Energy for Sustainable Development 28 (2015) 10–20

Contents lists available at ScienceDirect

Energy for Sustainable Development

# Investment needs for climate change adaptation measures of electricity power plants in the EU☆

Wietze Lise [a,b,d,*], Jeroen van der Laan [c,d]

[a] AF-Mercados EMI, Ankara, Turkey
[b] ECORYS Research and Consulting, Ankara, Turkey
[c] Trinomics, Rotterdam, the Netherlands
[d] Energy & Environment unit, ECORYS, Rotterdam, the Netherlands

ARTICLE INFO

*Article history:*
Received 26 July 2013
Revised 22 May 2015
Accepted 11 June 2015
Available online xxxx

*JEL Classification:*
Q4
Q54
G32

*Keywords:*
Power plants
Climate change adaptation
Risk assessment model

ABSTRACT

Climate change is expected to have impacts on the power sector, leading to, among others, a need for adaptation measures in the sector in the near future. This paper analyses the need to adapt to climate change impacts for power generation technologies in Europe until 2100. Europe is broadly divided into four geographic climate zones, for which regional climate change impacts are quantified with the help of the ENSEMBLES RT2b data. The European future technology mix is based on two Eurelectric energy scenarios: 'Baseline 2009' and 'Power Choices'. A Risk Assessment Model is formulated which assesses the cost to power plants for adapting to climate change. The analysis shows that thermal generation units most urgently need adaptation measures against floods, whereas off-shore wind power plants would need to take adaptation investments against sea level rise. Furthermore, electricity grids need to adapt to the increased incidence of storms. Finally, hydro generation in the Mediterranean regions needs to adapt to lower levels of precipitation.


## Introduction

Climate change, as indicated in the IPCC's Fifth Assessment Report, is expected to heavily impact on today's society, including the power sector (IPCC, 2014). 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 power 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 climate change adaptation measures for electricity generating facilities in the near future and the quantification of these investments is one of the purposes of this paper, as well as estimating the costs for lost generation due to climate change.

The European Strategy on adaptation to climate change, adopted in June 2013, established climate change adaptation as a core feature of the EU's climate change policy (EC, 2009a, 2009b; European Council, 2013). Climate change mitigation aims at reducing possible future impacts by dealing with the drivers of climate change (e.g. reducing greenhouse gas emissions), while climate change adaptation aims at minimising the impacts and negative consequences of climate change by building resilience into sensitive systems or by exploiting potential benefits. Clearly mitigation is not coming about quickly enough, due to the stalled conference of parties (COP) negotiations and as a result adaptation measures need to be considered urgently to prepare for the impact of climate change.

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

The European Strategy on adaptation to climate change proposes a framework, following the published Commission's Impact Assessment of April 2014, for EU-wide policy action strategy at EU, Member State and local levels (EC, 2007, 2013). It enlists the possible climate change impacts on the power sector, particularly through its link to water supply, rising sea levels and coastal area management. The Impact Assessment suggests that existing legislation should be integrated, e.g.

☆ We thank the European Commission (DG Energy) for funding this project under contract number TREN/09/NUCL/SI2.547222, EUR 24769. We are grateful for the Journal's editor for providing detailed comments and referee's comments, which helped improve the paper's exposition considerably. However, opinions and conclusions expressed are solely the author's.

* Corresponding author at: ODTU Teknokent, Met Alanı, Mustafa Kemal Mahallesi, Dumlupınar Bul. No:208, D Blok No:3 Çankaya-ANKARA/TURKEY. Tel. +90 312 385 9354; fax: +90 312 354 6927.
*E-mail address:* wietze.lise@afconsult.com (W. Lise).

http://dx.doi.org/10.1016/j.esd.2015.06.003
0973-0826/

European Water Framework Directive, European Floods Directive, and the European Marine Strategy Framework Directive. It also sheds some light on future policy developments. Change in water supply, increased incidence of floods and sea level rise can be considered a major threat for operating power plants.

IPCC Working Group 1 (Solomon et al., 2007) expects the global average temperature to increase by about 0.2 °C per decade for the next two decades. Moreover, the impacts of climate change vary regionally; Northern Europe is expected to experience increased annual precipitation and higher winter temperatures, while Mediterranean Europe is expected to experience decreased precipitation and will be most vulnerable to increased summer temperatures and droughts. The average wind speed is likely to increase, leading to an increase of extreme weather events and a higher output of wind generation. 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 is projected to decrease. The increased occurrence of heat waves, for instance, is likely to affect the cooling of nuclear and gas-fired power plants, but could also lead to increased demand from peak plants (gas turbines and pumping stations). Droughts would reduce the output from hydro power plants, due to lower levels of water inflows into the hydro reservoirs. Electricity networks may be overloaded because of sudden increases in the power demand for cooling, which increases also the chances of contingencies due to extraordinary hot weather events.

Parry et al. (2007) provides a detailed overview of possible effects on the power sector in the 21$^{th}$ century and regional variations of the impacts. This is important as the regions have different electricity generation mixes, available resources and climate- or electricity-related policies and agreements. Climate change impacts will vary depending on the electricity generation technology concerned (i.e. fossil fuels, renewable energy sources (RES) and nuclear). Following Parry et al. (2007), one of the purposes of this paper is to categorise and assess the impact of the different climate change effects per electricity generation technology.

This paper is original in its focus on adaptation measures to climate change throughout the power sector value chain. Seljom et al. (2011) identify the effects of climate change to the power system in Norway and shows, among others, that the reduction in cooling demand far outweighs the increase in heating demand. Dowling (2013) takes this one step further by identifying the impacts of climate change on the EU energy system and concludes, for instance, that the impacts will be larger in Southern Europe than in Northern Europe. Taseska et al. (2012) studies the climate change impacts on energy demand in Macedonia and looks especially at the costs of no action and benefits of adaptation. Chu and Majumdar (2012) discuss the challenges for reaching a sustainable energy future and focus on climate change mitigation. Mideksa and Kallbekken (2010) make a review of the impact of climate change on the electricity market, while Tung et al. (2013) apply this to the Taiwanese power market. Hence, climate change impact adaptation in the power sector is not well-covered in the literature.

