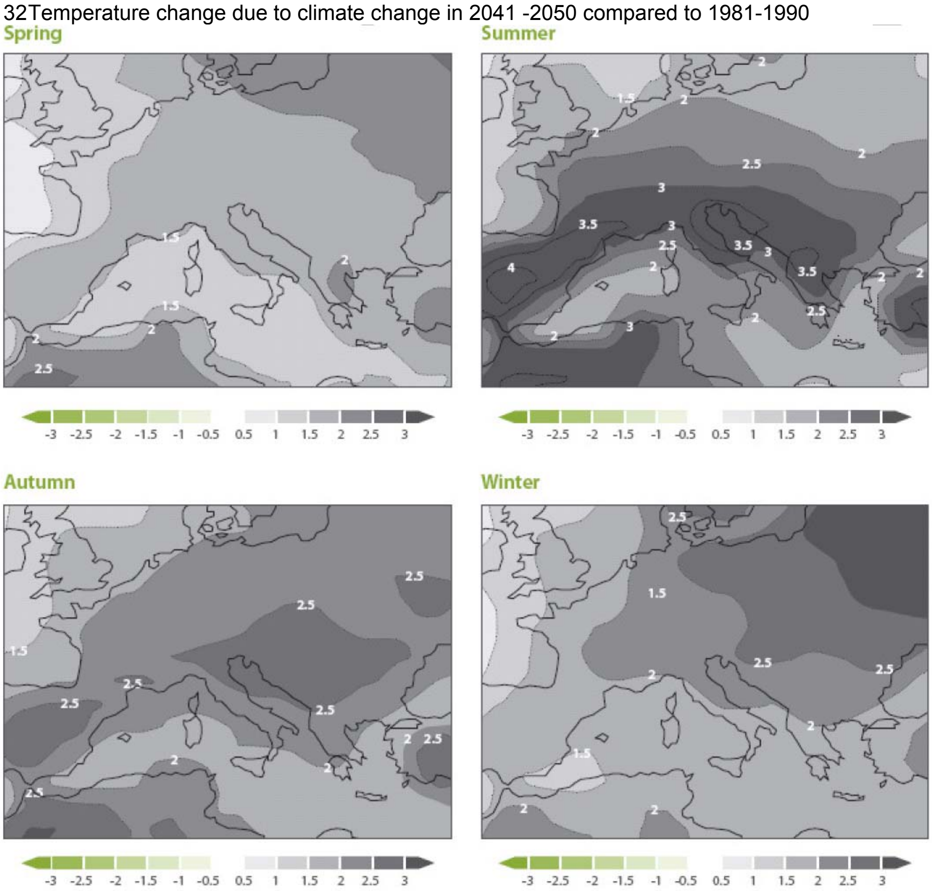
Figure 31 Relation between ambient temperature and efficiency of PV cells.



Source: Pašičko, 2010.

Pašičko (2010) also presents a figure of the expected temperature change in the period 2041 -2050 compared to 1981-1990 (see figure below).

Figure 32Temperature change due to climate change in 2041 -2050 compared to 1981-1990

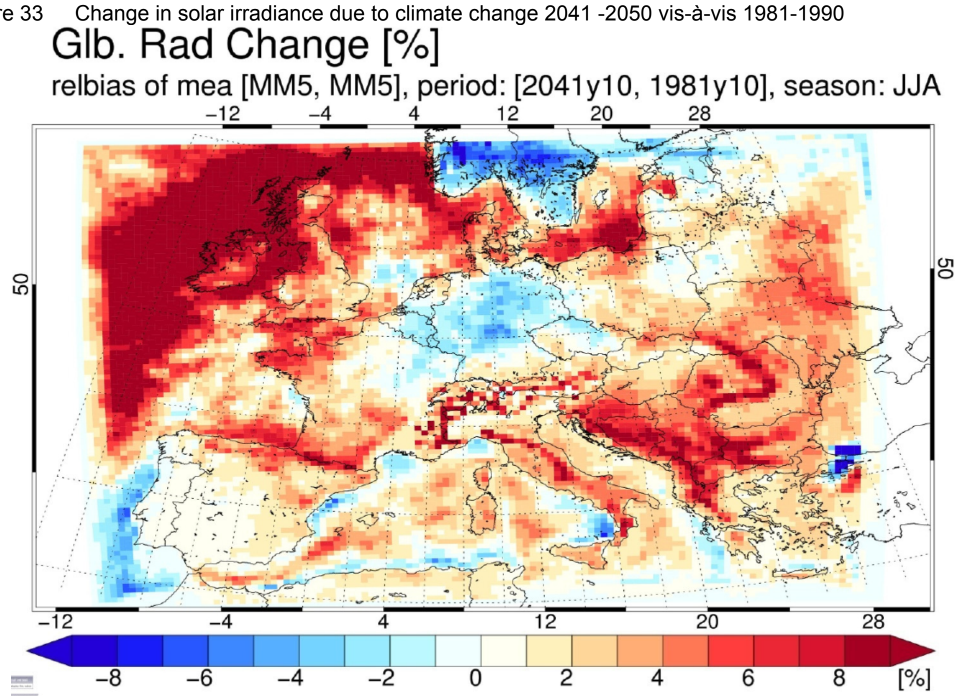


Source: Pašičko, 2010.

The *ambient temperature* may rise by up to 4°C in Spain in the summer and 1 to 2.5°C in other seasons. Assuming an 'effective' temperature increase of 2°C for Mediterranean countries - factoring in the large share of solar energy in the summer compared to other seasons - the impact on the efficiency of solar cells in the Mediterranean would be -1 percent, e.g. a reduction from 15 percent to 14 percent efficiency.

The figure below shows Pašičko's projections for solar irradiance in summer.

Figure 33 Change in solar irradiance due to climate change 2041 -2050 vis-à-vis 1981-1990



Source: Pašičko, 2010.

The solar irradiance, the sum of direct and diffused radiation, is influenced by cloud cover. In the Mediterranean, solar irradiance may increase by 5-10 percent in summer and autumn, and by -2 percent to +8 percent in spring, partially offsetting large increases in summer and autumn. Therefore, the increase of solar irradiance in the Mediterranean may be +7 percent on average (for Slovenia +8 to +10 percent). As the yield of PV is proportional to the solar irradiance, the yield would increase by 7 percent on average.

Pašičko (2010) expects few projected changes with regard to *snow cover* for Slovenia.

Overall, PV systems will probably receive more solar energy because of 10 percent less precipitation and higher temperatures in winter, meaning fewer days with snow cover.

Extreme events would have only minor effects on PV in Slovenia:

- Higher temperatures and less precipitation will result in more forest fires which may affect PV systems; the risk is hard to quantify, but can be reduced by choosing appropriate locations for PV;
- Expected increase in strong winds and storm events can impact PV panels if not considered in the design.

Scoping analysis for PV systems in Norway

(Fidje and Martinsen, 2006) analysed the impact of climate change on solar energy (PV) in Scandinavia, making use of IPCC scenarios for the period 2071-2100. The ambient temperature increase ranges from 2.5-3.0°C in Trondheim (Norway) to 4.6-4.7°C in Helsinki (Finland). According to Figje and Martinsen (2006), this temperature increase would not affect the yield of PV systems.

In contrast to the projections for the Mediterranean, the solar irradiance in Scandinavia is expected to decrease by 2 percent. According to the authors, there are other factors that negatively impact the yield of solar PV, e.g. decreased reflection due to less snow cover, a disproportionate decrease in diffuse solar irradiation which relatively strongly impacts the yield due to a higher reflection of the diffuse component of diffuse solar irradiation compared to direct solar irradiation. The combined effect would entail a reduction of the yield of PV systems of 6 percent.

Concentrating Solar Power (CSP)

Introduction

Concentrating solar power (CSP) plants are categorised according to whether the solar flux is concentrated by parabolic trough-shaped mirror reflectors (30-100 suns concentration)[33], central tower receivers requiring numerous heliostats (500-1000 suns), or parabolic dish-shaped reflectors (1000-10,000 suns). The receivers transfer the solar heat to a working fluid, which, in turn, transfers it to a thermal power-conversion system based on Rankine, Brayton, combined or Stirling cycles. To give a secure and reliable supply with capacity factors at around 50 percent rising to 70 percent by 2020[34], solar intermittency problems can be overcome by using supplementary energy from natural gas- or coal-fired power as well as by storing surplus heat (IPCC, 2007). By 2009, the global capacity of CSP stood at 606 MW_e, 70 percent of which in the USA and the balance in Spain.

Solar thermal power plants are confined to lower latitudes in areas receiving high levels of direct insolation. In these areas, 1 km^2 of land is enough to generate some 125 GWh/year from a 50 MW_e plant at 10 percent conversion of solar energy to electricity. Thus about 1 percent of the world's desert areas (240,000 km^2), if linked to demand centres by High Voltage Direct Current (HVDC) cables, could, in theory, be sufficient to meet total global electricity demand as forecast out to 2030. (IPCC, 2007) puts the global technical potential of CSP at 630 GW_e installed by 2040 or 4,700 GW_e by 2030.

The most mature of CSP technologies is the parabolic trough technology with a maximum (peak) efficiency of 21 percent (conversion of direct solar radiation into electricity). CSP tower technology has been successfully demonstrated by two 10 MW_e systems in the USA with the prospect of giving long-term levelised electricity costs similar to trough technology. Future technologies include troughs with direct steam generation or molten salt as the heat transfer medium, Fresnel collectors using flat mirrors may reduce costs by 20 percent, energy storage including molten salt, integrated combined-cycle systems and advanced Stirling dishes. The latter are getting renewed interest and may provide opportunities for further cost reductions.

CSP is based on mirrors, either in the solar trough configuration or in the solar tower configuration. Alternatively, Compact Linear Fresnel Reflector (CLFR) technology may be applied, which shows resemblance to parabolic trough technology. CSP plants may be integrated into a natural gas-fired combined cycle (CC) power plant, resulting in a hybrid solar/natural gas-based power plant. Also, with the use of thermal energy storage (TES) system, CSP plants may store excess thermal heat collected during periods of high solar radiation and shift the electricity output to periods where little or no solar radiation is available (i.e. evenings), providing medium or base load instead of intermittent power. Energy storage technology is an important adjunct to the solar generation, enabling the capacity factor to be extended. It has been a significant advantage of the CSP technology over the photovoltaic units.

Parabolic trough technology

Parabolic trough technology is the most common type of mirror-based systems. A parabolic trough is a solar concentrator that follows or tracks the sun around a single rotational axis. Sunlight is reflected from parabolic-shaped mirrors and is concentrated onto the receiver tube at the focal

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[33] The term 'suns concentration' for concentrating solar power as well as concentrating PV refers to the concentration factor compared to normal sunlight.

[34] Integration of CSP in, e.g., a combined cycle (CC) based on gas may increase the capacity factor to 70% in 2020.

point. Synthetic heat transfer oil is pumped through the receiver tube and is heated to approximately 400°C. The oil transports the heat from the solar field to the power block where high-pressure steam is generated in a series of heat exchangers, and used to drive a conventional steam turbine.

In the 1980s and 1990s, nine commercial-scale CSP plants were built and operated in the California Mojave desert. The capacity ranges from 14 to 80 MW_e and their combined capacity is 354 MW_e. Most CSP plants built since then are trough plants. Large fields of parabolic trough collectors supply thermal energy used to produce steam for a Rankine steam turbine cycle.

Solar tower technology

Parabolic trough technology is the most widely applied technology with commercial-scale plants in the USA and Spain. Also, it is currently the technology of choice for countries like Algeria, Egypt, India, Iran, Mexico and Morocco. *Solar tower based CSP* is next in line in terms of development stage. On tower systems, a heliostat field comprised of movable mirrors, is oriented according to the solar position in order to reflect the solar radiation concentrating it up to 600 times on a receptor located on the upper part of the tower. The heat is transferred to a fluid to generate steam and drive a generator (see figure below). Currently, the maximum steam temperature of solar tower CSP plants is 550°C and the maximum steam pressure is 160 bar, well in excess of corresponding parameters of parabolic trough plants. Therefore, solar tower CSP plants are more energy efficient than parabolic trough plants. They may also be equipped with the added capability of heat storage, which gives them 6,500 hours/year of full-load hours (capacity factor ~75%).

Figure 34 Parabolic through CSP plant

Source: DOE, 2009.

Figure 35 Solar tower CSP plant (Abengoa)

Source: Ausra, 2007.

Compact Linear Fresnel Reflector (CLFR) technology

A third option based on a Compact Linear Fresnel Reflector (CLFR) is a variant of parabolic trough technology. A linear system using elevated long steam pipe receivers is illuminated by long heliostats below. Concentrated sunlight generates saturated or superheated steam for use in power generation. CLFR technology builds on the experience with troughs and towers, and may be cost effective. Several plants are under construction (Ausra, 2007; Mills and Morgan, 2008).

Figure 36 Compact Linear Fresnel Reflector CSP plant

Source: Ausra, 2007.

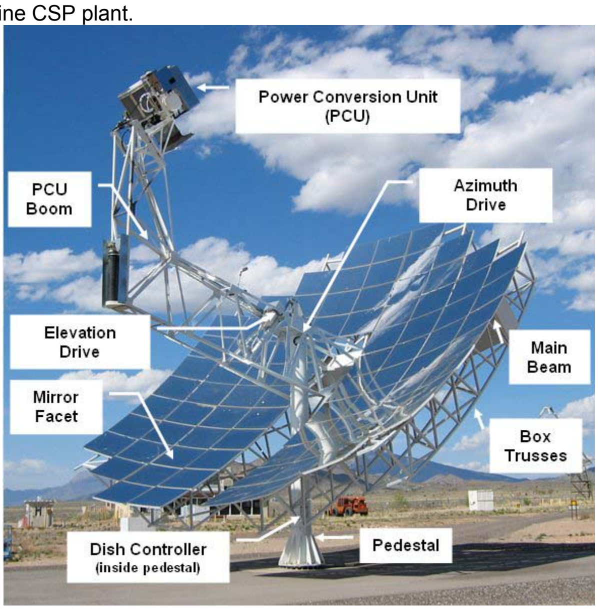
Stirling engine technology

Finally, CSP may be based on solar dish technology making use of Stirling engines. Parabolic central receiver dishes reflect sunlight onto a focal point above the dish, while also tracking the sun. Most dishes have a small generator at the focal point. They do not require a heat transfer fluid or cooling water, and boast the best solar-electric conversion rate among CSP systems. The dish receivers reach up to 649°C. They are small in size, i.e. with a capacity of 25 kW_e. Generally, a number of dishes are combined for electricity production. The so-called Suncather has a yield per unit area of 629 kWh/m^2 (260 kWh/m^2 for parabolic troughs). The technology also lays claim to significantly lower water usage than other CSP technologies. It appears to be suitable for smaller scale projects of 50MW_e and below rather than for large-scale power generation.

A 750 MW_e CSP plant based on solar dish technology will be built in California (REW, 2010):

- 30,000 solar dish Stirling systems (SunCatcher) of 25 kW_e each;
- Designed to automatically track the sun (two-axis tracking);
- Collecting and focusing solar energy onto a power conversion unit (PCU) - Stirling engine - which drives a generator;
- Sited on 2424 ha of land in Imperial County, California.

Figure 37 Stirling engine CSP plant.



Source: Ausra, 2007.

Figure 38 Artist's rendering of multi-MW dish-engine CSP Field

Source: NREL, 2007.

Possible climate change impacts

Cooling water

The main impact of climate change on Concentrating Solar Power plants is reduced availability or absence of cooling water. This problem can be more serious than for conventional thermal power stations, as CSP plants are usually located in arid regions already suffering from water shortages, while thermal plants are located with cooling needs in mind. CSP plants are designed with either wet or dry cooling systems, but if water availability decreases dry cooling may be favoured.

