IVM Institute for Environmental Studies

Adaptation in the Dutch electricity sector

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Summary

Our climate is changing, which is *very likely* the result of anthropogenic greenhouse gas emissions. Both mitigation and adaptation measures are needed, since they are complementary: bringing down greenhouse gas emissions improves the chance of milder consequences, lowering the costs and efforts of adaptation. Climate change is also expected to have an impact on the likelihood of the occurrence and duration of extreme weather events. The aim of this research is to explore and identify adaptation options against present and future extreme weather events that are relevant for stakeholders in the Dutch electricity sector. Including the perspectives of stakeholders will increase the legitimacy of the advised adaptation strategy for policy. In this research, the perspectives of stakeholders are obtained in a series of interviews.

In 2006 the Royal Netherlands Meteorological Institute (KNMI) published four climate scenarios for the Netherlands until 2050. In every scenario the temperature increases during summer and winter time with respect to the current climate. This leads to a greater likelihood of occurrence of heat waves. Precipitation during the summer in the scenarios with more westerly circulations decreases, whereas unchanged circulation leads to wetter summers. In all scenarios the amount of rainfall per event will increase, leading to more extreme rainfall events. No changes in extreme storm activity have been found. The expected sea-level rise for 2100 is between 35 and 85 centimeters.

Based on demand and supply scenarios published by Energy Centre the Netherlands (ECN) and the Netherlands Environmental Assessment Agency (PBL), there is an expected growth in supply of and demand for electricity. The largest part of the electricity supply will continue to come from large-scale, thermal production units, although there can be an expected growth in renewable and small-scale production when set and intended national and European policies are executed. The growth in size of the electricity system makes it more vulnerable to the impacts of extreme weather events; the risk of damages from the impacts of extreme weather events becomes higher as the size of the exposure is raised.

For the research nine interviews have been conducted. Interviewees were asked to assess fourteen adaptation options that were selected during the literature study. The assessment entailed scoring the fourteen adaptation options based on four evaluation criteria. Hereafter, the interviewees were asked to rank the evaluation criteria. The

scores and the ranking of the evaluation criteria were used as input for a multi-criteria analysis (MCA). The resulting output is an evaluation criterion-based ranking of the selected adaptation options.

The highest ranked adaptation options are the option to invest in research and development (option 14) and the option to have a greater deployment of decentralized electricity generation (option 3), followed by further increasing the interconnectivity with the European electricity market (option 6). After conducting a sensitivity analysis, the results can be seen as robust. The lowest ranked options are the option to build new power plants in the East (option 12) and the option to diversify the modes of coal delivery (option 8).

The main reason given for the high scores of Investment in research and development (option 14) is that it is seen as generally important. More specifically, the resulting techniques are supposed to be more resilient and adaptable to extreme weather events. Also, the possibility of climate change mitigation through innovative technologies and future economic benefits were given as reasons. The option was ranked relatively moderate with respect to feasibility; the main reason for this is the current economic crisis. Also, the government is perceived to be reluctant to invest in innovative technologies.

More decentralized electricity generation (option 3) is seen as a way to spread risk and make the supply of electricity more resilient when facing (climate) uncertainties. A greater deployment of decentralized electricity production is also deemed to be relatively feasible, mainly because it is technologically possible. However, some interviewees indicated that the techniques are still costly.

Increasing the interconnectivity with the European electricity markets (option 6) is seen as a way to make the electricity system more reliable; problems with electricity supply caused by extreme weather events, can be overcome when connected countries (partially) provide the electricity supply and thereby limit the amount of damage. It is recognized by the interviewees that the Netherlands is already fairly interconnected with other countries. However, it is also recognized that the increased interconnectivity could lead to problems with ensuring transport capacity and the needed investments to overcome them.

The three highest ranked adaptation options are concerned with making the electricity system more resilient to the impact from extreme weather events by increasing the diversity of the supply system, thereby increasing the complexity of the system. The complementary nature of the three highest ranked adaptation options leads to the conclusion that they should be pursued in tandem. Policy implications are that the results demand a government that is actively involved by setting policy goals not aimed at short-term efficiency or cost-effectiveness, but at the long-term by stimulating a diverse and complex energy system. However, current policy points into another direction. Increasing diversity and resilience may turn out to be the key to linking adaptation to mitigation efforts.

1 Introduction

1.1 Introduction

We are addicted to it, and it is available with the switch of a button: electricity. There is hardly any activity, social or economical, that does not involve the use of electricity either directly or indirectly. This dependence makes our electricity supply of vital importance and worth protecting from threats. One of the threats and challenges faced by the electricity sector comes from extreme weather events, produced by the climate system. However, the climate system is changing due to human influences. The first working group of the Intergovernmental Panel on Climate Change (IPCC) concluded that the largest part of the increase in average temperature since mid-twentieth century is *very likely* the result of increased anthropogenic greenhouse gas emissions (Van Dorland and Jansen, 2007, p. 12). Furthermore, due to the inertness of the climate system, even when anthropogenic emissions are brought back to pre-industrial levels, societies will experience changes in climate conditions. This indicates the need to adapt to climate change (Vasileiadou, forthcoming). However, both adaptation and mitigation efforts are needed; they are complementary: bringing down greenhouse gas emissions improves the chance of milder consequences, lowering the costs and efforts of adaptation (Van Dorland & Jansen, 2007). Climate change is also expected to change the likelihood of the occurrence and duration of extreme weather events (Klein Tank & Lenderink, 2009, p. 7); when the overall probability distribution of a climate variable changes, the changes in extremes at the end of the distribution are also likely to be affected (IPCC, 2012, p. 5).