The main research questions of this paper are: Which climate change impacts are relevant for electricity generation technologies? What will be the severity of these impacts? To address these research questions, this paper details the possible impacts of climate change effects for each electricity generation technology. From a policy perspective, this paper aims at detailing preventive investments and operational changes that can be taken by power plant operators in the EU to reduce 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 climate zones. The main objectives of this paper are, first, to quantify the costs due to lost generation by power generation units by adapting to climate change impacts and, second, to identify investment needs to make power units more resilient against climate change impacts.

The outline of the paper is as follows. The next Section presents the underlying energy scenarios from which the future technology mix can be derived, whereas the third Section presents the climate change scenarios used, which aims at sketching a possible future with substantial mitigation effort (Power Choices, over 90% greenhouse gas reduction by 2050 in the power sector) or no substantial mitigation effort (Baseline 2009). The method for risk assessment for climate change adaptation by power plants is presented in the fourth Section, whereas the fifth Section motivates the quantification of costs needed for climate change adaptation by power plants. The results are presented and discussed in the sixth Section. The final section concludes and provides recommendations.

## Energy scenarios

In order to estimate the size of the EU power sector, the level of generation in 2050 by various technologies in the "Baseline 2009" and the "Power Choices" scenarios of Eurelectric (2010) are used. The main reason for working with these scenarios is that they have a relatively long time horizon, namely until 2050, and it includes all existing climate and energy policies implemented or planned to be installed by 2020, and these are also being used for EU policy making. The Baseline 2009 is in line with the IPCC A1B climate change scenario, whereas the Power Choices scenario is a situation with more ambitious and successfully implemented mitigation measures. In the latter scenario the climate change impact is lower, namely a global average temperature increase of 2 °C as compared to an increase of 3.4 °C in the Baseline 2009. Therefore, the climate change impacts under Power Choices are 41% (1–2/3.4) lower than in the Baseline 2009.[1]

Hence, two energy scenarios of Eurelectric (2010) are followed:

Baseline 2009: A baseline scenario, where today's trends are extrapolated until 2050.

Power Choices: A mitigation scenario, where a 75% greenhouse gas reduction target will be achieved overall by 2050 (over 90% in the power sector).

Table 1 shows the development in terms of the share in main technologies in 2010 and 2050 and the changes in demand which drive the two Eurelectric (2010) scenarios.[2]

Thermal power plants, including biomass combustion, can be considered jointly together in the sense that all would not respond well to floods and that they have a need for cooling. They differ when the demand for water is concerned (Macknick et al., 2012), where stand-alone gas turbines need negligible water, if any. Hydro will be particularly sensitive to the water cycle, which is also sensitive to climate change. Finally, mostly intermittent, renewable technologies are relatively new and largely insensitive to climate change impacts. The transmission and distribution grid, however, even today, is already quite susceptible to weather conditions (Mei et al., 2011) and will be in need of precautionary measures to adapt to climate change.

[1] Alternatively other scenarios could also have been followed. However, these two scenarios were among the first to have a time horizon until 2050 at the time when our research was undertaken. Such other scenarios are not evaluated in our paper. Such scenarios could also include additional small-scale distributed solar PV and importation of concentrated solar-generated power from North Africa, among others.

[2] The two energy scenarios used in this study also have demand projections. We would like to stress that these scenarios also show two paths of demand development. The electricity demand in the baseline 2009 scenario is expected to grow slower than in the Power Choices scenario. This reflects opportunities to replace electricity generation with low carbon renewable technologies in achieving a 75% reduction in greenhouse gas emissions. Hence, demand could vary and are dependent, in part, on changes in climate. This is especially true for year to year changes in periods of excessive heat (expected to increase with climate change) and periods of excessive cold (expected to decrease with climate change). The paper points out the adaptation costs for power plants under these extreme events.

**Table 1**
Share of main generation technologies and the demand increase in four decades.

| | | Baseline 2009 | Power choices |
|---|---|---|---|
| | 2010 | 2050 | 2050 |
| Nuclear | 28% | 28% | 27% |
| Fossil fuels | 53% | 39% | 35% |
| Hydro | 10% | 8% | 7% |
| Other RES | 9% | 25% | 31% |
| Demand | 0% | +42% | +61% |

## Climate change scenarios

For the development of climate change scenarios it is important to have a thorough understanding of the complexity of climate data, assumptions, uncertainties and restrictions. There is no single global climate model that can take into account the overall dynamism of climate systems and exogenous meteorological influences. Therefore, there are multiple Global Climate Models (GCMs), with accompanying scenarios, that focus on specific climate change related issues that may be relevant for any specific region, climatic zone or climatic feature. The IPCC scenarios are projected by about 25 GCMs leading to multiple outcomes for the IPCC scenarios that would need to be reviewed and analysed in relation to one another.

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) differs 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 the GCMs as the range of scenario output is smaller, and as such the accuracy level of RCM output is lower than that of GCMs.

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. The following scenarios are the basis of our analysis:

- The IPCC A1B scenario is chosen as the point of departure (also the point of departure in the Baseline 2009 energy scenario). This scenario is referred to and used in comparable studies as the baseline development (IPCC, 2007). In this scenario, the impacts of climate change will be most severe and more adaptation measures are needed in the power sector to avoid these climate change impacts.
- The experiments of the ENSEMBLES RT2b project scenario database (RCM) have been used to divide the IPCC A1B scenario into regional and localised climatic impacts (Ensembles, 2009). The RT2b data is based on the IPCC A1B scenario. The ENSEMBLES RT2b project scenario projects monthly data for the European climate system within the IPCC A1B scenario boundaries until 2100. In other words, the RT2b data can be used for scaling down the global IPCC A1B scenario (GCM) to a regional level.

To identify regional differences in climate change impacts, the EU has been divided into four different climate zones. The following qualitative criteria for allocating EU Member States to a climate zone were taken into consideration: North versus South Europe, coastal versus non-coastal location and limiting the climatic differences within a region and maximising the differences between regions. This led to the following four climate zones (see Fig. 1): Baltic region (Region A), North Sea region (Region B), Central and Eastern Europe (Region C) and Mediterranean region (Region D).

This bundling of the EU into 'climate zones' helps to distinguish between relevant aspects regarding electricity generating technologies, climate change impacts and investment needs on a regional level, without needing to go into the tedious details at the country level. For example, the conditions for generating electricity in the North are different compared to the South. Furthermore, the electricity generation technology mix in broad terms varies greatly within these four climate zones.