Al-Soud and Hrayshat (2009) state that from a technical point of view the most efficient cooling technology is cooling via evaporation. The most cost efficient cooling technology mainly depends on the cost for water at the site. Since best sites are generally located in the desert, local competition over water is often already fierce. Dry cooling provides an alternative, using enforced convection through a fan. Dry cooling is *inter alia* favoured for CSP in Jordan, which suffers from water shortages. Dry cooling has in principle three drawbacks: higher parasitic losses, lower steam-cycle efficiency and higher investment costs, quantified in the table below.

Table 30 Comparison of cooling technologies for 50 MW parabolic through CSP plant without storage

Cooling technology		Wet cooling	Dry cooling
Steam cycle efficiency	[%]	37	35
Parasitic energy consumption	[MW]	5	7
Electricity yield	[GWh]	117	109
Evaporated water	[m^3/MWh]	3 [a]	-
Investment	[million $US\$_{2008}$/MW]	~ 4.800	~ 5.000

Source: Al-Soud and Hrayshat, 2009; IEA, 2010.

According to Al-Soud and Hrayshat (2009), the total investment cost of a 50 MW_e CSP plant would be 170 million JD ≈ 240 million US$ ($ 4,800/kW_e). The difference in cost between dry and wet cooling is approximately $200/$kW_e$.

CSP plants are preferably placed in deserts, where water is too scarce to be used for cooling, and additionally, vapour plumes from cooling towers can shadow the collectors. Instead, dry cooling can be used, using ambient air as cooling medium. Dry cooling will increase the construction costs (3-6%) as well as operation and management costs (1-3%), and decrease the performance (5-9%) of the plant, costs varying widely with site specifications. Even if dry cooling is used, there can still be minor water requirements, for collector washing, boiler make-up in steam cycles etc (Pihl, 2009).

A number of future CSP plants in the Mediterranean region will also be built with dry cooling. Also, the solar dish technology (based on Stirling engines) lays claim to significantly lower water usage than other CSP technologies. This technology, however, is not as well as developed as other CSP technologies. As arid lands are most appropriate for CSP plants, there tend to be few competing land uses, so that the main competition is over water. It may therefore be necessary to apply cooling technology with low cooling water demands, even without considering impacts of climate change. Consequently, climate change impacts on future CSP projects will probably be relatively minor, as the need for low cooling water demands is already factored in at the design of the plan.

More frequent or vehement storms

Another impact of climate change may be more frequent or vehement storms. This may impact the support structure. The support structure, which is typically made of metal, holds the mirrors in accurate alignment while resisting the effects of the wind. More frequent or vehement storms may be accommodated by slightly more robust design, which will presumably not incur significant costs.

A.5 Electricity transmission and distribution facilities

Safe and reliable electricity networks

A climate-proof grid is essential for a reliable[35] electricity system, as electricity networks form the link between supply facilities and end users and are as such essential for an effective supply of power. If a single power plant fails, others can fill the gap, but alternative network routes are not always available. Moreover, supply and demand must be balanced, excessive voltages and frequency fluctuations must be avoided, and the systems should not pose a threat to health, safety or the environment. This means that operating temperature must be kept at safe levels, grids should not be interrupted, and maintain a safe distance from people and buildings.

[35] Two common measures of network reliability exist. The System Average Interruption Frequency Index (SAIFI) represents the share of connected customers that experiences power interruption in a given year. The System Average Interruption Duration Index (SAIDI) indicates the average outage time per connected customer. Usually, neither includes storm-related outages (Peters et al, 2006).

Climate conditions affect this in four ways – through wind and storms, temperature, drought and flooding. For the purpose of this analysis, network infrastructure is divided into lines and nodes. The nodes consist of facilities like substations, generating facilities and demand centres. They are connected by lines, usually overhead transmission lines or underground cables.

Wind speed and storms

Network operators are most concerned about a potential increasing frequency of high winds and storms due to climate change. This can cause serious damage, toppling pylons and downing overhead lines, as has already occurred in the past:

- RWE Netz had to re-enforce 28,000 pylons of its transmission grid following icy winter storms in 2005. This cost the company €500 million;
- France suffered severe storms in January 1999, with gusts of up to 200 km per hour, during which 3.5 million customers lost power. The resulting costs to EdF were €1.1 billion (Peters et al, 2006);
- In the Netherlands, five pylons of Tennet's transmission grid were blown over in a thunder storm in July 2010. The pylons were installed in 1971, and should have lasted 50 to 100 years. Tennet has since engaged in a comprehensive analysis of the potential impacts of climate change on electricity transmission.

Table 31 Impacts of increasing wind speed and storms on electricity networks

Impact	System affected	Threshold	Level of impact	Area affected
Wind and storm damage	Overhead lines and pylons	Variable	Variable: estimates range from €1.600 per fault to €17,000 per pylon and attached lines	North sea & Baltic
Increasing heat convection	Overhead lines	Continuous	+20% possible load (A) with each m/s rise in wind speed	North sea & Baltic

Network operators in vulnerable areas are prepared for such events, and most systems are fairly resilient already. Moreover, storm disruption is often highly localised, so that only a small share of electricity supply is affected, if power flows can be re-routed. For example, one respondent expects that even with a 50 km/h (13.8 m/s) increase in wind speed 90 percent of electricity could still be transported.

Strengthening networks to prevent storm damage is considered important by several network operators in (Western) Europe. In France, RTE is improving the 'mechanical security' of its network following extensive storm damage in 1999. By 2017, it will have strengthened 45.000 km of overhead lines, and developed a strategy to restore power within five days if outages occur. The €2.4 billion programme is already bearing fruit. In January 2009, during storms comparable to the 1999 event, outages occurred on only half the number of overhead lines and one-third of the number of substations (RTE, 2010).

Threshold values for wind and storm damage are difficult to define, and the costs of the damage vary widely, depending on the design of the grid and the local environments. Maximum design wind speed ranges from around 130 km/h for older lines to 180 km/h for critical lines in vulnerable areas (Peters et al, 2006). Damage cost estimates range from €1,600 per fault for a single line breakage (Martikainen et al, 2007) to €17,000 per pylon and attached lines in cases of widespread disruption (ADAM, 2009).

Increasing wind speeds can also have a minor positive effect on overhead lines. Provided winds remain below damage levels, stronger winds help cool overhead lines by increasing heat convection. Lines can then carry a larger electric load while staying within temperature limits (usually 80°C). Additional capacity can be as much as 20 percent for each m/s increase in wind speed (Verbund Austrian Power Grid, 2005).

Temperature

Electricity networks are also affected by temperature. The regulated maximum temperature at which network equipment is bounded is usually 80°C, at the conductor surface. If this is exceeded, overheating can damage the systems and poses a fire hazard. Apart from safety concerns, network capacity declines with rising temperature, as the resistance of metals increases and the systems sooner reach their maximum operating temperature.

The safe load on network technologies decreases when ambient temperature rises, because the systems sooner reach their maximum operating temperature. The capacity of transformers, for example, can decrease by up to 1 percent for each 1°C (Martikainen et al, 2007). Similarly, the resistance of copper lines increases by approximately 0.4 percent for each 1°C. Altogether, network capacity falls by around 1 percent for each for each 1°C. Consequently, network losses can increase 1 percent if temperature increases 3°C, in a network with initial losses of 8 percent (IEA, 2008).

Table 32 Impacts of increasing temperature rises on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
De-rating	Transformers	Continuous	Approx. -1% load per °C rise	All, especially Mediterranean
Decreased conductivity	Overhead lines & underground cables	Continuous	Resistance increase approx. 0.4% for each °C temperature rise -0,5 to -1% line load (A) per °C rise	All, especially Mediterranean
Sag	Overhead lines	50°C	Approx. 4.5 cm per °C rise at the conductor surface[36].	All, especially Mediterranean
Thawing permafrost	Substations & pylons	Variable with local conditions	Potentially full loss of supply locally	Baltic

Regulation specifies a minimum ground clearance for transmission lines to limit potential harmful effects of magnetic fields[37]. This can be exceeded when the material expands with temperature, so that sag of the line increases. The extent of sagging depends on the conductor material; the span width and other environmental conditions like wind-speed. For conventional aluminium cables it is approximately 4.5 cm per 1°C rise at the conductor surface.

In Nordic regions, higher temperatures can cause permafrost to thaw. Consequently, the foundations of network assets like substations that are built on permafrost can start to shift and break up, necessitating major repairs. In extreme cases the whole substation must be rebuilt. This problem is limited to the sparsely populated North of Scandinavia.

36 Taking a conventional aluminium conductor at an ambient temperature of 35°C and a span of 400 m (Pink, 2010).

37 Transmission lines create magnetic fields in their direct environment. The impact of these fields on humans and the environment is still disputed, but regulation stipulates that overhead lines must pass at a minimum distance from the ground and surrounding buildings as a precaution. Typically, minimum layout clearances range from 7.0 meter for medium voltage (110 – 132 kV) to 9.5 meter for extra-high voltage (>330 kV).

Drought

Drought due to changing precipitation patterns and/or increasing evaporation may cause soil around underground cables to dry out[38]. This lowers the conductivity of the cable, and thereby the carrying capacity. Cable rating can drop by up to 29 percent if the soil around it dries out thoroughly (Gouda et al, 1997). This starts when the surface temperature of the cable reaches around 55°C, depending on soil conditions. Ambient air temperature must rise above 30 - 35°C for this to happen (Gouda et al, 1997).

Table 33 Impacts of drought on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
Moisture migration	Underground cables	>55°C at cable surface	-29% cable capacity	All, especially Mediterranean
Dry soil movement	Underground cables	Variable	Repair costs approx. €3.200 per fault[39]	All, especially Mediterranean

Underground cables can be damaged as a result of dilatation and underground soil movement in extremely dry soils during droughts. In August 2003, 4,000 people in the Bordeaux region of France were left without power for several hours as a result.

Flooding

Flooding can increase in areas of Europe as a result of climate change because of changing precipitation patterns and extreme weather events. Northwest Europe, and the British Isles in particular, are vulnerable.

Network assets in flood-prone areas can be damaged during flooding. Like storms, these are inherently infrequent events, so a general threshold at which damage occurs, and their impact varies with local conditions. At worst, floods disrupt all electricity supply locally, and the effects spread into the network, leading to outages in areas unaffected by the water. At best, damage remains restricted to a few minor assets, and supply can be re-routed. The impacts of supply at a national level are limited in most cases. Extreme flooding due to extreme precipitation (for example, a doubling of average precipitation over a short period) or significant sea level rise (0,5 m) would affect only 0-10 percent of supplies in most countries.

Flooding has been a particular concern in the UK because of flood events in 2007[40]. Since the events of 2007, National Grid has reviewed flood risk of its transmission infrastructure, finding that 28 electricity substations are at significant risk (greater than 1 in 75 risk of flooding in any year). When designing new substations, it now evaluates local flood contour information from the Environment Agency. It is also investing in mobile flood defences to provide interim cover for low-probability events (House of Commons Select Committee, 2008).

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38 Such 'moisture migration' occurs automatically as heat dissipated by the cables causes water to move away from the surrounding soil.

39 Martikainen et al, 2007.

40 In June 2007, National Grid's Neepsend substation in South Yorkshire was flooded, affecting supply to the CE Electric distribution grid and 36,000 domestic and commercial customers lost supply (House of Commons Select Committee, 2008). The subsequent month, the company prevented such extensive impact when Walham substation in Gloucester came close to flooding. Long-lasting damage to the transformers and switchgear could only be avoided through placing sandbags and continuous pumping for several days.

Table 34 Impacts of flooding on electricity networks

Impact	Systems affected	Threshold	Level of impact	Area affected
Inundation	Substations	Varies with local conditions	Potentially 100% loss of supply locally	North sea & Baltic
Cable breakage	Underground cables	Varies with local conditions	Potentially 100% loss of supply locally Repair costs from €3.200 per fault[41]	North sea & Baltic

Underground cables can be damaged when flooding causes ground to subside. As with soil movement due to drought, local conditions determine the level of risk and potential damage.

[41] Martikainen et al, 2007.

Annex B Climate change scenarios

In this Annex the datasets for the selected climate change scenarios are presented. The below tables represent the data from the WIND, TEMP and RAIN respectively.

In the column 'Specified effect' the selected variable from the Climate Data Explorer is mentioned, as well as the abbreviation and the proxy for which climate effect the variable has been selected.

Table 35 Climate change scenario data Wind scenario – WIND

Effects	Climate zones	Specified effect	Years		
			2020	**2050**	**2080**
Δ water temperature	Region A	oC change water temperature sst (Sea Surface Temperature) [K]	0,97	1,75	2,83
	Region B		0,83	1,30	2,00
	Region C		1,08	1,93	3,01
	Region D		1,04	1,97	2,88
Δ air temperature	Region A	oC change air temperature tas (2-meter Temperature) [K]	0,98	1,74	2,88
	Region B		0,83	1,32	2,07
	Region C		0,58	1,82	3,00
	Region D		1,05	1,93	2,91
Δ precipitation	Region A	% change precipitation pr (Precipitation) [kg m-2 s-1]	4,85%	5,29%	4,82%
	Region B		2,69%	-2,45%	-6,10%
	Region C		-1,35%	0,74%	-7,51%
	Region D		-4,92%	-1,14%	-13,27%
Δ average wind speeds	Region A	[m s-1] change wind speeds wss (10-meter Wind Speed) [m s-1]	0,010	0,005	-0,011
	Region B		0,075	0,006	0,008
	Region C		-0,003	0,005	-0,004
	Region D		-0,031	-0,016	-0,080
Δ sea level	Region A	m change water level Average temperature *0.13 (based on IPCC scenario)	0,12	0,22	0,35
	Region B		0,12	0,22	0,35
	Region C		0,12	0,22	0,35
	Region D		0,12	0,22	0,35
Occurrence of floods	Region A	% change in floods prls (Large-scale Precipitation) [kg m-2 s-1]	8,74%	15,67%	24,10%
	Region B		7,84%	13,17%	21,06%
	Region C		10,26%	17,27%	30,28%
	Region D		10,47%	18,70%	29,14%
Occurrence of heat waves	Region A	% change in heat waves tasmax (Daily Maximum 2-meter % change reported with respect to 10 oC	8,74%	15,67%	24,10%
	Region B		7,84%	13,17%	21,06%
	Region C		10,26%	17,27%	30,28%
	Region D		10,47%	18,70%	29,14%
Occurrence of storms	Region A	% change in storm intensity wsgsmax (10-meter Daily Maximum Wind Speed incl. Gust) [m s-1]	8,74%	15,67%	24,10%
	Region B		7,84%	13,17%	21,06%
	Region C		10,26%	17,27%	30,28%
	Region D		10,47%	18,70%	29,14%

Table 36 Climate change scenario data Temperature scenario – TEMP

Effects	Climate zones	Specified effect	Years		
			2020	2050	2080
Δ water temperature	Region A	oC change water temperature sst (Sea Surface Temperature) [K]	1,74	3,01	4,20
	Region B		1,06	2,10	3,03
	Region C		2,13	3,24	4,91
	Region D		1,07	2,38	3,64
Δ air temperature	Region A	oC change air temperature tas (2-meter Temperature) [K]	1,73	3,01	4,23
	Region B		1,08	2,08	3,02
	Region C		2,04	3,12	4,72
	Region D		1,10	2,41	3,67
Δ precipitation	Region A	% change precipitation pr (Precipitation) [kg m-2 s-1]	6,46%	11,58%	14,31%
	Region B		0,16%	-1,31%	-0,23%
	Region C		0,48%	3,01%	-0,47%
	Region D		1,47%	-9,80%	-11,43%
Δ average wind speeds	Region A	[m s-1] change wind speeds wss (10-meter Wind Speed) [m s-1]	0,007	0,012	-0,017
	Region B		-0,009	-0,036	-0,096
	Region C		0,044	-0,038	-0,016
	Region D		-0,019	-0,130	-0,121
Δ sea level	Region A	m change water level Average temperature *0.13 (based on IPCC scenario)	0,19	0,35	0,51
	Region B		0,19	0,35	0,51
	Region C		0,19	0,35	0,51
	Region D		0,19	0,35	0,51
Occurrence of floods	Region A	% change in floods prls (Large-scale Precipitation) [kg m-2 s-1]	17,30%	30,14%	42,29%
	Region B		10,78%	20,84%	30,25%
	Region C		20,43%	31,21%	47,17%
	Region D		11,03%	24,10%	36,74%
Occurrence of heat waves	Region A	% change in heat waves % change reported with respect to 10 oC wrt surface temperature (tas)	17,30%	30,14%	42,29%
	Region B		10,78%	20,84%	30,25%
	Region C		20,43%	31,21%	47,17%
	Region D		11,03%	24,10%	36,74%
Occurrence of storms	Region A	% change in storm intensity vas (10-meter V wind; N-ward) [m s-1]	17,30%	30,14%	42,29%
	Region B		10,78%	20,84%	30,25%
	Region C		20,43%	31,21%	47,17%
	Region D		11,03%	24,10%	36,74%