Table 2 shows the difference in generation technologies across the EU by presenting their share in the four climatic zones in the EU for the Baseline 2009 scenario for the year 2050. This shows for instance that nuclear is mainly concentrated in the North Sea region (France is located here), whereas hydro has the highest concentration in the Baltic region (even though Norway is excluded). Table 2 also 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.

The ENSEMBLES RT2b project scenario data has been retrieved via the Climate Data Explorer of the Dutch Meteorological Institute of The Netherlands (KNMI). The Climate Data Explorer covers several datasets of the ENSEMBLES framework programme. Several experiments are available within these ENSEMBLES RT2b datasets, each individually representing specific climatological or geographical impacts. The experiments within the RT2b datasets are projected by different European meteorological institutes with different RCMs that have different sensitivity levels for the climate variables, namely wind, precipitation and surface temperature. These main climate variables were identified as most important for electricity generation according to the sector and expert groups.

In order to get the regional climate change impacts in the four climate zones as identified in Fig. 1, average values of climate variables are taken in a square area bounded by longitudes and latitudes (left lower corner, right upper corner) as shown in Table 3. 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.

The climate change scenarios were accordingly developed following the experiments in the ENSEMBLES RT2b data, based on the extremes (in terms of experiment data outputs). The experiments have been selected in such a way that a wide coverage is possible for the key climate change variables wind, temperature and precipitation. As a result, the following experiments have been selected as proxies for the scenarios:

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

The data for climate change variables 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 to an annual basis.

The following eight relevant climate change variables were identified could be quantified using RT2b data. These relate to changing weather patterns, e.g. the level of precipitation, cloud coverage, temperature profiles, wind intensities and flows (where the proxy for quantifying the climate change impact is given in the brackets):

1. Water temperature changes (proxy: sea surface temperature);
2. Air temperature changes (proxy: 2-meter land surface temperature);
3. Precipitation changes (proxy: % change in precipitation levels);
4. Wind speed changes (proxy: 10-meter land surface wind speed);
5. Sea level changes (proxy: average temperature (air + water) changes times IPCC sea level increase factor (0.13 m/°C temperature rise));
6. Occurrence of floods (proxy: % change in intense precipitation events);
7. Occurrence of heat waves (proxy: % change in 2-meter land surface maximum air temperature);
8. Occurrence of storms (proxy: % change in 10-meter land surface maximum wind speeds including gust).

Climate is relatively stable, whereas weather is changeable. Therefore, climate data should be averaged over a longer time period for a

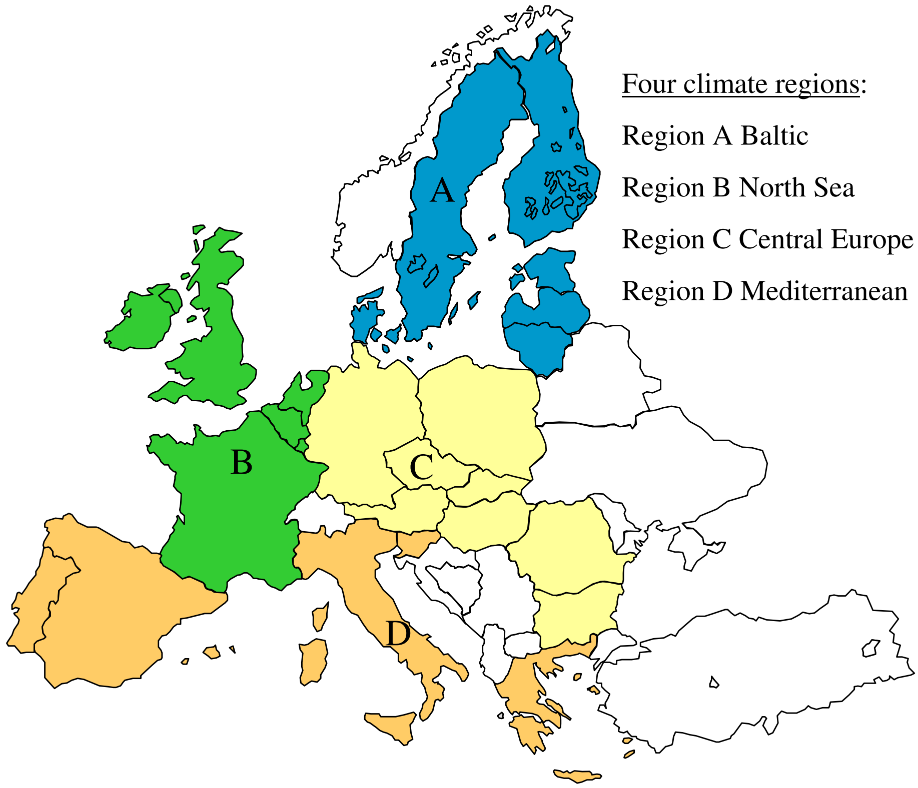


**Fig. 1.** Geographic climate zones in the EU. Note: At time of the research Croatia had not yet joined the EU and therefore the map shows the EU with 27 Member States.

meaningful analysis. The data range (1950-2100) of the retrieved climate variables was therefore averaged into two aggregates, namely the reference period (1950-2000) and 2080 (2060-2100).

Fig. 2 reports the results for three key climate variables for two situations based on two energy scenarios (Baseline 2009 and Power Choices as introduced in Section 2). These three variables are chosen, as they have the most distinct variation and their variations also drive the variability of the other five climate variables. They are based on the average values from the three regional climate change scenarios (WIND, TEMP and RAIN), as explained above. Since the Baseline 2009 scenario corresponds with A1B, the values as derived from the three regional climate change scenarios can be used directly. The Power Choices scenario corresponds to a less severe climate change impact due to substantially more mitigation efforts, namely that the temperature increase will not exceed 2 °C by 2080. The Baseline 2009 scenario corresponds to an expected temperature increase of 3.4 °C until 2080. Hence, the climate change impacts are expected to be 41% less severe under Power Choices by 2080. This assumption has been applied to all climate change effects. It is further assumed that the climate change impacts under Power Choices are 10% less severe than under the Baseline 2009 for 2050 to represent a gradual path to 2080. In this way the energy and climate change scenarios have been aligned.

Perhaps the most important impact of climate change is an increase in the average world surface temperature varying between 1.5–3.5 °C until 2100 (see Fig. 2). 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 is a relatively minor climate change impact, with a tendency towards a slight decrease.

**Table 2**
Share of generation technology per climatic zone in 2050 (Baseline 2009).

| | Region A | Region B | Region C | Region D | EU |
|---|---|---|---|---|---|
| Nuclear | 34% | 43% | 15% | 22% | 28% |
| Fossil | 17% | 30% | 52% | 43% | 39% |
| Hydro | 22% | 4% | 8% | 8% | 8% |
| Other RES | 27% | 23% | 25% | 27% | 25% |
| Thermal total | 68% | 77% | 73% | 70% | 73% |
| Share in generation in EU | 8% | 34% | 31% | 26% | 100% |

## Climate change impacts and risk assessment

### *Qualitative climate change impacts in the power sector*

In 2010, for all generation technologies, power plant operators and regulators have been interviewed in all EU Member States to identify and quantify the climate change impacts that will affect the power sector in the EU.[3] Table 4 shows the qualitative interpretation of these interview results, namely whether there is a link between generation technologies and transmission networks and eight climate change impacts (as identified in Section 3), together with the expected severity.

Table 4 shows the technology-wise vulnerability to various climate change indicators. It is important to note that these technology-wise vulnerabilities are perceived vulnerabilities rather than calculated impacts. The table shows that an increased occurrence of floods is assessed as having the most severe impacts, 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 are expected to be severe and preventive investments

[3] The detailed questionnaires, nine in total, which is specific for each type of technology, can be found in DG Energy (2011). These questionnaires are not repeated here to reduce the size of the paper.

**Table 3**
Latitudes and longitudes for climate zones.

| | Baltic | | North Sea | | Central & Eastern Europe | | Mediterranean | |
|---|---|---|---|---|---|---|---|---|
| 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 |

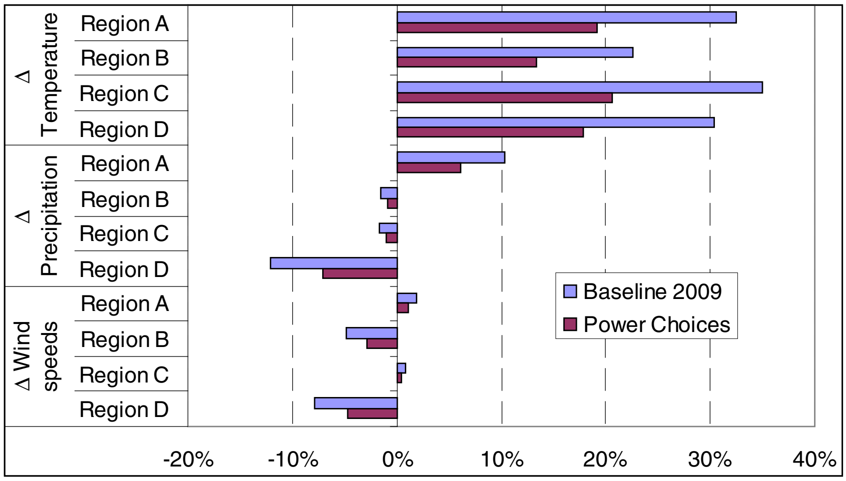


**Fig. 2.** Values of three key climate change variables and different climate zones in Europe. Note: Δ Temperature is expressed in percentages, where a 1% change is equivalent to a temperature increase of 0.1 °C, Δ Precipitation = % change in precipitation amounts, Δ Wind speeds = % change in average wind speeds. Here the difference between 1950-2000 and 2060-2100 is shown. The figure shows the average values of the three selected experiments: WIND, RAIN and TEMP.

will be needed to adapt to the new climatic situation. The other medium to small climate change impacts, would generally only lead to a loss in generation, without the need for adaptation investments.

The table also 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. Furthermore, regional changes in precipitation patterns will also affect hydro generation; with an increase in precipitation by about 10% in the Baltic region and decrease in precipitation by more than 10% in the Mediterranean region (see Fig. 2). 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, biomass has the same climate change sensitivities as thermal generation technologies. Furthermore, the relatively new solar technologies and geothermal show only minor climate change sensitivities and only under some extreme events. Finally, grids are the most sensitive to climate changes, with high sensitivities for air temperature (reduction in current carrying capacity or thermal ratings) and increased storm damage, whereas other extreme events also need to be taken into consideration even though the climate sensitivity is relatively low.

*Formulation of the risk assessment model*

The quantitative assessments of the interviews fed into the quantitative assessment of climate change impacts that are described below. Here, the quantitative climate change and energy scenarios are joined together with adaptation cost estimates in the Risk Assessment Model, which goes through the following steps:

- Divide EU into four climate zones, with maximum difference between the zone and minimal difference within the zones (Fig. 1).
- Linking climate change impact indicators to generation technologies and networks, and identifying the relevant indicator-technology pairs (Table 4).
- Quantification of climate change indicators using three relevant regional models (Fig. 2).
- Estimate climate change adaptation cost functions (Table 5), namely:
  - Loss of generation (gradual/incremental loss).
  - Investment needs after critical threshold.
- Electricity scenarios to estimate the generation volume per technology (Section 2).
- Estimate total costs for adapting to the situation in 2080 (Section 5).

Depending on the severity of the impact, a threshold point needs to be found beyond which investments are necessary to be able to continue power plant operation. Fig. 3 shows that climate change can lead to a gradual/incremental loss in power generation (slope effect) or lead to an investment need once a certain threshold value of climate change is exceeded.

## Costs for climate change adaptation measures at power plants

There are three major climate change impacts which have serious financial consequences for power plants, namely higher air and water temperatures and precipitation changes. These are presented and discussed below.