Table 37 Climate change scenario data Precipitation scenario – RAIN

Effects	Climate zones	Specified effect	Years		
			2020	**2050**	**2080**
Δ water temperature	Region A	oC change water temperature sst (Sea Surface Temperature) [K]	0,29	1,49	2,42
	Region B		0,24	0,86	1,46
	Region C		0,52	1,33	2,41
	Region D		0,41	1,17	2,19
Δ air temperature	Region A	oC change air temperature tas (2-meter Temperature) [K]	0,34	1,71	2,93
	Region B		0,39	1,06	1,98
	Region C		0,58	1,56	2,94
	Region D		0,59	1,48	2,90
Δ precipitation	Region A	% change precipitation pr (Precipitation) [kg m-2 s-1]	2,70%	5,95%	11,98%
	Region B		-0,25%	-1,56%	1,57%
	Region C		-0,28%	-0,95%	2,94%
	Region D		-2,12%	-5,40%	-11,41%
Δ average wind speeds	Region A	[m s-1] change wind speeds wss (10-meter Wind Speed) [m s-1]	0,024	0,043	0,083
	Region B		0,015	-0,047	-0,056
	Region C		0,062	0,000	0,046
	Region D		0,062	-0,047	-0,036
Δ sea level	Region A	m change water level Average temperature *0.13 (based on IPCC scenario)	0,05	0,17	0,31
	Region B		0,05	0,17	0,31
	Region C		0,05	0,17	0,31
	Region D		0,05	0,17	0,31
Occurrence of floods	Region A	% change in floods prls (Large-scale Precipitation) [kg m-2 s-1]	3,22%	16,05%	27,48%
	Region B		4,20%	10,51%	19,59%
	Region C		6,05%	15,73%	29,30%
	Region D		6,19%	15,17%	29,81%
Occurrence of heat waves	Region A	% change in heat waves tasmax (Daily Maximum 2-meter % change reported with respect to 10 oC	3,22%	16,05%	27,48%
	Region B		4,20%	10,51%	19,59%
	Region C		6,05%	15,73%	29,30%
	Region D		6,19%	15,17%	29,81%
Occurrence of storms	Region A	% change in storm intensity wsgsmax (10-meter Daily Maximum Wind Speed incl. Gust) [m s-1]	3,22%	16,05%	27,48%
	Region B		4,20%	10,51%	19,59%
	Region C		6,05%	15,73%	29,30%
	Region D		6,19%	15,17%	29,81%

Annex C Electricity scenarios

C.1 Validation electricity scenarios with alternative scenarios

The Consortium has validated both Eurelectric projections against the DG Energy projections to 2030 that were published in 2010 (Capros et al., 2010). This provides insight into the implications of the results of the study for DG ENER's own data for the power sector. This annex describes the result of the validation.

DG Energy baseline scenario

The DG Energy baseline is an update of the previous trend scenarios, such as the European energy and transport - Trends to 2030 published in 2003 and its 2005 and 2007 updates. The Baseline 2009 was finalized in December 2009.

The economic context has dramatically changed since the 2007 baseline scenario, due to the economic downturn in 2008. Energy and electricity demand dropped rapidly as a result. The baseline scenario determines the development of the EU electricity system to 2030, taking account of current trends on population and economic development and the highly volatile energy import price environment of recent years. The scenario includes all concrete national and EU policies and measures implemented until April 2009, such as the ETS and several energy efficiency measures, but the renewable energy targets and the non-ETS obligations will not necessarily be achieved.

The 2009 Baseline, takes into account electricity efficiency gains, penetration of new technologies and renewable energy, as well as changes in the electricity mix driven by relative prices and costs.

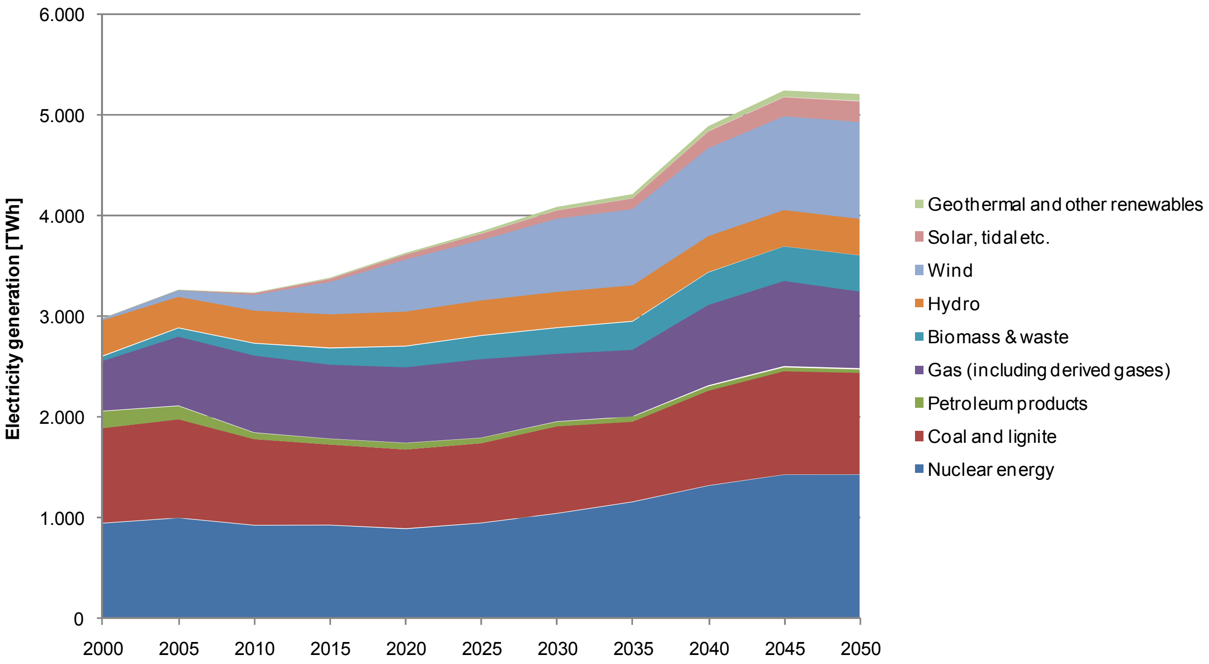
Despite the slower growth of electricity demand than in the 2007 analysis, installed power plant capacity grows in the baseline scenario, to meet the still increasing demand and replace obsolete plants that are decommissioned:

- Coal and lignite generation decreases significantly, ending up at 22% of total generation in 2030, compared to 33% currently;
- Gas-fired generation grows, but its total market share declines slightly;
- Nuclear energy remains roughly stable to 2030, but the nuclear shares in Baseline 2009 are higher than in Baseline 2007, because ETS prices drive higher nuclear investment, and the plans for building new nuclear power plants in the UK, Italy and Poland;
- Renewable energy generation grows considerably, becoming the largest source of generation in 2020 (26%), and account for almost one third of generation in 2030. This is 9.2% higher than in the 2007 baseline. Onshore wind, offshore wind and solar power are the main renewable sources.

Eurelectric Power Choices scenario

Meeting the ambitions of the Power Choices scenario requires a radical decarbonisation of the electricity sector to reduce greenhouse gas emissions by 75%. This is achieved by increasing the contributions of renewable energy, nuclear power and CCS, and making electricity use more efficient. Power generation from renewable sources rises most rapidly, ending up more than 400 TWh higher than in the baseline case in 2050. Nuclear and coal with carbon-capture and storage (CCS) grow substantially in the latter half of the 40-year period. Energy becomes a major fuel for heating and transport, so that the overall power demand grows. At 5,214 TWh, overall demand is therefore 526 TWh higher than in the baseline in 2050.

Figure 39 Electricity generation in the EU-27 to 2050 in the Power Choices scenario



Methodology for the comparison

Up to 2030, the DG Energy data could be compared directly with the Eurelectric scenarios. Beyond that, the extrapolation was required to determine the expected developments in the four regions to 2050. For this, the Consortium used the existing NTUA projections to 2050 (Capros et al., 2007) to project development in supply and demand for the whole of the EU. The trends leading up to 2030 provided the main guidance for dividing this over the four regions, ensuring a smooth transition between the DG Energy projections and the extrapolated data.

The EU-27 projection to 2050 by the NTUA formed the starting point of the extrapolation, which followed in three stages:

- First, it established the distribution of electricity generation over the four regions for each technology in 2030, according to the DG Energy projection for that year. For instance, 12% of nuclear power would be generated in the Baltic region, 55% in the North Sea region, 16% in the Central and Eastern region, and 17% in the Mediterranean region in 2030;
- Secondly, the EU-27 projection was divided between the regions per technology between 2030 and 2050, assuming that the regional shares remain constant during that period[42]. For instance, the Baltic maintains its 12% share of nuclear power generation, but the total production grows with the EU total. This yields projections for power generation per region to 2050 in GWh per year;
- Lastly, the forecast for power generation was converted to installed capacity (in MW), assuming that the capacity factor for each technology per region remains as in 2030.

Results of the comparison

The Eurelectric Baseline and Power Choices scenarios present more radical decarbonisation of the European electricity sector than the DG Energy projections. However, they follow similar paths until 2030. In Eurelectric's scenarios, total electricity demand is slightly higher, while fossil fuel generation plays a smaller role, compensated by a larger contribution of renewable energy.

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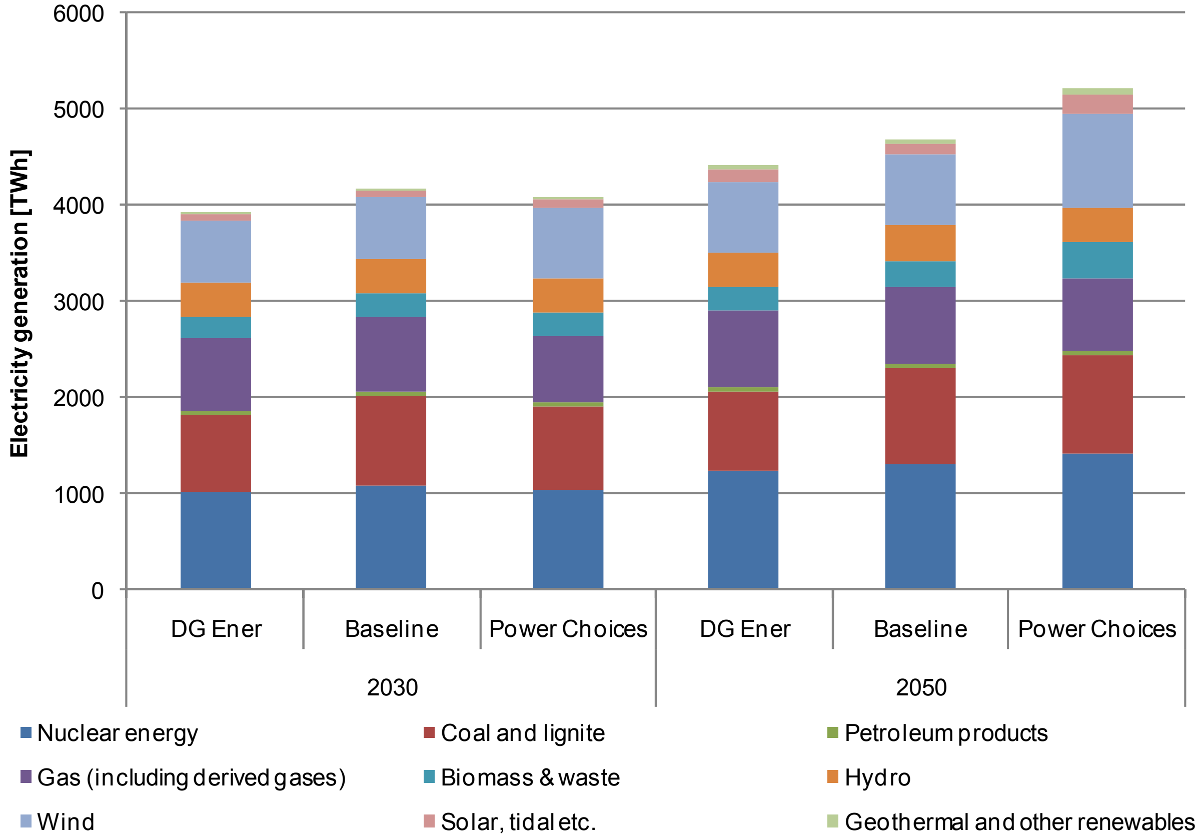
42 The relative shares of different sources have changed little over the 2000 to 2030, so the assumption was made that radical changes are unlikely in the subsequent 20 years.

Figure 40 Electricity generation in the EU-27 in the three scenarios in 2030 and 2050



The defining differences emerge between 2030 and 2050. Electricity demand expands significantly in the Power Choices scenario, as transport and heating are largely electrified. Total power generation in 2050 is 5,214 TWh, about 800 TWh higher than in the extrapolated PRIMES scenario. With 4,688 TWh, the Eurelectic baseline is in between the two other cases.

In Power Choices, carbon-emitting power sources have replaced low-carbon alternatives. Baseload electricity from coal and lignite plants is about 200 TWh lower, compensated primarily by nuclear power. All renewables grow rapidly, so they account for 38% of total generation, compared to 34% in the extended PRIMES scenario, despite the larger total power production. Wind, hydro and biomass dominate, with 967 TWh, 366 TWh and 356 TWh respectively. Solar and geothermal make smaller contributions, but are still 74% and 58% higher than in the extrapolated PRIMES scenario. The Eurelectric baseline also has more nuclear and renewables than the extended PRIMES scenario, but decarbonisation is not as radical as in Power Choices.