*Higher air temperature*

The main effect of higher average air temperatures (which also lead to more extreme summer heat waves) is that the efficiency of turbines will decrease due to the lower difference between outside (ambient) and turbine temperature. The interviews with power plant operators showed that this is mainly relevant for natural gas, oil and nuclear, but negligible for coal and biomass where the outside temperature would not affect power plant operation. In addition, the output of gas turbines

**Table 4**
Qualitative link between technologies and climate change effect.

| Technology | Δ air temperature | Δ water temperature | Δ precipitation | Δ wind speeds | Δ sea level | Floods | Heat waves | Storms |
|---|---|---|---|---|---|---|---|---|
| Nuclear | 1[a] | 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 [b] | - | - | - | - | - | 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 |
| *Total count* | *6* | *5* | *1* | *2* | *1* | *9* | *7* | *6* |

[a] 3 = Severe impact, 2 = medium impact, 1 = small impact, - = no impact.
[b] CSP = concentrated solar power.
Note: Adapted from Table 14 in DG Energy (2011).

**Table 5**
Quantifying climate change effects: the cost of lost generation and investment need after a critical threshold is crossed.

| Climate change effect | Technology | Lost power generation €/MWh/climate change effect | Investment Need €/kW | Threshold value | Remark |
|---|---|---|---|---|---|
| Change in air temperature | Nuclear | 0.07 | 50 | 5 | 0.1% less per 1 °C increase |
| | Biomass | 0 | 150 | 5 | Negligible impact |
| | Natural gas | 0.07 | 75 | 5 | 0.1% efficiency decrease per 1 °C |
| | Coal | 0 | 100 | 5 | Negligible impact |
| | Oil | 0.07 | 85 | 5 | 0.1% efficiency decrease per 1 °C |
| | Grids | 0.14 | 40 | 5 | 0.2% extra transmission losses per 1 °C |
| Change in water temperature | Nuclear | 0.14 | 50 | 5 | 0.2% per 1 °C increase |
| | Biomass | 0.14 | 150 | 5 | Small plants have larger cost per unit |
| | Natural gas | 0.14 | 75 | 5 | Low investment costs |
| | Coal | 0.14 | 100 | 5 | |
| | Oil | 0.14 | 85 | 5 | Higher than natural gas |
| Change in precipitation | Hydro | -70 | 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 of measurement in %. |
| Change in wind speeds | Wind onshore | -4.7 | 350 | 100% | 1% lower yield for 0.15 m/s lower average wind speed according to stakeholder. Need for more sensitive rotor |
| | Wind offshore | -4.7 | 500 | 100% | |
| Change in sea level | Wind offshore | 0 | 500 | 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 | 0 | 100 | 25% | |
| | Hydro | 0 | 100 | 25% | |
| | Biomass | 0 | 150 | 25% | |
| | CSP | 0 | 200 | 50% | CSP plants are in arid areas |
| | Geothermal | 0 | 200 | 50% | |
| | Natural gas | 0 | 100 | 25% | |
| | Coal | 0 | 150 | 25% | |
| | Oil | 0 | 110 | 25% | |
| | Grids | 0.07 | 40 | 50% | |
| Occurrence of heat waves | Nuclear | 0.7 | 50 | 100% | |
| | Biomass | 0.7 | 150 | 100% | Heat waves are mainly an issue in the Mediterranean area |
| | PV | 0.7 | 250 | 100% | |
| | Natural gas | 0.7 | 75 | 100% | |
| | Coal | 0.7 | 100 | 100% | |
| | Oil | 0.7 | 85 | 100% | |
| | Grids | 0.07 | 40 | 100% | |
| Occurrence of storms | Hydro | 0 | 250 | 100% | |
| | Wind onshore | 0.7 | | 100% | Loss of power generation due to storms |
| | Wind offshore | 0.7 | | 100% | Loss of power generation due to storms |
| | PV | 0 | 250 | 100% | Extreme events would have only minor effects on PV |
| | CSP | 0 | 250 | 100% | Extreme events would have only minor effects on CSP |
| | Grids | 0.07 | 50 | 25% | Stronger construction needed |

will be lower due to lower atmospheric pressure under higher temperatures. Furthermore, the losses of electricity networks increase with rising temperatures due to reduction in thermal ratings of power lines.[4]

[4] Thermal rating measure the current carrying capacity of power transmission lines.

Another major issue with power transmission is sagging lines, where due to higher temperatures lines may hit tree tops and lead to an outage. A too low air temperature could lead to icing problems, but under a temperature increase scenario such events are projected to become less frequent, hence having a small positive impact. However, this small positive impact will be offset by the previously mentioned negative climate change impacts and as a whole there will be a negative impact on

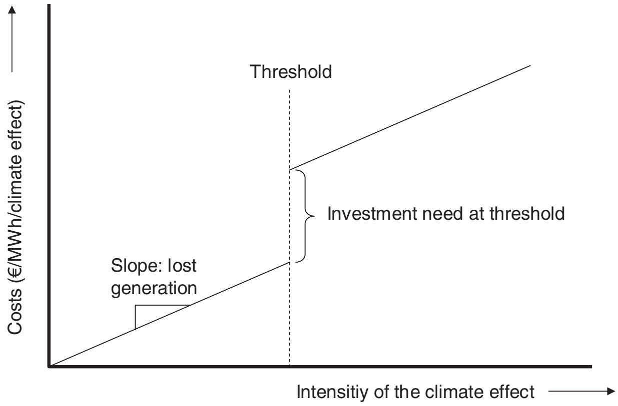


**Fig. 3.** Investment needs and power generation losses due to climate change.

power transmission lines due to global warming. There are also indirect effects of higher temperatures in the day to day demand patterns, where the level of demand in summer grows more quickly, which is also the period when the power plants are most vulnerable, leading to new challenges in balancing the power system. In summary, we derived from the interviews with power plant operators, the following quantified climate change impacts:

- This effect of higher air temperatures can be roughly quantified as 0.1% efficiency reduction for every increase in temperature by 1 °C for natural gas and oil fired power plants, which translates into a 0.2%/°C loss in power generation. This translates into higher generation costs, due to higher fuel consumption;
- For nuclear it is estimated that there is 3 MW less available per °C. For an average plant size of 3000 MW this translates into a 0.1%/°C loss in power generation;

The following investment needs are identified:[5]

- Preventive investment is possible by constructing a cooling tower. This is often a standard equipment of new combined cycle natural gas fired power plant, 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 also quite common for various coal fired power plants;
- 2.5 M€ (≈2.5 €/kW) is the cost to refurbish 4 existing cooling towers leading to 2–3 °C cooler water. Four new cooling towers would cost around 80 M€ (≈80 €/kW), which would be more expensive than refurbishment;
- To avoid "thermal inversion" (rare but possible at outside temperatures of 45 °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 a relatively low benefit;
- High-temperature transformers, gas-insulated lines and real-time temperature rating can help reduce the temperature impacts on network capacity.