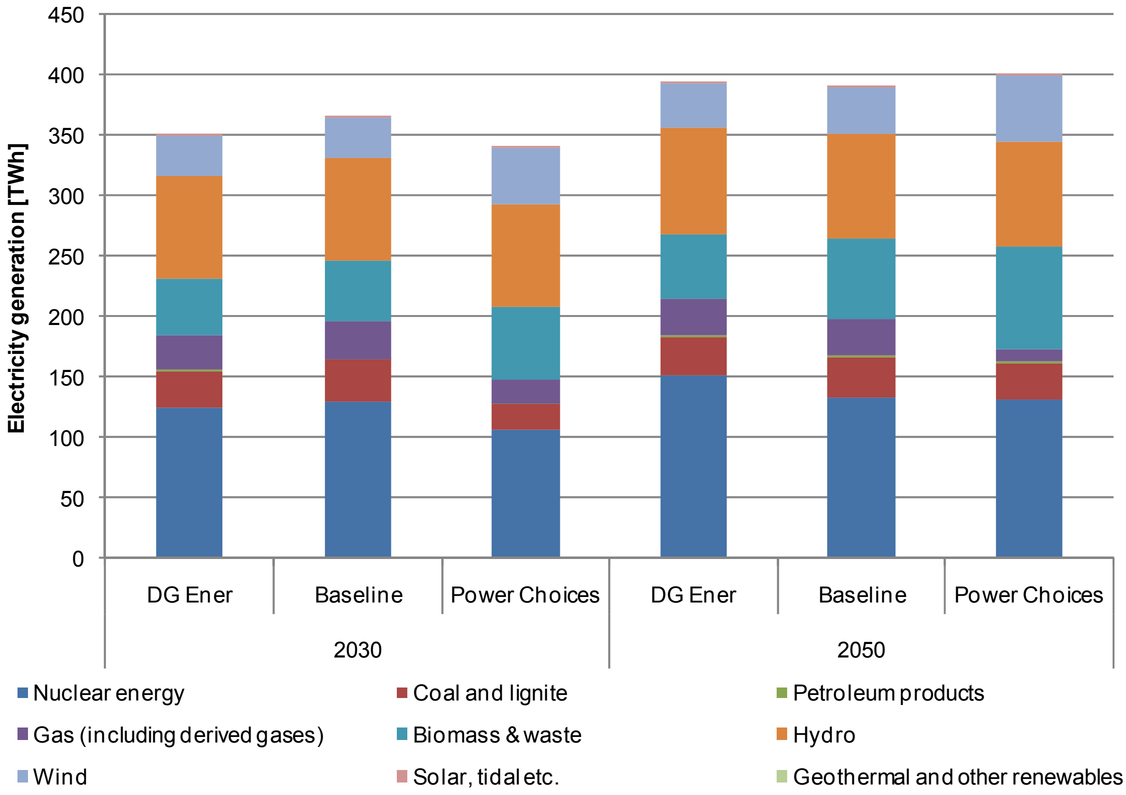
The distribution of total power generation between the regions in 2030 is broadly comparable the three scenarios. Two-thirds of electricity is produced in the North Sea and Central and Eastern regions. Nuclear power is mainly in northwest Europe (roughly 55%), while about 60% of coal and lignite energy is produced in the Central and Eastern regions. The Mediterranean leads in generating electricity from gas (41% of the EU-total), solar (~45% of the EU-total), and geothermal (~48% of the EU-total). The Baltic produces only around 5% of wind electricity in 2030, while the remainder is evenly distributed over the other regions. Biomass and hydro are shared equally between the four regions.

In the Power Choices scenario, the Mediterranean increases its contribution to overall EU electricity generation from 25% to 28% between 2030 and 2050, but the distribution between the other regions remains as in 2030. Nuclear power grows everywhere, but the contribution of the North Sea region declines form 56% to 49%. The relative distribution of coal, lignite and gas power generation shifts from Eastern Europe to the North Sea region. The Mediterranean region expands its share of total EU wind and solar electricity generation, ending up at 30% and 57% in 2050 (respectively). The regional distribution of biomass, hydro and geothermal remains broadly as in 2030.

Baltic region

In the Baltic region, total generation is highest in the Eurelectric baseline, followed by the DG Energy scenario Power Choices. In Power Choices, fossil power production is smallest too, being compensated by biomass power and wind power. The Eurelectric baseline has the highest contribution from nuclear power.

Figure 41 Electricity generation in the Baltic region in the three scenarios in 2030 and 2050

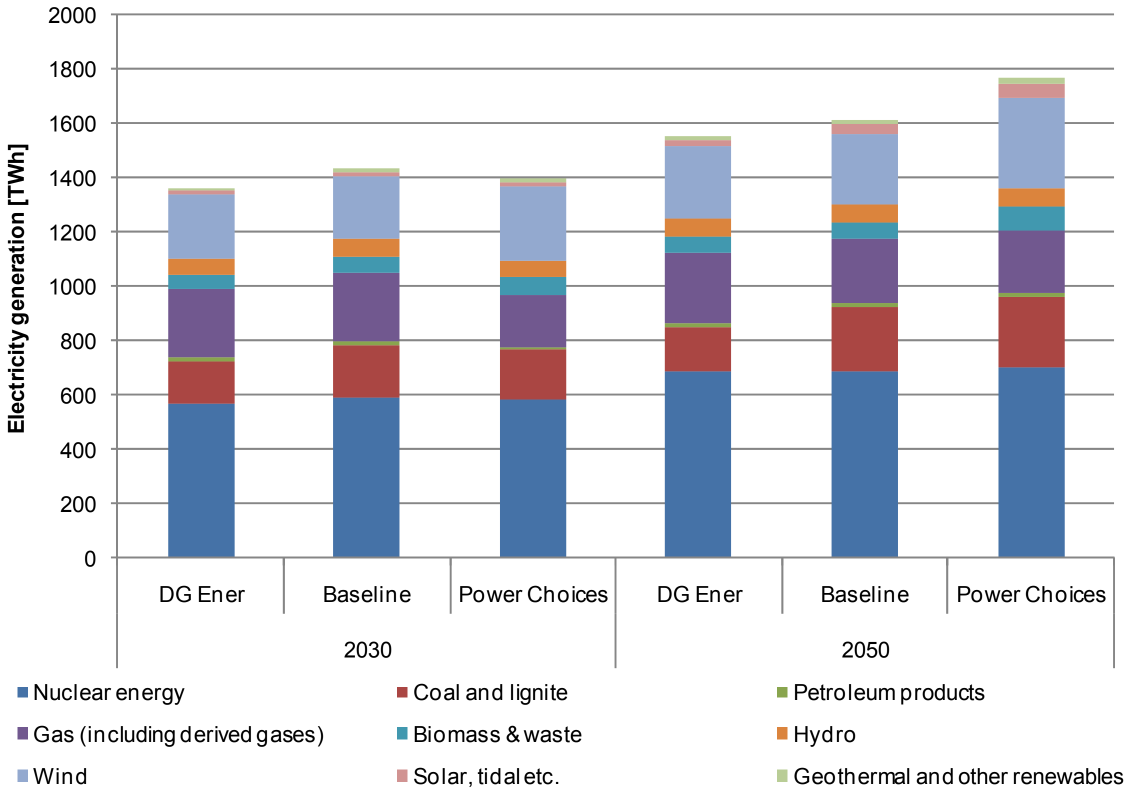


By 2050 the Power Choices scenario has overtaken the baseline and extrapolated PRIMES scenario in terms of power generation, reaching 401 TWh (around 80 TWh higher than the other two). Nuclear plays a larger role in the extended DG ENER case (20 TWh higher), while Eurelectric places more emphasis on renewable electricity generation. In Power Choices, the most extreme case, biomass energy is 32 TWh higher than in the DG ENER scenario, and wind power 16 TWh.

North Sea region

Electricity generation around the North Sea in Eurelectric's scenarios is not much different from DG Energy's projections in 2030. Total generation is slightly higher, mainly due to the uptake of CCS, which allows for more coal power production. Wind and biomass also play a larger role, while Power Choices expects less gas-fired electricity than the other two cases (~60 TWh lower).

Figure 42 Electricity generation in the North Sea region in the three scenarios in 2030 and 2050

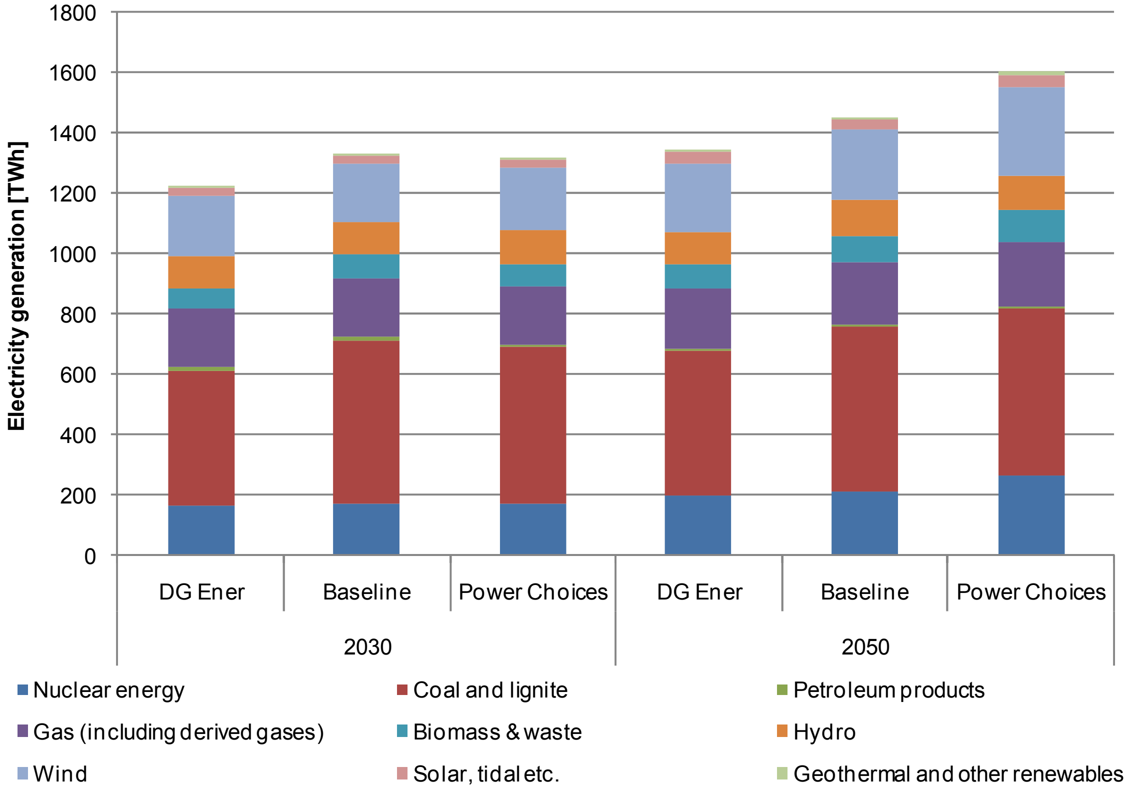


By 2050, Power Choices expects the electricity sector to have expanded rapidly in northwest Europe, producing 1,766 TWh electricity each year, or 16% more than in the extrapolated PRIMES scenario and 9% more than the baseline. According to Eurelectric, the sector has also decarbonised more, replacing coal, lignite and gas power plants by nuclear power and renewable energy. In both the baseline and Power Choices, wind becomes a major source of energy, second only to nuclear power. Projected generation from biomass and solar also exceed those in the extended PRIMES scenario.

Central and Eastern European region

The difference between Eurelectric's scenarios and the DG Energy projections to 2030 is largest in the Central and Eastern region. Eurelectric expects that overall generation will reach 1,320 to 1330 TWh, compared to 1,219 TWh in the DG Energy case. Nuclear, coal and biomass all contributed to the extra 100 TWh.

Figure 43	Electricity generation in the Central and Eastern European region in the three scenarios in 2030 and 2050

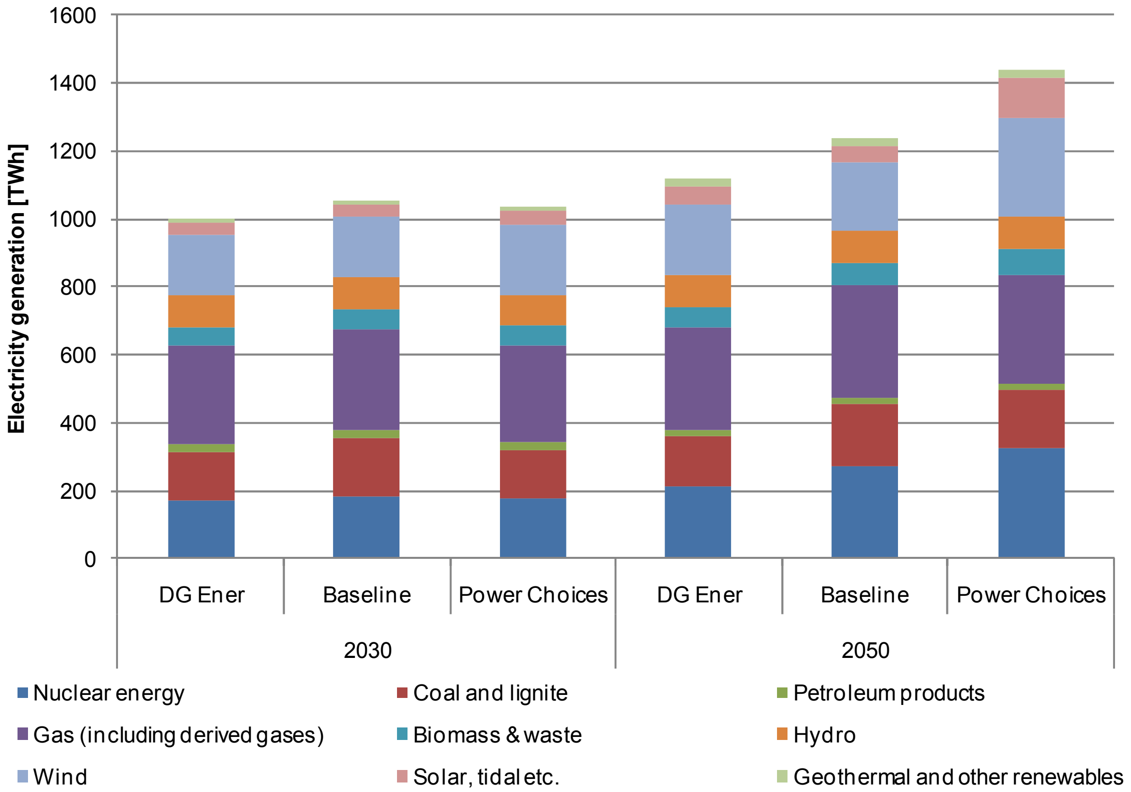


In Power Choices, the growth of electricity generation continues, so that in 2050 1,607 TWh is produced annually. Total generation is only 1,369 TWh in the extrapolated DG ENER case, and 1,447 in the baseline. Eurelectric expects that generation from all baseload power options are larger than in the DG Energy scenario. The difference is largest in Power Choices, where nuclear is 33% higher, coal 17%, and natural gas (+6%) are also higher. Renewable power generation in the DG Energy case and Eurelectric baseline is comparable, but 90 to 100 TWh higher in Power Choices, mainly because wind and biomass produce more. Surprisingly, Eurelectric expects less solar power than the extended DG Energy projection.

Mediterranean region

The projections for the Mediterranean are comparable in the three scenarios to 2030. Total generation is slightly higher in the Eurelectric projections. The additional energy comes from coal and lignite in the baseline, and from wind and solar in Power Choices.

Figure 44 Electricity generation in the Mediterranean region in the three scenarios in 2030 and 2050



According to Eurelectric, electricity production in the Mediterranean will grow rapidly between 2030 and 2050, particularly in Power Choices, ending up at 1,440 TWh, 28% higher than according to the extrapolated DG ENER projection. All sources of energy contribute to the higher total. Power Choices expects a radical shift towards nuclear power, growing from 179 TWh to 326 TWh from 2030 to 2050, overtaking gas on the way (319 TWh in 2050). In Eurelectric's projections, coal and lignite maintain their share of total generation due to the deployment of CCS, ending up between 170 and 180 TWh in 2050, which is about 15% higher than in the extended PRIMES. Power Choices has higher hopes for renewables in the Mediterranean than the other two cases. Wind and solar lead the way to generate 288 TWh and 117 TWh in 2050, both substantially higher than in the other cases.

C.2 Nuclear electricity scenarios

Based on the electricity baseline scenario described above, the Consortium has developed two additional scenarios for the uptake of nuclear power: a high nuclear and a low nuclear case. A range of existing nuclear electricity projections has been analyzed for this work.

National policies
National policies on the use of nuclear power have an important impact on the future deployment of the nuclear energy technology. In the last 10 years, many European countries that had turned away from nuclear energy have started reconsidering its use, and have decided or are debating extending the lifetime of existing plants, and/or building new ones. The following tables show the current status of the nuclear energy capacity, the number of nuclear reactors and national policies regarding nuclear electricity generation by region and Member State (based on De Jong, 2010).

Baltic region

Developments in Finland and Sweden will determine the future of nuclear energy power in the Baltic region (Table 38). Finland is already expanding its installed base, and will continue to do so in the future. The present Swedish government plans to replace the existing plants, and is considering expanding its fleet in the future. The realization of these plans depends on the preferences regarding nuclear of new coalition government, following the general elections of last 19 September. Pro-nuclear parties won the elections, but failed to obtain an overall majority. Overall capacity is expected to grow in the Baltic region.