*Higher water temperature*

The main effect of higher water temperatures is that the allowable cool-water inlet temperature can become too high for cooling the turbines (generally during a summer heat wave, which will be longer and more frequent under higher average temperatures). Then the ability to generate will reduce due to cooling constraints. This is relevant for all Rankine cycle power plants that use water for cooling, including biomass and nuclear, due to regulatory requirements concerning discharge water temperatures. The water temperature of interest is that coming out of the cooling tower, which is determined by wet bulb atmospheric temperature. 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 impacts on nature (aqua life and bio-organisms) from 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.

The following investment needs are identified:

- Preventive investment may be needed to increase the pumping capacity to circulate more water to keep the water outlet temperature at the desired level as needed by regulation;
- 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 region. In total the hydro output in Europe would be about equal, whereas a higher output in the north would compensate a lower output in the south. An increase (decrease) in precipitation 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. As a regulatory constraint the flux of water can be constrained as well, which will also lead to a loss in power generation.

Another climate change impact is the increased frequency of storms, which is expected even though the average wind speed is not expected to change or to drop somewhat. These increased storm events would also lead to a higher intensity of lightning, which would in particular affect networks.

The following investment needs are identified:

- 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. Water management should therefore take a comprehensive approach to harmonising 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 needs to be stand-by.

*Quantification of power plant adaptation costs*

Table 5 indicates per climate change effect and electricity generating technology:

1. the lost power generation (in €/MWh/climate change effect, measured as °C for temperature changes and % for other climate change effects);
2. the investment needs (in €/kW), also for adding additional generation capacity to make up for the generation shortfall;

[5] We would like to add a disclaimer to this paper that cost estimates are uncertain and may change due to new technological developments, global market sentiments and volatile prices of material costs, among others. This paper tries to make a cautious estimate of the order of magnitude for the EU power sector to adapt to expected climate change impacts, given the currently commonly used generation technologies.

3. the threshold value for which a climate change effect will create an investment need (see Fig. 3).

As has been discussed in the previous section, the determination of the data in Table 5 is motivated by the discussion in Sections 5.1–5.3, which is based on extensive stakeholder interviews, using the questionnaires as presented in the Annex D to DG Energy (2011) and expert judgment.

Table 6 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 are commonly used values, e.g. ECF (2010).

The cost of generation loss is based on the assumption of 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.

## Results

Figs. 4 and 5 present the results of the risk assessment analysis in monetary terms for the four climatic zones in the EU in 2080 for two scenarios, where the monetary impacts are much larger for the Baseline 2009 (Fig. 4) than for the Power Choices scenario (Fig. 5). The figures present the aggregated 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 adaptation cost. A distinction has to be made between "investment needs" and incremental costs of adaptation. The bars with solid border indicate that there is an investment need where 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 would otherwise risk a shut-down. The other bars indicate the incremental costs of adaptation, when electricity generation technologies in that climatic zone face efficiency losses. However, the critical climate change threshold value for that technology and climatic zone are not crossed yet and investments are not needed for the successful continuation of electricity generation.

The main results in terms of climate change adaptation costs by power plants in the EU in the year 2080, with main focus on the Baseline 2009 scenario, are as follows:

- Gradual increases in climate change impact lead to lower amounts of generation output, whereas additional investments are needed for adaptation for the following two cases:
  - lower precipitation severely affecting hydro in the South;
  - Sea level rise affecting off-shore wind.

- Changes in precipitation benefits the North, but the estimated total cost to the South is at least two times greater.

**Table 6**
Technology-wise capacity factor and the resulting multiplier to convert investment needs from €/kW to €/MWh.

| | Capacity factor | Multiplier |
|---|---|---|
| Nuclear | 80% | 0.011 |
| Hydro | 40% | 0.023 |
| Wind (onshore) | 30% | 0.031 |
| Wind (offshore) | 35% | 0.026 |
| Biomass | 70% | 0.013 |
| PV | 18% | 0.051 |
| CSP | 25% | 0.037 |
| Geothermal | 70% | 0.013 |
| Natural gas | 75% | 0.012 |
| Coal | 75% | 0.012 |
| Oil | 25% | 0.037 |
| Grids | 60% | 0.015 |

- Extreme events pose the greatest adaptation challenge:
  - Floods would affect nuclear, hydro and 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.

Hence, this paper finds that possible effects of climate change are that certain renewable energy technologies will become more difficult to realise, whereas the efficiency of thermal power plants tends to decrease. This would lead to more fossil fuel consumption and thereby exacerbating the GHG emission and climate change problem. This effect would be most pronounced in the Baseline 2009 scenario, whereas it could be considered insignificant in the Power Choices scenario. This is a further motivation for implementing the Power Choices scenario.

In this paper *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 (1429 million € in Baseline 2009; 479 million € in Power Choices).
- An increase in the sea level will require preventive investments for offshore wind power plants (5172 million € in Baseline 2009; 2198 million € in Power Choices).
- An increase in the occurrence of floods will require preventive investments for thermal generation technologies (5846 million € in Baseline 2009; 745 million € in Power Choices and only in Central Europe).
- An increase in the occurrence of storms will require preventive investments for networks (3868 million € in Baseline 2009; 565 million € in Power Choices and only in Central Europe).

Next, two other climate change impacts are qualified as medium, meaning that these climate change impact are not yet expected to require investments for the consulted scenarios, but would need investments in the event that climate change impacts would 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, no impacts in central Europe, while there is a projected decrease in the south.

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 would decrease the output of onshore and offshore wind parks.
- A higher frequency of flooding events could pose a threat to concentrated solar power, geothermal and grids.
- A higher frequency of heat waves would decrease the output of all thermal generation technologies, but also of solar PV and could lead to a reduction in current carrying capacity or thermal ratings of grids.
- A higher frequency of storm events would decrease the output of various renewable generation technologies, namely hydro, onshore and offshore wind, solar PV and concentrated solar power.

Planning for new generation technologies needs to prepare the power plant operator for the possible impacts of climate change and avoid unexpected disruption of generation, where, in addition to the

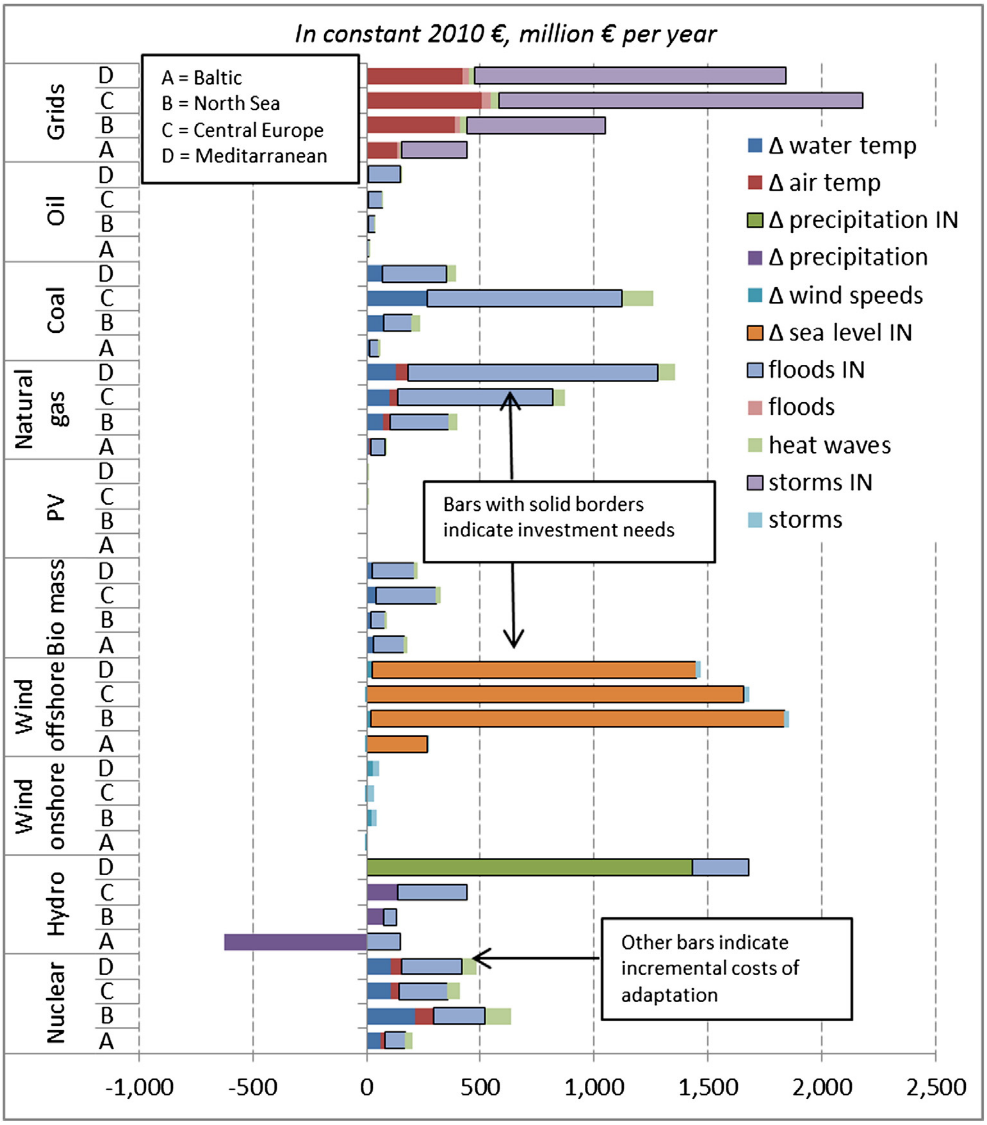


**Fig. 4.** EU wide monetary impacts of climate change on power plant operation for four climatic regions (Baseline 2009). Note: On the vertical axis the electricity generation technologies are listed, including the climatic zones classification. On the horizontal axis the adaptation cost are presented, where a 'positive' adaptation costs are an increase in operational costs, whereas 'negative' adaptation costs are an increase in operational benefits. These costs are yearly costs expressed in 2010 million € and are needed in the years when the climate change impacts materialise.

climate change impacts mentioned above, the expected lifetime of a power plant is an important aspect to consider as well.

## Conclusions, synthesis and recommendations

The analysis of this paper 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 will need to be 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, because the technology is renewed and replaced relatively often.

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 and behavior is a necessary condition.

It is common in the power industry to assume particular (economic) lifetimes for generation technologies. This paper has used 20 years for each technology considered. This is an in-between assumption, where a 10 years financing period is often used by bankers, whereas the physical lifetime could be much longer, e.g. 50 years for coal/nuclear, or even up to 100 years for hydro. Making lifetime an integral part of the Risk Assessment Model would be an area for future research.

The analysis in this paper is driven by two energy scenarios which have thermal generation as the dominant technology in Europe to generate electricity for the coming decades until 2050. This analysis 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;