Table 38 Current installed capacity and nuclear policy in the Baltic region

Country	Capacity 2010 [GW_e]	Number of reactors	Policy
Denmark	0	0	No nuclear electricity
Estonia	0	0	No nuclear electricity
Finland	2.7	4	Expand installed capacity
Latvia	0	0	No nuclear electricity
Lithuania	1.1	1	Maintain installed capacity
Sweden	9.0	10	Maintain installed capacity, possibly expansion of capacity

North Sea region

Both France and the UK are planning an expansion of nuclear power over the next 20 years (Table 39), so that the role of nuclear energy will grow in the North Sea region. Due to the long time-to-market of nuclear power plants, the increase is unlikely to start before 2018, when EDF expects its first new plants to be ready, and the UK governments aims to have the first new plants commissioned. Until then installed capacity will probably decline slightly.

Table 39 Current installed capacity and nuclear policy in the North Sea region

Country	Capacity 2010 [GW_e]	Number of reactors	Policy
Belgium	5.8	7	Lifetime extension
France	63.4	59	Lifetime extension of existing plants and expand existing capacity
Ireland	0	0	No nuclear electricity
Luxembourg	0	0	No nuclear electricity
Netherlands	0.49	1	Lifetime extension of existing plants, possibly expand existing capacity
UK	11	17[43]	Lifetime extension of existing plants and expand existing capacity

Central and Eastern region

Bulgaria, the Czech Republic, Hungary, Poland, Romania and the Slovak Republic are all planning to build new nuclear power plants in the next 10 years, but developments in the Central and Eastern region hinge on the future of nuclear power in Germany, which has the largest installed capacity by far (Table 40).

[43] The four reactors of the Magnox plant are not included in the UK total, as these are to be decommissioned soon (before 2015).

The German government has expressed a preference for extending the lifetime of the existing plants by around 8 to 15 years, and the possibility to build reactors has not been ruled out. Opponents of nuclear power exist in all major parties, though, so a nuclear renaissance is by no means secured. With the expected lifetime extension, capacity in this region would increase to beyond 2030 at least.

Table 40 Current installed capacity and nuclear policy in the Central and Eastern region

Country	Capacity 2010 [GW_e]	Number of reactors	Policy
Austria	0	0	No nuclear electricity
Bulgaria	1.9	2	Lifetime extension of existing plants and expand existing capacity
Czech Rep.	3.7	6	Lifetime extension of existing plants and expand existing capacity
Germany	20.5	17	Lifetime extension
Hungary	1.9	4	Lifetime extension of existing plants and expand existing capacity
Poland	0	0	Lifetime extension of existing plants and expand existing capacity
Romania	1.3	2	Lifetime extension of existing plants and expand existing capacity
Slovak Rep.	1.8	4	Lifetime extension of existing plants and expand existing capacity

Mediterranean region

To date, nuclear power has played a minor role in the power supply in the Mediterranean, but this may change in the next 40 years. In the long term, nuclear capacity in the Mediterranean could grow strongly.

Spain is the only country with substantial nuclear capacity in the Mediterranean currently. At least so far, the country has maintained its opposition to renewing or expanding its installed base, focusing on renewable energy instead (Table 41), but the phase-out may be reconsidered due to budget constraints.

In case Spain's moratorium on nuclear remains, Italy may well fill the gap in the future. The Italian government has called to overturn its nuclear moratorium to reduce its reliance on imported gas and electricity, and the consequent high electricity prices. The country has sufficient technical and engineering expertise to achieve this, but political uncertainty and complex planning procedures could slow the construction of new nuclear power plants.

Table 41 Current installed capacity and nuclear policy in the Mediterranean region

Country	Capacity 2010 [GW_e]	Number of reactors	Policy
Cyprus	0	0	No nuclear electricity
Greece	0	0	No nuclear electricity
Italy	0	0	Expand existing capacity
Malta	0	0	No nuclear electricity
Portugal	0	0	No nuclear electricity
Slovenia	0.67	1	Lifetime extension and expansion
Spain	7.5	8	Lifetime extension

Existing European projections for the development of nuclear power

Various studies have projected the deployment of nuclear electricity in Europe to 2050, including analysis by the International Energy Agency (IEA), the International Atomic Energy Agency (IAEA) and the E3M Lab of the NTUA. Table 42shows an overview of existing projections to 2050.

Table 42 Existing projections of nuclear power capacity and generation in Europe in 2030 and 2050

Source	Scenario	2030		2050	
		Capacity [GW_e]	Electr. [TWh]	Capacity [GW_e]	Electr. [TWh]
IEA Techn. Outlook '10[44]	Baseline	N/A	N/A	117	804
	Blue Map	N/A	N/A	162	1,065
IAEA[45]	Low estimate	~118	~900	N/A	N/A
	High estimate	~200	~1,500	N/A	N/A
NTUA[46]	Baseline	102.4	~840	108,9	~860
	Climate Action	108.1	~840	N/A	N/A
	New nuclear	142.0	1,126	147.6	1,098
Eurelectric	Baseline	134	1,082	161	1,312
	Power Choices	132	1,043	175	1,428
ECN[47]	Kernenergie & Brandstofmix	97	N/A	1,020	NA
DG ENER	PRIMES 2010 (extrapolated)	134	1,030	162	1,246
CASCADE MINT[48]	Phase-out	N/A	0	N/A	0
	Renaissance	N/A	N/A	~1,800	~2,000

The extended DG baseline and the Eurelectric baseline are broadly comparable, validating this path as the medium business as usual case. The Power Choices scenario is at the higher end of the spectrum. Eurelectric's The Role of Electricity scenario, published in 2007, had a higher contribution from nuclear (35% instead of 28%), but this was based on the economic conditions predating the economic crisis of 2008. As such it provides no longer realistic projections for development of the European power sector. In the Power Choices scenario, Eurelectric has updated this scenario, taking into account economic conditions in 2010.

Description of the selected nuclear scenarios

The three nuclear scenarios used for the analysis are:

- High-nuclear scenario – Eurelectric Power Choices scenario;
- Medium-nuclear scenario – Eurelectric baseline scenario;
- Low-nuclear scenario – adapted Eurelectric baseline scenario.

The three nuclear scenarios have been selected based on the information obtained from existing projections. The medium and the high-nuclear scenarios have been taken from Eurelectric. For the

[44] International Electricity Agency (IEA) and Nuclear Electricity Agency (NEA): *Projected Costs of Generating Electricity*, 2010 Edition, Paris, 2010.

[45] International Atomic Energy Agency (IAEA): *Energy, Electricity and Nuclear Power Estimates for the Period up to 2030*. 2009 Edition, Vienna, August 2009.

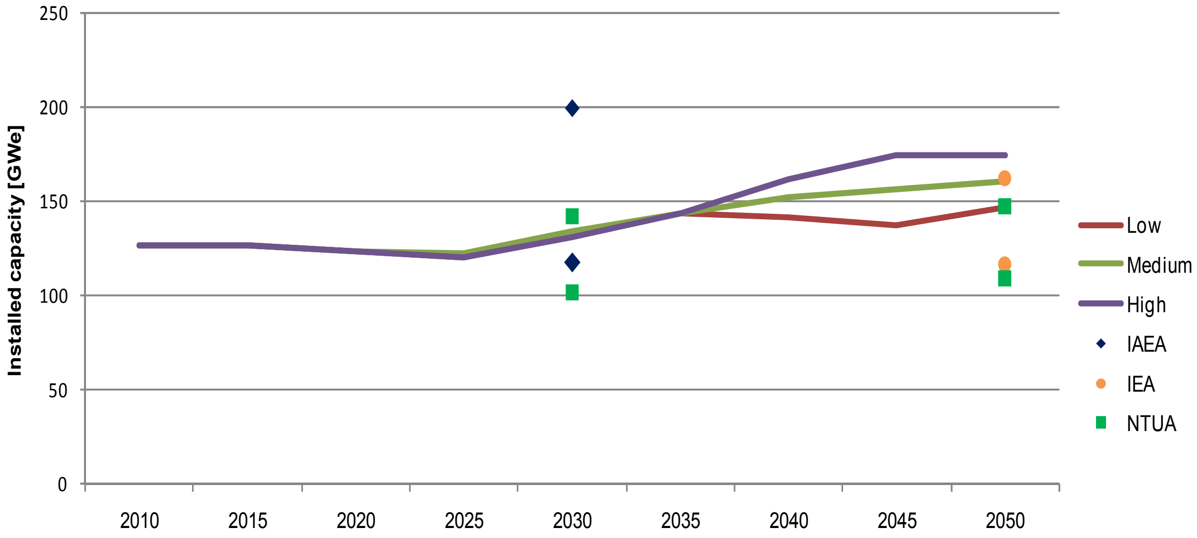
[46] Capros, P.: *The Role of Nuclear in European Scenarios aiming at lowering GHG Emissions*. Presentation at the European Nuclear Energy Forum. November 2008.

[47] Seebregts, A.J. et al. (2010): *Kernenergie & Brandstofmix. Effecten van nieuwe kerncentrales na 2020 in de kernenergiescenario's uit het Energierapport 2008*. ECN-E--10-033. Petten, May 2010.

[48] Uyterlinde, M.A. et al. (2006): *The contribution of nuclear energy to a sustainable energy system*. Policy Brief in the CASCADE-MINT project. ECN-C--05-085. Petten, March 2006.

low case, the nuclear generation capacity of the Eurelectric baseline has been reduced by the same difference as exists between the medium-nuclear case and the high-nuclear case. As a result, the medium-nuclear is right in the middle of the two extremes. The reduction in nuclear capacity has been compensated by additional coal and gas power plants (50% from each).

Figure 45 Projections for the development of nuclear electricity capacity in Europe to 2050



Until 2035 the three scenarios follow similar paths (Figure 45). Installed capacity declines slightly until 2025 as existing reactors close down and few new plants are completed, due to the time required for building a nuclear power plant. From 2025 to 2035, the nuclear generation capacity grows steadily to 132 to 134 MW_e, as new reactors come online.

Differences between the three cases emerge after 2035, but only gradually, so that the difference between the high and low nuclear energy scenarios is only 28 GW_e apart in 2050:

- In the **high-nuclear case**, the growth trend of 2025 to 2035 continues in the following decade, leveling off only from 2045. The slowdown is mainly due to the projected decline in over electricity demand from 2045 onwards in this scenario. The contribution of nuclear power in the generation mix therefore still grows;
- In the **medium-nuclear scenario**, nuclear power capacity growth still grows from 2035 to 2050, but at a slower rate than in the high-nuclear case, as emission reduction targets are less ambitious;
- In the **low-nuclear scenario**, installed nuclear capacity declines from 2035 to 2045, mirroring the path of the high-nuclear case. This decline is compensated for in the next ten years, so that overall installed capacity increases slightly in this scenario. This reflects the necessity of reducing GHG emissions in any case, and the important contribution that nuclear power can make to decarbonising the energy sector.

Table 43 shows the installed capacity per region for the three cases in 2030 and 2050. The largest differences between the three cases are in the Central and Eastern and Mediterranean regions, especially because of the political uncertainty surrounding nuclear power in Germany and Italy. If both countries would aggressively expand their current installed capacity, the development of the nuclear sector could follow the path of the high-nuclear scenario. The differences between the scenarios are much smaller in the Baltic and North Sea regions, as future policies in the main countries are broadly known.

Table 43 Nuclear capacity by region in the three nuclear scenarios in 2030 and 2050

Region	2030			2050		
	Low	Medium	High	Low	Medium	High
Baltic	16,4	17,0	16,4	15,8	15,9	15,8
North Sea	72,3	73,8	72,3	85,4	86,4	87,4
Central and Eastern	21,6	21,8	22,0	20,6	27,1	33,5
Mediterranean	20,9	21,4	20,9	25,9	32,0	38,1
EU-27	132	134	132	147	161	175

C.3 Electricity scenario data

The following tables show the projected electricity generation and installed capacity for the baseline scenario used in this study, based on the baseline scenario from Eurelectric's Power Choices study.

Electricity generation

Table 44 Electricity generation – EU-27 Member States

EU-27	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
Total	2992	3274	3309	3549	3791	4007	4183	4320	4448	4558	4688
Nuclear electricity	945	998	927	937	929	988	1082	1176	1241	1271	1312
Coal and lignite	945	981	888	934	947	934	931	924	917	941	991
Petroleum products	170	133	67	72	70	63	49	55	50	44	41
Gas (incl. derived gases)	507	694	791	804	862	865	786	780	795	815	808
Biomass & waste	45	84	128	162	189	216	239	240	254	263	276
Hydro	353	307	323	332	340	349	355	358	362	364	366
Wind	22	70	161	269	398	516	638	669	697	714	732
Solar, tidal etc.	0	1	17	32	46	60	75	86	96	106	118
Geothermal / other	5	5	6	7	10	16	28	32	35	39	43

Table 45 Electricity generation – Baltic region

Baltic region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
Total	275	295	295	317	343	362	365	372	380	387	390
Nuclear electricity	88	106	90	104	119	132	131	133	134	134	133
Coal and lignite	39	38	40	38	38	35	34	34	33	33	34
Petroleum products	7	4	4	3	2	2	1	3	2	2	2
Gas (incl. derived gases)	25	28	36	35	34	31	30	29	29	30	29
Biomass & waste	14	21	29	35	41	46	51	54	60	64	66
Hydro	96	90	84	84	85	85	85	86	86	86	87
Wind	5	8	12	18	24	30	33	34	34	37	38
Solar, tidal etc.	0	0	0	0	0	0	0	1	1	1	1
Geothermal / other	0	0	0	0	0	0	0	0	0	0	0

Table 46 Electricity generation – North Sea region

North Sea region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
Total	1107	1181	1178	1264	1338	1385	1432	1480	1528	1569	1615
Nuclear electricity	552	585	559	571	572	578	594	630	650	669	690
Coal and lignite	198	207	184	203	194	182	190	195	199	212	236
Petroleum products	16	19	8	12	13	13	12	16	14	12	12
Gas (incl. derived gases)	250	279	287	281	274	278	258	245	254	252	237
Biomass & waste	13	26	35	43	48	51	55	57	60	60	61
Hydro	74	58	63	63	63	66	67	67	67	67	66
Wind	2	7	40	86	164	203	233	242	247	253	258
Solar, tidal etc.	0	0	1	3	6	8	12	17	22	28	35
Geothermal / other	0	0	0	1	3	5	11	12	14	16	19

Table 47 Electricity generation – Central and Eastern European region

Central and Eastern European region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
Total	1001	1084	1108	1159	1209	1277	1331	1357	1382	1409	1447
Nuclear electricity	237	244	213	196	159	161	174	197	201	209	215
Coal and lignite	539	539	509	515	527	538	538	529	517	524	541
Petroleum products	15	15	9	11	16	13	11	13	12	10	8
Gas (incl. derived gases)	97	144	184	185	209	215	199	197	208	211	207
Biomass & waste	13	23	42	51	60	67	74	70	73	77	87
Hydro	90	89	90	96	103	108	112	113	115	116	117
Wind	9	29	54	90	115	151	192	205	222	227	235
Solar, tidal etc.	0	1	8	14	19	23	27	29	31	32	32
Geothermal / other	0	0	0	0	1	2	3	3	4	4	4

Table 48 Electricity generation – Mediterranean region

Mediterranean region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh	TWh
Total	608	715	728	810	901	983	1055	1111	1158	1194	1236
Nuclear electricity	67	63	65	65	79	117	183	215	256	259	274
Coal and lignite	168	197	155	179	187	179	170	167	168	173	180
Petroleum products	131	96	47	47	39	36	25	23	21	20	19
Gas (incl. derived gases)	134	242	285	302	345	341	299	309	303	323	334
Biomass & waste	5	15	22	33	41	51	59	60	61	62	62
Hydro	93	69	86	88	89	91	91	92	94	95	96
Wind	6	27	55	75	95	132	179	189	194	198	202
Solar, tidal etc.	0	0	8	15	21	28	36	39	43	46	50
Geothermal / other	5	5	6	6	6	9	14	17	18	19	21

Installed capacity

Table 49 Installed capacity – EU-27 Member States

EU-27	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe
Total Capacity	654	716	816	901	944	1009	1095	1139	1187	1228	1268
Nuclear electricity	134	134	127	127	124	123	134	144	152	156	161
Coal and lignite	194	187	184	183	166	154	165	150	150	153	157
Petroleum products	71	62	56	46	42	40	36	33	34	34	35
Gas (incl. derived gases)	129	167	218	249	249	266	268	298	313	324	331
Biomass & waste	12	18	24	30	36	42	48	51	56	63	69
Hydro	100	105	107	110	114	115	116	117	117	118	118
Wind	13	41	84	126	172	215	259	269	278	284	290
Solar, tidal etc.	0	2	15	28	39	50	61	69	77	86	95
Geothermal / other	1	1	1	1	2	4	7	8	9	11	12

Table 50 Installed capacity – Baltic region

Baltic region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe
Total Capacity	72	72	74	79	81	85	88	88	91	92	94
Nuclear electricity	15	14	12	15	16	17	17	16	16	16	16
Coal and lignite	15	14	14	12	11	9	9	7	7	7	8
Petroleum products	7	6	6	5	3	2	1	1	1	2	2
Gas (incl. derived gases)	8	8	9	11	11	13	14	14	14	13	14
Biomass & waste	4	6	6	7	7	8	11	13	15	16	16
Hydro	21	21	21	21	22	22	22	22	22	22	22
Wind	3	4	6	8	10	13	14	14	14	15	15
Solar, tidal etc.	0	0	0	0	0	0	0	1	1	1	1
Geothermal / other	0	0	0	0	0	0	0	0	0	0	0

Table 51 Installed capacity – North Sea region

North Sea region	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe	GWe
Total Capacity	224	235	258	289	308	326	351	366	395	417	433
Nuclear electricity	80	81	80	80	79	72	74	78	81	84	86
Coal and lignite	46	43	40	38	30	28	31	28	29	32	35
Petroleum products	19	17	18	16	14	13	12	10	11	11	11
Gas (incl. derived gases)	52	62	71	87	88	97	100	109	123	129	129
Biomass & waste	4	5	6	8	10	11	12	11	14	15	17
Hydro	22	22	23	23	23	23	23	23	23	23	23
Wind	1	4	18	34	59	72	83	86	88	90	92
Solar, tidal etc.	0	0	1	3	5	7	11	15	20	25	32
Geothermal / other	0	0	0	1	2	3	4	5	6	7	8

Table 52 Installed capacity – Central and Eastern European region

Central and Eastern European region	2000 GWe	2005 GWe	2010 GWe	2015 GWe	2020 GWe	2025 GWe	2030 GWe	2035 GWe	2040 GWe	2045 GWe	2050 GWe
Total Capacity	217	228	254	285	296	312	333	350	363	371	382
Nuclear electricity	31	32	26	24	20	20	22	25	25	26	27
Coal and lignite	106	102	101	103	97	90	94	88	87	84	88
Petroleum products	12	10	9	7	11	11	10	10	10	10	11
Gas (incl. derived gases)	36	36	47	55	55	59	57	71	75	78	77
Biomass & waste	3	4	7	8	10	11	12	12	14	18	21
Hydro	24	23	25	27	29	29	30	30	31	31	31
Wind	6	19	31	46	54	66	80	84	89	91	94
Solar, tidal etc.	0	2	9	15	20	24	28	30	31	32	33
Geothermal / other	0	0	0	0	0	0	0	0	0	0	0

Table 53 Installed capacity – Mediterranean region

Mediterranean region	2000 GWe	2005 GWe	2010 GWe	2015 GWe	2020 GWe	2025 GWe	2030 GWe	2035 GWe	2040 GWe	2045 GWe	2050 GWe
Total Capacity	**141**	**180**	**230**	**248**	**259**	**286**	**324**	**334**	**339**	**348**	**359**
Nuclear electricity	8	8	8	8	9	14	21	25	30	30	32
Coal and lignite	28	28	29	30	28	26	30	26	26	29	26
Petroleum products	33	29	24	18	14	13	14	12	11	12	11
Gas (incl. derived gases)	34	61	90	96	95	97	99	104	102	104	111
Biomass & waste	1	3	5	7	9	12	14	14	14	14	15
Hydro	33	38	39	40	40	41	41	41	41	41	42
Wind	3	13	29	39	49	64	82	85	86	88	89
Solar, tidal etc.	0	1	5	10	14	18	22	24	26	27	29
Geothermal / other	1	1	1	1	1	1	2	2	3	3	4

Annex D Questionnaires

Questionnaire 1 – Nuclear regulatory authorities

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the energy sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as the Nuclear Regulatory Authority. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

The questionnaire will take some time to complete.

Upon completion, please return it to: climatechange@nrg.eu

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
What is the name of your organisation? What is your position in the organization? What is the ownership structure of the nuclear power plants in your country?	 ☐ Public ☐ Semi-public ☐ Private
Where are the nuclear power plants located in your country?	☐ at the seashore ☐ at a river ☐ at a lake
Technology What kind of reactor technology is used by the nuclear power plants in your country ?	 ☐ Pressurized Water Reactor ☐ Boiling Water Reactor ☐ Gas cooled reactor ☐ Pressurized Heavy Water Reactor Other (specify):
What has been the (approximate) capacity factor of each NPP in the last few years? (in %) When have the NPPs' been commissioned? What is the economic lifetime of each NPP? When are the periodic safety reviews taking place?	 Years ☐ Each two years ☐ Each ten years Other (specify):
Strategy regarding climate change Do you require presently, evaluation of the vulnerability of the NPP to climate-change related effects and the impact on its safety, as part of the periodic safety review(s) or other regular inspection program,	 ☐ yes ☐ no
If you do not presently request an evaluation of climate change effects, would you consider to request such evaluation in the near future	☐ yes ☐ no
Do you require the Licensee to developed a long-term strategy to respond to safety impacts due to climate-change related disruptions?	☐ yes ☐ no
Are you currently request the licensee to take provisions to protect the installations to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans? • If not considered such request, could you indicate why not? • If considered, could you give an impression of investments needed for such a protection and indicate which climate change risks are mitigated per investment?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
Section 2 - Climate Change Effects	
Cooling water impacts Do you have National regulations for the maximum temperature at the NPP cooling water outlet (or maximum temperature of the surface water from which the cooling water is extracted)? When confronted with an increasingly higher surface water	

Questions	Answers
temperature in the near future, would you consider adapting the regulations or would you request the Licensee to take provisions[49] to keep sufficient cooling capacity for operating the NPP? Could you provide information on the bandwidth of cooling water temperatures that is currently agreed with preconditions for operating the NPPs at nominal and maximum output? In case that this maximum temperature would be reached, would you impose the NPP to stop the power production at all or allow continuing operation at reduced capacity? In the case no sufficient electricity supply can be imported from abroad to the national grid, would you foresee any (temporary) relaxation of the permissible maximum temperature at the cooling water outlet by national regulation (possibly at reduced capacity)? Do you have National regulations for maximum/minimum water levels at the cooling water intake of the NPPs. Do you have National regulations for maximum/minimum water levels at the cooling water intake when operating the NPPs. Do you have National regulations for maximum/minimum ambient temperature when operating the NPPs. Do you have National regulations for the maximum wind speed above no operation of the NPPs is allowed? Do you have National regulations for a maximum hourly precipitation (rain/snow) above which the operation of the NPP is not allowed?	
Extreme weather conditions Concerning an increase in occurrence of potential future extreme weather conditions, how would the operation of the NPP be affected? Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers) and could lead to a higher probability of station black-out	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
Indirect effects Climate change effects are likely to impact on your regulatory activity/inspections indirectly, e.g. in terms of **changing environmental conditions for the NPP** and **higher electricity demand** (seasonal or structural), which may affect planning of outage (refuelling, maintenance, etc). Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:	

49 Examples of technical measures to cooling water systems for inland sites to be implemented, would be the use of cooling towers (before/after) the condenser. Construction of water reservoirs that would be an additional cooling water supply in case of ‘hot’ summers. Examples of envisaged technical measures for cooling water systems for seaside sites, to ensure operation of the facility, are protective measures against high water levels.

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Koen Rademaekers	Jaap Jansen	Jan van Hienen
Ecorys	ECN	NRG

Questionnaire 2 – Nuclear power utilities

Dear Sir/Madam

On behalf of the European Commission, our consortium, consisting of ECORYS, ECN and NRG, is performing a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you as nuclear utility to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

The questionnaire takes about 30 minutes to complete.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the utility?	☐ Public ☐ Semi-public ☐ Private
4 - Where are your nuclear power plants located (addresses and country)?	
Technology	
5 - Please indicate the power generation technology used (PWR, BWR, etc.)	
6 - Please describe the cooling technology used (e.g. cooling tower, seawater, river water, or a combination of these)	
7 - Does the plant capture exhaust heat for serving an economically justifiable heat demand?	☐ yes ☐ no
8 - What is the utility policy regarding the lifetime of the nuclear power generation facilities?	
9 – What Is the utility policy with regard to re-investments (e.g. retrofitting, significant upgrades) in the nuclear power generation facilities?	
Regulation and investment regime	
10 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
11 - If yes, what are the methods used to determine tariff levels?	☐ Price cap ☐ Cost recovery on asset base Other:
12 - How have investments in new equipment and basic technology been funded in recent years?	☐ Public funding ☐ Parent company ☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:

Section 2 - Climate Change: Safety-related Aspects	
Strategy regarding safety-related aspects of climate change	
13 - Have you evaluated the safety-related risks and vulnerability to climate-related changes of your nuclear power generation facilities?	☐ yes ☐ no
14 - If yes, what has been done in detail?	
15 - Have you developed a long-term strategy to respond to safety-related aspects of climate changes?	☐ yes ☐ no
16 - If yes, what has been done in detail?	
17 - Are you considering safety-related provisions to adapt to climate change effects, as part of lifetime extension programmes, contingency plans? • If not considered, could you indicate why not? • If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
The following questions deal with safety-related aspects of specific climate changes for your nuclear power plants	
18 - Cooling water impacts on safety	
The questions of item 18 relate to changes in cooling water temperatures, and only apply to installations using water-cooling. Please move to the next item if this does not apply to your facilities.	
A - Could you provide information on the maximum temperature of the seawater/river water when you have to expect high levels of fish, mobile invertebrates (*e.g.* jellyfish, copepods, mysids) and drifting algae, including eggs and larval stages present in the cooling water source body, forcing to stop the input of cooling water.	
B - In case the licensed **maximum temperature** of the cooling water source body has been reached, how much margin do you have before to stop the inlet of cooling water?	
C - When confronted with an increasingly higher level s of marine life in the cooling water source body , what kind of provisions[50] do you envisage for keeping **sufficient cooling capacity** for operating your facilities?	
D - What types of assets need to be invested in for adapting the power generation facilities to the **effects on cooling water fouling** outlined above?	
E - Please estimate the associated investment costs per plant, if possible.	€

facilities

Section 2 - Climate Change: Safety-related Aspects	
19 - Air temperature change	
A - When confronted with a **change in air temperature**, to what extent is the safety of your facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - Would a change of the air temperature have consequences for the working environment conditions at your facilities?	
20 - Precipitation change	
A - When confronted with a **change in precipitation**, to what extent will the safety of your facilities be affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - To what extent does flooding cause a risk for your facilities?	
C - To what extent could the availability of personnel be influenced by flooding?	
Extreme weather conditions	
Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)	
21 - Hail and rain storms	
A - Concerning an increase in occurrence of potential future **hail and rain storms**, to what extent is the safety of the facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - What types of assets need to be invested in your facilities to mitigate the safety impacts of facilities more frequent and intense hail and rain storms?	
C - Please estimate the associated investment costs, if possible	€
22 - Higher wind speeds (storms, occurrence of twisters)	
A - Concerning an increase in occurrence of potential **future higher wind speeds**, to what extent is the safety of the facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - What types of assets need to be invested in the protection of the facilities to reduce vulnerability to higher wind speeds?	
C - Please estimate the associated investment costs, if possible	€
23 - More frequent lightning	
A - Concerning an increase in occurrence of potential future more frequent **and more powerful lightnings**, to what extent is the safety of the facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - What types of assets need to be invested in the facilities to reduce its vulnerability to more frequent and more powerful lightnings?	
C - What types of assets need to be invested in the power	

Section 2 - Climate Change: Safety-related Aspects	
transmission lines in the area of the facilities to reduce its vulnerability to more frequent and more powerful lightnings?	
D - Please estimate the associated investment costs, if possible	€
24 - Higher incidence of **external fires (including the ones induced by lightnings) that affect power transmission (external switch yards, auxiliary transformers)**	
A - Concerning an increase in occurrence of potential future higher incidence of external fires, to what extent is the safety of the facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
B - What types of assets need to be invested in for adapting the protection of the facilities to reduce the safety impacts of higher incidence of external fires?	
C - Please estimate the associated investment costs, if possible	€
25 - Comments related to other safety aspects	
Please add any further comments related to other safety aspects of Climate Change	

Section 3 - Climate Change: Economic Aspects	
The following questions deal with economic aspects of specific climate changes for your nuclear power plants	
Strategy regarding economic aspects of climate change	
26 - Have you evaluated the economic implications of climate changes for your nuclear power generation facilities?	☐ yes ☐ no
27 - If yes, what has been done in detail?	
28 - Have you developed a long-term strategy to respond to economic aspects of climate changes?	☐ yes ☐ no
29 - If yes, what has been done in detail?	
30 - Are you considering provisions to adapt to climate change effects, as part of normal business planning? • If not considered, could you indicate why not? • If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
31 - Cooling water impacts	
The questions of item 31 relate to changes in cooling water temperatures, and only apply to installations using water-cooling. Please move to the next item if this does not apply to your facilities.	
A - Could you provide information on the bandwidth of outlet **cooling water temperatures** that is currently agreed with preconditions for operating your facilities at nominal and maximum output? Please differentiate between coastal and river based facilities, if necessary.	
B - Please indicate the legal maximum temperature according to your licenses.	
C - In case this **maximum temperature** is reached, do you have to fully stop the power production or may you continue operation at reduced capacity?	
D - When confronted with an increasingly higher surface water temperature, how are the facilities affected?	Coastal locations: 0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much River locations: 0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
E - Please describe how the normal operation and maintenance of the	

Section 3 - Climate Change: Economic Aspects		
facilities would be affected.		
F - When confronted with an increasingly higher surface water temperature , what kind of provisions[51] do you envisage for keeping **sufficient cooling capacity** for operating your facilities?		
G - What types of assets need to be invested in for adapting the power generation facilities to the **effects on cooling water** outlined above?		
H - Please estimate the associated investment costs per plant, if possible.	€	
I – If insufficient electricity supply can be imported from abroad to the national grid, would you foresee any relaxation of **the permissible maximum temperature** at the cooling water outlet by national regulation (possibly at reduced capacity)?		
32 - Air temperature change		
A - When confronted with a **change in air temperature**, to what extent are your facilities affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
	Lower	**Higher**
B - Please describe how the normal operation and maintenance of the facilities would be affected.		
C - What would be the costs per plant associated with a **change in air temperature** due to implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/˚C or % loss of operation/˚C)?		
D - What level of **change in air temperature** would substantially influence the operations of your production facilities?	˚C	˚C
E - Would you consider major investments to overcome the reduced operation?		
F - Please estimate the associated investment costs, if possible.	€	€
G - What types of assets need to be invested in for adapting your facilities to a **change in air temperature**? - Lowe temperature: - Higher temperature:		
33 - Precipitation change		
A - When confronted with a **change in precipitation**, to what extent are your facilities ecomically affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
	Lower	**Higher**

[51] Examples of technical measures to cooling water systems for inland sites to be implemented, would be the use of cooling towers (before/after) the condenser. Construction of water reservoirs that would be an additional cooling water supply in case of 'hot' summers. Examples of envisaged technical measures for cooling water systems for seaside sites, to ensure operation of the facilities, are protective measures against high water levels.