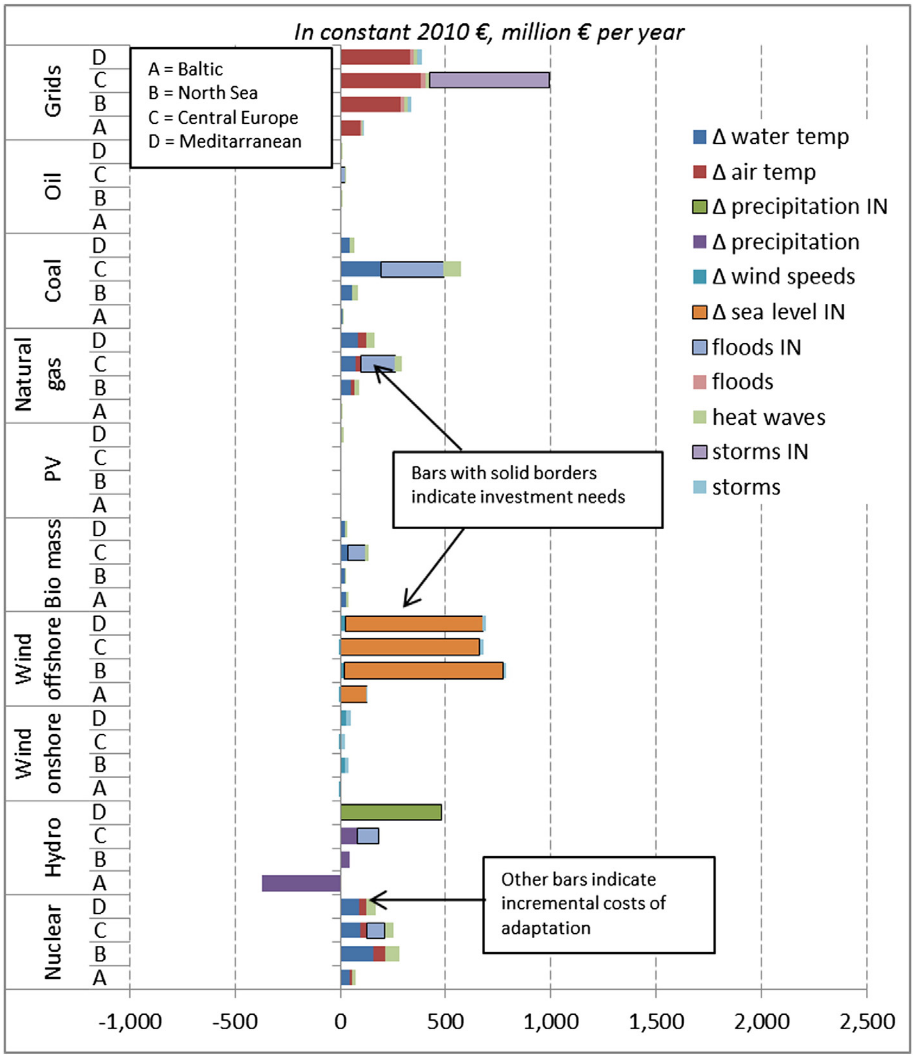


**Fig. 5.** EU wide monetary impacts of climate change on power plant operation for four climatic regions (Power Choices). Note: On the vertical axis the electricity generation technologies are listed, including the climatic zones classification. On the horizontal axis the adaptation cost are presented, where a 'positive' adaptation costs are an increase in operational costs, whereas 'negative' adaptation costs are an increase in operational benefits. These costs are yearly costs expressed in 2010 million € and are needed in the years when the climate change impacts materialise.

- 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 with the current technology without making investments, possibly at the cost of a gradual loss of output.

In practice hardly any investment needs to adapt to climate change have been identified. This is because climate change has not yet crossed a critical threshold, but without mitigation, it is becoming likely that it will cross this threshold within the 21$^{st}$ century. Climate change, being 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.

The main recommendations from this paper 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;
- 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. However, since the renewable energy share is still relatively low and technology development is ongoing, adaptation to climate change can be expected.

## References

Chu S, Majumdar A. Opportunities and challenges for a sustainable energy future. Nature 2012;488:294–303.

DG Energy. Investment needs for future adaptation measures in EU nuclear power plants and other electricity generation technologies due to effects of climate change. Final report, European Commission, Directorate General Energy; 2011. [http://ec.europa.eu/energy/nuclear/studies/doc/2011_03_eur24769-en.pdf].

Dowling P. The impact of climate change on the European energy system. Energ Policy 2013;60:406–17.

EC. 'Green Paper: Adapting to Climate Change in Europe – Options for EU Actions', June 2007, Brussels, COM (2007) 354. European Commission; 2007.

EC. White Paper: Adapting to Climate Change – Towards a European framework for action, April 2009, Brussels, COM (2009) 174. European Commission; 2009a.
EC. Commission Staff Working Document accompanying the White Paper: Adapting to Climate Change – Towards a European framework for action, April 2009, Brussels, SEC (2009) 338. European Commission; 2009b.
EC. 'Commission Staff Working Document Impact Assessment Part 1 accompanying the document: An EU Strategy on adaptation to climate change', April 2013, Brussels, SWD(2013) 132 final. European Commission; 2013.
ECF. Roadmap 2050 – Practical guide to a prosperous, low-carbon Europe – Annex A: Generation, European Climate Foundation, vol. 1; 2010 [Brussels, http://www.roadmap2050.eu/attachments/files/Vol1_Appendices.zip].
Ensembles. ENSEMBLES, Climate change and its impacts at seasonal, decadal and centennial timescales, Summary of research and results from the ENSEMBLES project. http://ensembles-eu.metoffice.com/docs/Ensembles_final_report_Nov09.pdf, 2009.
Eurelectric. Power Choices, Pathways to Carbon-Neutral Electricity in Europe by 2050. http://www.eurelectric.org/PowerChoices2050/, 2010.
European Council. An EU strategy on adaptation to climate change – Council conclusions'. June 2013, 11151/13, General Secretariat, Council of the European Union; 2013.
IPCC. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team. In: Pachauri RK, Reisinger A, editors. Geneva, Switzerland: IPCC; 2007. p. 104. [Intergovernmental Panel on Climate Change].
IPCC. Fifth Assessment Report (AR5). http://www.ipcc.ch/, 2014.
Macknick J, Newmark R, Heath G, Hallett K. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ Res Lett 2012;7(4):045802.
Mei S, Wu S, Zhang X, Wang G, Xia D. Power system blackout model with transient constraints and its criticality. Eur Trans Electr Power 2011;21:59–69.
Mideksa TK, Kallbekken S. The impact of climate change on the electricity market: A review. Energ Policy 2010;38:3579–85.
Parry ML, Canziani OF, Palutikof JP, Van der Linden PJ, Hanson CE, editors. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2007.
Seljom P, Rosenberg E, Fidje A, Haugen JE, Meir M, Rekstad J, et al. Modelling the effects of climate change on the energy system–A case study of Norway. Energ Policy 2011;39:7310–21.
Solomon S, et al, editors. Climate Change 2007: The Physical science Basis. Contribution of Working Group I to the Fourth Assessment report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press; 2007.
Taseska V, Markovska N, Callaway JM. Evaluation of climate change impacts on energy demand. Energy 2012;48:88–95.
Tung C, Tseng T, Huang A, Liu T, Hu M. Impact of climate change on Taiwanese power market determined using linear complementarity model. Appl Energy 2013;102:432–9.