Section 3 - Climate Change: Economic Aspects		
B - Please describe how the normal operation and maintenance of the facilities would be affected.		
C - What would be the costs per plant associated with a **change in precipitation** due to implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/m or % loss of operation/m)?		
D - What level of **change in precipitation** would significantly influence the operations of your production facilities?	m	m
E - Would you consider major investments to overcome the reduced operation?		
F - Please estimate the associated investment costs, if possible.	€	€
G - What types of assets need to be invested in for adapting the generation facilities to a **change in precipitation?** - Lower precipitation level: - Higher precipitation level:		
34 - Comments related to other economic aspects Please add any further comments related to other economic aspects of Climate Change		
35 - Other Comments Please add any other comments concerning aspects of Climate Change that are of particular importance for your facilities		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Koen Rademaekers	Jaap Jansen	Jan van Hienen
Ecorys	ECN	NRG

Questionnaire 3 – Fossil-fuelled power utilities

Dear Sir/Madam

On behalf of the European Commission, our consortium, consisting of ECORYS, ECN and NRG, performs a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire takes about 30 minutes to complete.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private ☐ Other (please specify)
4 - Where is the plant located (address and country)?	
Technology	
5 - Please describe the power generation technology used	
6 - Please describe the cooling technology used (if any)	
7 - What is the capacity of the plant (in MW_e)?	
8 - What has been the (approximate) capacity factor (operation time during the year) in the last five years? (in %)	
9 - What is the (approximate) electrical efficiency of the plant? (in %)	
10 - When has the power or CHP plant been commissioned?	
11 - What is the expected economic lifetime of the power/CHP plant?	Years
12 - When would re-investments (e.g. retrofitting, significant upgrades) in the power generation facility be needed?	
Strategy regarding climate change	
13 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
14 - If yes, what has been done in detail?	
15 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
16 - If yes, what has been done in detail?	
17 - Are you considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	

Questions	Answers
18 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
19 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
20 - How have investments in new equipment and basic technology been funded in recent years?	☐ Public funding ☐ Parent company ☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:
Section 2 - Climate Change	
The following questions deal with the specific climate change effects for your power plant	
21 - Cooling water impacts	
The questions of item 21 relate to changes in cooling water temperatures, and only apply to installations using water-cooling. Please move to the next item if this does not apply to your facility.	
A - Could you provide information on the bandwidth of outlet **cooling water temperatures** that is currently agreed with preconditions for operating your facility at nominal and maximum output?	
B - Please indicate the legal maximum temperature according to your license.	
C - In case that this **maximum temperature** is reached, do you have to stop the power production at all or may you continue operation at reduced capacity?	
D - When confronted with an increasingly higher surface water temperature, how is the facility affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
E - Please describe how the normal operation and maintenance of the facility would be affected.	
F - What would be the costs associated with a **change in cooling water temperature** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/˚C or % loss of operation/˚C)?	
G - When confronted with an increasingly higher surface water temperature , what kind of provisions[52] do you envisage for keeping **sufficient cooling capacity** for operating your facility?	

[52] Examples of technical measures to cooling water systems for inland sites to be implemented, would be the use of cooling towers (before/after) the condenser. Construction of water reservoirs that would be an additional cooling water supply in case of 'hot' summers. Examples of envisaged technical measures for cooling water systems for seaside sites, to ensure operation of the facility, are protective measures against high water levels.

Questions	Answers	
H - What types of assets need to be invested in for adapting the power generation facility to the **effects on cooling water** outlined above?		
I - Please estimate the associated investment costs, if possible.	€	
J – If sufficient electricity supply cannot be imported from abroad to the national grid, would you foresee any relaxation of **the permissible maximum temperature** at the cooling water outlet by national regulation (possibly at reduced capacity)?		
22 - Air temperature change		
	Lower air T	**Higher air T**
A - Please describe how the normal operation and maintenance of the facility would be affected at different levels of air temperature change.		
B - What level of **change in air temperature** would substantially influence the operations of your production facility, leading to a major investment, and would be considered critical?	˚C	˚C
C - What types of assets need to be invested in for adapting the generation facility to a **change in air temperature** at the critical level**?**		
- Increase:		
- Decrease:		
D - Please estimate the associated investment costs, if possible.	€	€
E - What other costs might be associated with **a critical change in air temperature** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/˚C or % loss of operation/˚C)?		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in air temperature** to the critical level without any precautionary provisions?	%	%
23 - Precipitation change		
	Lower precipitation	**Higher precipitation**
A - Please describe how the normal operation and maintenance of the facility would be affected at precipitation levels different to the up-to-date average.		
B - What level of **change in precipitation** would significantly influence the operations of your production facility, leading to a major investment, and would be considered critical?	m	m
C - What types of assets need to be invested in for adapting the generation facility to a **change in precipitation** at the critical level?		
- Increase:		
- Decrease:		

Questions	Answers	
D - Please estimate the associated investment costs, if possible.	€	€
E - What other costs might be associated with a **change in precipitation** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/m or % loss of operation/m)?		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in precipitation** to the critical level without any precautionary provisions?	%	%
24 - What other structural climate change effects would affect the normal operation and maintenance of the facility?		
A - When confronted with a change in the specified effect, to what extent is the facility likely to be affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
	Lower	**Higher**
B - Please describe how the normal operation and maintenance of the facility would be affected.		
C - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and would be considered critical?	unit	unit
D - What types of assets need to be invested in for adapting the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
E - Please estimate the associated investment costs, if possible	€	€
F - What would be the costs associated with a **change in the specified effect** due to implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/unit or % loss of operation/unit)?		
G - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
25 - Extreme weather conditions		
Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)		
A - Concerning an increase in occurrence of potential future extreme weather conditions, to what extent is the facility affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
B - Please describe how the normal operation and maintenance of the facility would be affected.		
C - What types of assets need to be invested in for adapting the		

Questions	Answers	
generation facility to reduce vulnerability to extreme weather conditions?		
D - Please estimate the associated investment costs, if possible	€	
26 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future?		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Koen Rademaekers
Ecorys

Jaap Jansen
ECN

Jan van Hienen
NRG

Questionnaire 4 – Hydropower utilities

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire will take overall about 15 minutes.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private
4 - Where is the plant located (address and country)?	
Technology	
5 - What is the capacity of the plant (in MW)?	
6 - What has been the (approximate) capacity factor in the last few years? (in %)	
7 - When has the generation facility been commissioned?	
8 - What is the economic lifetime of the generation facility?	Years
9 - When would re-investments (e.g. retrofitting, significant upgrades) in the generation facility be needed?	
Strategy regarding climate change	
10 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
11 - If yes, what has been done in detail?	
12 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
13 - If yes, what has been done in detail?	
14 - Are you currently considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	
15 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
16 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
17 - How have – thus far – investments in new equipment and basic technology been funded?	☐ Public funding ☐ Parent company

Questions	Answers	
	☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:	
Section 2 - Climate Change		
The following questions deal with the specific climate change effects for your power plant		
18 - Water level change (increase / decrease of the sea level and connected consequences, increase of lake/river level if relevant)	**In case of a lower water level**	**In case of a higher water level**
A - Do you believe that a **change in water level** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - What would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in water level** per meter of increase/decrease (please provide an estimation)?	€ / m	€ / m
D - What level of **change in water level** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	m	m
E - How much would the investment be to adapt the generation facility to a **change in water level** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in water level** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in water level** at the critical level**?**		
- Increase:		
- Decrease:		
19 - Precipitation change	**In case of a lower precipitation**	**In case of a higher precipitation**
A - Do you believe that a **change in precipitation** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in precipitation** per meter of increase/decrease (please provide an estimation)?	€ / m	€ / m
D - What level of **change in precipitation** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	m	m
E - How much would the investment be to adapt the generation facility to a **change in precipitation** at the critical level**?**	€	€

Questions	Answers	
F - What percentage of the average produced electricity could still be generated in the facility following a **change in precipitation** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in precipitation** at the critical level?		
- Increase:		
- Decrease:		
20 - What would be another structural climate change effect? Please specify: **Effect:**	**In case of a lower effect**	**In case of a higher effect**
A - Do you believe that a **change in the specified effect** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in the specified effect** per unit of increase/decrease (please provide an estimation)?	€ / unit	€ / unit
D - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	unit	unit
E - How much would the investment be to adapt the generation facility to a **change in the specified effect** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
21 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Questionnaire 5 – Wind power utilities

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire will take overall about 15 minutes.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private
4 - Where is the plant located (address and country)?	
Technology	
5 - What is the capacity of the plant (in MW)?	
6 - What has been the (approximate) capacity factor in the last few years? (in %)	
7 - When has the generation facility been commissioned?	
8 - What is the economic lifetime of the generation facility?	Years
9 - When would re-investments (e.g. retrofitting, significant upgrades) in the generation facility be needed?	
Strategy regarding climate change	
10 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
11 - If yes, what has been done in detail?	
12 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
13 - If yes, what has been done in detail?	
14 - Are you currently considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	
15 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
16 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
17 - How have – thus far – investments in new equipment and basic technology been funded?	☐ Public funding ☐ Parent company

Questions	Answers	
	☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:	
Section 2 - Climate Change		
The following questions deal with the specific climate change effects for your power plant		
18 - Wind speed change	**In case of a lower wind speed**	**In case of a higher wind speed**
A - Do you believe that a **change in wind speed** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in wind speed** per km/h of increase/decrease (please provide an estimation)?	€ / km/h	€ / km/h
D - What level of **change in wind speed** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	km/h	km/h
E - How much would the investment be to adapt the generation facility to a **change in wind speed** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in wind speed** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in wind speed** at the critical level**?**		
- Increase:		
- Decrease:		
19 - What would be another structural climate change effect? Please specify: **Effect:**	**In case of a lower effect**	**In case of a higher effect**
A - Do you believe that a **change in the specified effect** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in the specified effect** per unit of increase/decrease (please provide an estimation)?	€ / unit	€ / unit
D - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	unit	unit
E - How much would the investment be to adapt the generation facility	€	€

Questions	Answers	
to a **change in the specified effect** at the critical level**?**		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
20 - Extreme weather conditions		
Concerning an increase in occurrence of potential future extreme weather conditions, how is the facility affected? Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
21 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Questionnaire 6 – PV power utilities

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire will take overall about 15 minutes.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private
4 - Where is the plant located (address and country)?	
Technology	
5 - What is the capacity of the plant (in MW)?	
6 - What has been the (approximate) capacity factor in the last few years? (in %)	
7 - When has the generation facility been commissioned?	
8 - What is the economic lifetime of the generation facility?	Years
9 - When would re-investments (e.g. retrofitting, significant upgrades) in the generation facility be needed?	
Strategy regarding climate change	
10 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
11 - If yes, what has been done in detail?	
12 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
13 - If yes, what has been done in detail?	
14 - Are you currently considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	
15 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
16 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
17 - How have – thus far – investments in new equipment and basic technology been funded?	☐ Public funding ☐ Parent company

Questions	Answers	
	☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:	
Section 2 - Climate Change		
The following questions deal with the specific climate change effects for your power plant		
18 - Wind speed change	**In case of a lower wind speed**	**In case of a higher wind speed**
A - Do you believe that a **change in wind speed** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in wind speed** per km/h of increase/decrease (please provide an estimation)?	€ / km/h	€ / km/h
D - What level of **change in wind speed** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	km/h	km/h
E - How much would the investment be to adapt the generation facility to a **change in wind speed** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in wind speed** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in wind speed** at the critical level**?**		
- Increase:		
- Decrease:		
19 - Solar radiation patterns change	**In case of a decreased solar radiation**	**In case of an increased solar radiation**
A - Do you believe that a **change in solar radiation patterns** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in solar radiation patterns** per % of increase/decrease (please provide an estimation)?	€ / %	€ / %
D - What level of **change in solar radiation patterns** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	%	%
E - How much would the investment be to adapt the generation	€	€

Questions	Answers	
facility to a **change in solar radiation patterns** at the critical level**?**		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in solar radiation patterns** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in solar radiation patterns** at the critical level**?**		
- Increase:		
- Decrease:		
20 - What would be another structural climate change effect? Please specify: **Effect:**	**In case of a lower effect**	**In case of a higher effect**
A - Do you believe that a **change in the specified effect** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in the specified effect** per unit of increase/decrease (please provide an estimation)?	€ / unit	€ / unit
D - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	unit	unit
E - How much would the investment be to adapt the generation facility to a **change in the specified effect** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
21 - Extreme weather conditions		
Concerning an increase in occurrence of potential future extreme weather conditions, how is the facility affected? Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
22 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns.		

Questions	Answers	
Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Questionnaire 7 – CSP power utilities

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire will take overall about 15 minutes.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private
4 - Where is the plant located (address and country)?	
Technology	
5 - What is the capacity of the plant (in MW)?	
6 - What has been the (approximate) capacity factor in the last few years? (in %)	
7 - When has the generation facility been commissioned?	
8 - What is the economic lifetime of the generation facility?	Years
9 - When would re-investments (e.g. retrofitting, significant upgrades) in the generation facility be needed?	
Strategy regarding climate change	
10 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
11 - If yes, what has been done in detail?	
12 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
13 - If yes, what has been done in detail?	
14 - Are you currently considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	
15 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
16 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
17 - How have – thus far – investments in new equipment and basic technology been funded?	☐ Public funding ☐ Parent company

Questions	Answers	
	☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:	
Section 2 - Climate Change		
The following questions deal with the specific climate change effects for your power plant		
18 - Cooling water impacts		
A - What would be the maximum temperature at your **cooling water outlet** in accordance with your license or national regulation (or maximum temperature of the surface water from which you extract your cooling water)?		
B - When confronted with an increasingly higher surface water temperature in the near future, what kind of provisions[53] do you envisage keeping **sufficient cooling capacity** for operating your facility?		
C - Could you provide information on the bandwidth of **cooling water temperatures** that is currently agreed with preconditions for operating your facility at nominal and maximum output?		
D - In case that this **maximum temperature** would be reached, do you have to stop the power production at all or may you continue operation at reduced capacity?		
E - In the case no sufficient electricity supply can be imported from abroad to the national grid, would you foresee any relaxation of **the permissible maximum temperature** at the cooling water outlet by national regulation (possibly at reduced capacity)?		
F - What types of assets need to be invested in to adapt the generation facility to the **effects on cooling water** outlined above?		
19 - Air temperature change	**In case of a lower air temperature**	**In case of a higher air temperature**
A - Do you believe that a **change in air temperature** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in air temperature** per degree of increase/decrease (please provide an estimation)?	€ / ˚C	€ / ˚C

[53] Examples of technical measures to cooling water systems for inland sites to be implemented, would be the use of cooling towers (before/after) the condenser. Construction of water reservoirs that would be an additional cooling water supply in case of 'hot' summers. Examples of envisaged technical measures for cooling water systems for seaside sites, to ensure operation of the facility, are protective measures against high water levels.

Questions	Answers	
D - What level of **change in air temperature** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	˚C	˚C
E - How much would the investment be to adapt the generation facility to a **change in air temperature** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in air temperature** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in air temperature** at the critical level**?**		
- Increase:		
- Decrease:		
20 - Wind speed change	**In case of a lower wind speed**	**In case of a higher wind speed**
A - Do you believe that a **change in wind speed** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in wind speed** per km/h of increase/decrease (please provide an estimation)?	€ / km/h	€ / km/h
D - What level of **change in wind speed** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	km/h	km/h
E - How much would the investment be to adapt the generation facility to a **change in wind speed** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in wind speed** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in wind speed** at the critical level**?**		
- Increase:		
- Decrease:		
21 - Solar radiation patterns change	**In case of a decreased solar radiation**	**In case of an increased solar radiation**
A - Do you believe that a **change in solar radiation patterns** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance	€ / %	€ / %

Questions	Answers	
activities due to a **change in solar radiation patterns** per % of increase/decrease (please provide an estimation)?		
D - What level of **change in solar radiation patterns** would substantially influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	%	%
E - How much would the investment be to adapt the generation facility to a **change in solar radiation patterns** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in solar radiation patterns** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in solar radiation patterns** at the critical level**?**		
- Increase:		
- Decrease:		
22 - Precipitation change	**In case of a lower precipitation**	**In case of a higher precipitation**
A - Do you believe that a **change in precipitation** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in precipitation** per meter of increase/decrease (please provide an estimation)?	€ / m	€ / m
D - What level of **change in precipitation** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	m	m
E - How much would the investment be to adapt the generation facility to a **change in precipitation** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in precipitation** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in precipitation** at the critical level?		
- Increase:		
- Decrease:		
23 - What would be another structural climate change effect? Please specify: **Effect:**	**In case of a lower effect**	**In case of a higher effect**
A - Do you believe that a **change in the specified effect** would affect the costs of your ordinary operation and maintenance activities?	☐ Yes ☐ No	☐ Yes ☐ No

Questions	Answers	
B - Could you please elaborate on your answer?		
C - If yes, what would be the additional costs (also including production losses) for your ordinary operation and maintenance activities due to a **change in the specified effect** per unit of increase/decrease (please provide an estimation)?	€ / unit	€ / unit
D - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and is therewith considered critical?	unit	unit
E - How much would the investment be to adapt the generation facility to a **change in the specified effect** at the critical level**?**	€	€
F - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
G - What types of assets need to be invested in to adapt the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
24 - Extreme weather conditions		
Concerning an increase in occurrence of potential future extreme weather conditions, how is the facility affected? Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
25 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Questionnaire 8 – Biomass-based power utilities

Dear Sir/Madam

On behalf of the European Commission, our consortium, consisting of ECORYS, ECN and NRG, performs a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire takes about 30 minutes to complete.

Thank you for your time.

The Project Team

Questions	Answers
Section 1 – General questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the plant?	☐ Public ☐ Semi-public ☐ Private ☐ Other (please specify)
4 - Where is the plant located (address and country)?	
Technology	
The technology information and subsequent questions can be answered for a group of plants in your portfolio if information on a plant-level is not available or relevant.	
5 - Please describe the power generation technology used (including the use of CHP, if relevant)	
6 - Please describe the cooling technology used (if any)	
7 - What is the installed capacity of the plant (in MW_e)?	
8 - What has been the (approximate) capacity factor (operation time during the year) in the last five years? (in %)	
9 - What is the (approximate) electrical efficiency of the plant? (in %)	
10 - When has the power or CHP plant been commissioned?	
11 - What is the expected economic lifetime of the power/CHP plant?	Years
12 - When would re-investments (e.g. retrofitting, significant upgrades) in the power generation facility be needed?	
Strategy regarding climate change	
13 - Have you evaluated the risks and vulnerability to climate-related disruption of the generation facility?	☐ yes ☐ no
14 - If yes, what has been done in detail?	
15 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
16 - If yes, what has been done in detail?	
17 - Are you considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are	

Questions	Answers
mitigated per investment?	
Regulation and investment regime	
18 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
19 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
20 - How have investments in new equipment been funded in the last five years?	☐ Public funding ☐ Parent company ☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:
Section 2 - Climate Change	
The following questions deal with the specific climate change effects for your power plant (s). If any of the impacts does not apply to your plant(s), please move to the next topic.	
21 - Cooling water impacts	
The questions of item 21 relate to changes in cooling water temperatures, and only apply to installations using water-cooling. Please move to the next item if this does not apply to your facility.	
A - Could you provide information on the bandwidth of outlet **cooling water temperatures** that is currently agreed with preconditions for operating your facility at nominal and maximum output?	
B - Please indicate the legal maximum temperature according to your license.	
C - In case that this **maximum temperature** is reached, do you have to stop the power production at all or may you continue operation at reduced capacity?	
D - When confronted with an increasingly higher surface water temperature, how is the facility affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
E - Please describe how the normal operation and maintenance of the facility would be affected.	
F - What would be the costs associated with a **change in cooling water temperature** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/˚C	

Questions	Answers	
or % loss of operation/˚C)?		
G - When confronted with an increasingly higher surface water temperature , what kind of provisions[54] do you envisage for keeping **sufficient cooling capacity** for operating your facility?		
H - What types of assets need to be invested in for adapting the power generation facility to the **effects on cooling water** outlined above?		
I - Please estimate the associated investment costs, if possible.	€	
J – If sufficient electricity supply cannot be imported from abroad to the national grid, would you foresee any relaxation of **the permissible maximum temperature** at the cooling water outlet by national regulation (possibly at reduced capacity)?		
22 - Air temperature change		
	Lower air T	**Higher air T**
A - Please describe how the normal operation and maintenance of the facility would be affected at different levels of air temperature change.		
B - What level of **change in air temperature** would substantially influence the operations of your production facility, leading to a major investment, and would be considered critical?	˚C	˚C
C - What types of assets need to be invested in for adapting the generation facility to a **change in air temperature** at the critical level**?**		
- Increase:		
- Decrease:		
D - Please estimate the associated investment costs, if possible.	€	€
E - What other costs might be associated with **a critical change in air temperature** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/˚C or % loss of operation/˚C)?		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in air temperature** to the critical level without any precautionary provisions?	%	%
23 - Biomass supply change		
	Lower biomass supply	**Higher biomass supply**
A - Please describe how the normal operation and maintenance of the facility would be affected.		

[54] Examples of technical measures to cooling water systems for inland sites to be implemented, would be the use of cooling towers (before/after) the condenser. Construction of water reservoirs that would be an additional cooling water supply in case of 'hot' summers. Examples of envisaged technical measures for cooling water systems for seaside sites, to ensure operation of the facility, are protective measures against high water levels.

Questions	Answers	
B - What level of **change in biomass supply** would substantially influence the operations of your production facility, leading to a major investment, and would be considered critical?	t	t
C - What types of assets need to be invested in for adapting the generation facility to a **change in vegetation (biomass supply)** at the critical level**?**		
- Increase:		
- Decrease:		
D - Please estimate the associated investment costs, if possible.	€	€
E - What other costs might be associated with a **change in biomass supply** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/t or % loss of operation/t)?		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in biomass supply** to the critical level without any precautionary provisions?	%	%
24 - Precipitation change		
	Lower precipitation	**Higher precipitation**
A - Please describe how the normal operation and maintenance of the facility would be affected at precipitation levels different to the up-to-date average.		
B - What level of **change in precipitation** would significantly influence the operations of your production facility, leading to a major investment, and would be considered critical?	m	m
C - What types of assets need to be invested in for adapting the generation facility to a **change in precipitation** at the critical level?		
- Increase:		
- Decrease:		
D - Please estimate the associated investment costs, if possible.	€	€
E - What other costs might be associated with a **change in precipitation** with implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/m or % loss of operation/m)?		
F - What percentage of the average produced electricity could still be generated in the facility following a **change in precipitation** to the critical level without any precautionary provisions?	%	%
25 - What other structural climate change effects could affect the normal operation and maintenance of the facility?		
A - When confronted with a change in the specified effect, to what extent is the facility likely to be affected?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	

Questions	Answers	
	Lower	**Higher**
B - Please describe how the normal operation and maintenance of the facility would be affected.		
C - What level of **change in the specified effect** would significantly influence the operations of your production facility, leading to a major investment, and would be considered critical?	unit	unit
D - What types of assets need to be invested in for adapting the generation facility to a **change in the specified effect** at the critical level?		
- Increase:		
- Decrease:		
E - Please estimate the associated investment costs, if possible	€	€
F - What would be the costs associated with a **change in the specified effect** due to implications on productivity, production costs, etc.? Could you give a quantitative estimation (in terms of €/unit or % loss of operation/unit)?		
G - What percentage of the average produced electricity could still be generated in the facility following a **change in the specified effect** to the critical level without any precautionary provisions?	%	%
26 - Indirect effects		
Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future?		

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team

Koen Rademaekers Ecorys	Jaap Jansen ECN	Jan van Hienen NRG

Questionnaire 9 – Electricity transmission and distribution companies

Dear Sir/Madam

Our consortium, consisting of ECORYS, ECN and NRG, has been tasked to follow a study on Investment needs in power generation facilities due to the effects of climate change. This study will be key in drafting new policies for the electricity sector.

An important result of the study will be to represent the interest of stakeholders involved in the sector, such as you. For this reason, we ask you to answer to a short questionnaire to help us collect information and to bring your interest to the attention of the European Commission.

This questionnaire will take overall about 15 minutes.

Thank you for your time.

The ECORYS Project Team

Questions	Answers
Section 1 – General Questions	
1 - What is the name of your organisation?	
2 - What is your position in the organization?	
3 - What is the ownership structure of the grid?	☐ Public ☐ Semi-public ☐ Private
4 - For what region is your institution responsible (country – ies)?	
Technology	
5 - In what category can the network facility be placed?	☐ Distribution ☐ Transmission ☐ Transmission and distribution
Strategy regarding climate change	
6 - Have you evaluated the risks and vulnerability to climate-related disruption of the networks within your remit?	☐ yes ☐ no
7 - If yes, please elaborate?	
8 - Have you developed a long-term strategy to respond to climate-related disruption?	☐ yes ☐ no
9 - If yes, please elaborate?	
10 - Are you currently considering provisions to adapt to climate change effects, as part of normal business planning, lifetime extension programmes, contingency plans?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
• If not considered, could you indicate why not?	
• If considered, could you give an impression of investment planning and indicate which climate change risks are mitigated per investment?	
Regulation and investment regime	
11 - Are your tariffs imposed by the regulator?	☐ Yes ☐ No
12 - If yes, what are the methods used to determine tariff levels in this case?	☐ Price cap ☐ Cost recovery on asset base Other:
13 - How have – thus far – investments in new equipment and basic technology been funded?	☐ Public funding ☐ Parent company ☐ Free Cash flow ☐ Bond or debt market sources Other, please specify:

Questions	Answers	
Section 2 – Climate Change Effects		
The following questions address the specific climate change effects that possibly impact on the electricity network.		
Water level change (increase / decrease of the sea level and connected consequences, increase of lake/river level if relevant)	**In case of a lower water level**	**In case of a higher water level**
16 - Do you believe that a **change in water level** would affect the costs of your ordinary activities?	☐ Yes ☐ No	☐ Yes ☐ No
17- Could you please elaborate on your answer?		
18 - If yes, what would be the additional costs (also in terms of gradual losses) for your ordinary activities due to a **change in water level** per meter of increase/decrease (please provide an estimation)?	€ / m	€ / m
19 - What level of **change in water level** would significantly influence your activity and the operations of the production facilities in your area leading to major investments and is therewith considered critical?	m	m
20 - What would be the costs to adapt the infrastructure to the effects of a **change in water level** at the critical level?	€	€
21 - What percentage of the average transported electricity could still be transported in the network following a **change in water level** to the critical level without any precautionary provisions?	%	%
22 - What types of assets need to be invested in to adapt the infrastructure to a **change in water level** at the critical level**?**		
- Increase:		
- Decrease:		
Air temperature change	**In case of a lower air temperature**	**In case of a higher air temperature**
23 - Do you believe that a **change in air temperature** would affect the costs of your ordinary activities?	☐ Yes ☐ No	☐ Yes ☐ No
24 - Could you please elaborate on your answer?		
25 - If yes, what would be the additional costs (also in terms of gradual losses) for your ordinary activities due to a **change in air temperature** per degree of increase/decrease (please provide an estimation)?	€ / ˚C	€ / ˚C
26 - What level of **change in air temperature** would significantly influence your activity and the operations of the production facilities in your area leading to major investments and is therewith considered critical?	˚C	˚C
27 - What would be the costs to adapt the infrastructure to the effects of a **change in air temperature** at the critical level?	€	€
28 - What percentage of the average transported electricity could still be transported in the network following a **change in air temperature**	%	%

Questions	Answers	
to the critical level without any precautionary provisions?		
29 - What types of assets need to be invested in to adapt the infrastructure to a **change in air temperature** at the critical level**?**		
- Increase:		
- Decrease:		
Wind speed change	**In case of a lower wind speed**	**In case of a higher wind speed**
30 - Do you believe that a **change in wind speed** would affect the costs of your ordinary activities?	☐ Yes ☐ No	☐ Yes ☐ No
31 - Could you please elaborate on your answer?		
32 - If yes, what would be the additional costs (also in terms of gradual losses) for your ordinary activities due to a **change in wind speed** per km/h of increase/decrease (please provide an estimation)?	€ / km/h	€ / km/h
33 - What level of **change in wind speed** would significantly influence your activity and the operations of the production facilities in your area leading to major investments and is therewith considered critical?	km/h	km/h
34 - What would be the costs to adapt the infrastructure to the effects of a **change in wind speed** at the critical level?	€	€
35 - What percentage of the average produced electricity could still be generated in the facility following a **change in wind speed** to the critical level without any precautionary provisions?	%	%
36 - What types of assets need to be invested in to adapt the infrastructure to a **change in wind speed** at the critical level**?**		
- Increase:		
- Decrease:		
Precipitation change	**In case of a lower precipitation**	**In case of a higher precipitation**
37 - Do you believe that a **change in precipitation** would affect the costs of your ordinary activities?	☐ Yes ☐ No	☐ Yes ☐ No
38 - Could you please elaborate on your answer?		
39 - If yes, what would be the additional costs (also in terms of gradual losses) for your ordinary activities due to a **change in precipitation** per meter of increase/decrease (please provide an estimation)?	€ / m	€ / m
40 - What level of **change in precipitation** would significantly influence your activity and the operations of the production facilities in your area leading to major investments and is therewith considered critical?	m	m

Questions	Answers	
41 - What would be the costs to adapt the infrastructure to the effects of a **change in precipitation** at the critical level?	€	€
42 - What percentage of the average produced electricity could still be generated in the facility following a **change in precipitation** to the critical level without any precautionary provisions?	%	%
43 - What types of assets need to be invested in to adapt the infrastructure to a **change in precipitation** at the critical level**?**		
- Increase:		
- Decrease:		
Extreme weather conditions		
44 - Concerning an increase in occurrence of potential future extreme weather conditions, how is the network affected? Extreme weather conditions to be considered may include (but are not limited to) more frequently occurring hail and rain storms, higher wind speeds (storms, occurrence of twisters), more frequent lightning, or higher incidence of external fires that affect power transmission (external switch yards, auxiliary transformers)	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
Climate adaptation driving network extension or upgrading		
45 - To what extent does climate-adaptation drive network extension or upgrading?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
46 - Have you considered increasing the share of underground cabling?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
47 - Have you considered developing new connections between network nodes to increase the number of pathways?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
48 - Have you considered strategies to lower the average distance between points of supply and load centres?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
49 - Have you considered installing (new) monitoring equipment to identify climate-related interruptions when these occur?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
50 - Have you considered other types of network development to climate-proof the grid?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
Climate-adaptation in the procedures for operating the electricity network		
51 - To what extent is climate-adaptation considered in the procedures for operating the electricity network?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much	
52 - Have you evaluated and tested the potential to island parts of the	0 1 2 3 4 5 6	

Questions	Answers
network and operate them independently?	Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
53 - Have you considered measures to reduce loads on vital parts to the network, for instance through incentive for users to reduce demand?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
54 - Have you considered other network operating procedures to improve resistance to climate change?	0 1 2 3 4 5 6 Not at all ☐ ☐ ☐ ☐ ☐ ☐ ☐ Very much
Indirect effects	
55 - Climate change effects are likely to impact on your activity indirectly, e.g. in terms of **higher electricity demand** (seasonal or structural), or in terms of **efficiency and safety** concerns. Would such climate change effects have an indirect impact on your activity? How? Are you taking any provisions to face those events in the future? Please elaborate:	

This is the end of the questionnaire. On behalf of the European Commission and of the project team, thank you for taking part in this important project. Your input will be of high value for our research.

Sincerely,

The project team