This report forms the end product of a research project for the Earth Sciences and Economics master (ES&S) at the Vrije Universiteit Amsterdam (VU), the Netherlands. The research has been a part of the collaborative project among the Royal Netherlands Meteorological Institute (KNMI), the Netherlands Environmental Assessment Agency (PBL) and the Institute for Environmental Studies (IVM) financed by the Dutch Organization for Scientific Research (NWO). The project is called 'Bridging the gap between stakeholders and climate modellers: demand-driven adaptation assessment for uncertain changes in weather extremes'. One of the three aims of the project is “the identification and exploration of climate adaptation options, inter alia through a dialogue on weather extremes including climate scientists and stakeholders from various sectors.” (Petersen, 2009, p. 7). Relevant information about weather extremes obtained from climate models may be missed by stakeholders from specific sectors, because they are not able to read the models or receive the information, giving rise to the 'communication gap'. The NPDA project is focused on bridging this gap, since the involvement of stakeholders will become more and more important for adaptation measures looking at future projections for the Netherlands (Petersen, 2009).

The main aim of this research is to explore and identify adaptation options against present and future extreme weather events in the Dutch electricity sector. In order to strengthen the competitiveness of the Dutch electricity sector, and because the electricity sector plays a key role in the economy of the Netherlands, the sector has been marked as an 'economic leading sector' (or in Dutch 'economische topsector') (Ministry of Economic Affairs, 2011, p. 3). Research commissioned by the European Commission shows that most actors in the European electricity sector do not explicitly consider climate change in their business operations, but are focussed on implementing government imposed mitigation regulations (Rademaekers et al., 2011, p. 55-77).

More specifically, this research aims to explore and identify adaptation options that are relevant for stakeholders in the Dutch electricity sector. According to De Bruin et al. (2009) "(…) [by] involving (local) stakeholders and experts in the development of a (national) adaptation strategy, the gap between the top-down and bottom-up approaches to adaptation can be bridged, thereby providing (national government) the ability to reach optimal policy decisions about adaptation (…)." (De Bruin et al., 2009, p. 25). As Cuppen suggests: "Participation of stakeholders in decision-making can increase the legitimacy and accountability, both of the decision-making process as well as of the outcomes (…), thereby increasing the likelihood that the outcome is useful." (Cuppen, 2009, p. 8). In this study the perspectives of stakeholders from the electricity sector on the possible adaptation options in the sector are obtained in a series of interviews.

1.2 Research questions

This leads to the following research question:

"Which adaptation options for present and future extreme weather events can be identified for the Dutch electricity sector, and which adaptation options are most

relevant from the perspective of stakeholders that are active in different parts of the sector?"

The aim is to find the most relevant adaptation options for the electricity sector. These options are identified through a literature study and stakeholder consultation. After the identification of the options, a multi-criteria analysis (MCA) is conducted using a series of interviews with stakeholders. In order to answer the main research question the following sub-questions need to be answered:

Sub-question 1: *"Which future extreme weather events are predicted by climate scenarios for the Netherlands?"* This question will be answered in section 2.1.

Sub-question 2: *"What is the current state of the Dutch electricity market in terms of composition and spatial distribution, demand and supply and production-mix and which future changes are predicted by electricity scenarios?"* This question will be answered in section 2.2.

Sub-question 3: *"Which current and future extreme weather events pose a potential risk for the different components of the Dutch electricity sector, what are the resulting vulnerabilities and which adaptation options to the vulnerabilities can be identified?"* This question will be answered in section 2.3.

Sub-question 4: *"Which of the identified adaptation options are most relevant from the perspective of stakeholders from the electricity sector?"* This question will be answered in chapter 4.

1.3 Outline of the report

Chapter 2 of the report contains a literature study. First, the expected changes in extreme weather events for the Netherlands are presented in section 2.1. Section 2.2 contains an overview of the Dutch electricity sector (2.2.1) and scenarios for future supply and demand for electricity in the Netherlands (2.2.2). Furthermore, it uncovers the relevant actors for this research. In section 2.3 the expected changes in extreme weather events and the vulnerabilities they induce for the Dutch electricity sector are described. Hereafter, adaptation options against the induced vulnerabilities are identified and selected in section 2.4. Chapter 3 describes the methodology that is used in the research to obtain the results. The results are presented in chapter 4.

Chapter 4 starts-off with descriptive statistics (4.1), followed by the ranking of the adaptation options in the MCA (4.2.1) and a qualitative analysis of the results (4.2.2). Chapter 5 entails the conclusion and discussion section.

2 Literature study

2.1 Extreme weather events in the Netherlands

Climate change can be identified by "(…) changes in the mean and/or the variability of its properties and that persist for an extended period, typically decades or longer." (IPCC, 2012, p. 3). The question of what is causing this change in climate is subject to debate, because "climate change may be due to natural internal processes or external forcing, or to persistent anthropogenic changes in the composition of the atmosphere or in land use." (IPCC, 2012, p. 3). The debate is moving towards a consensus; the 2007 IPCC report concludes that the largest part of the increase in average temperature since mid-twentieth century is *very likely* the result of increased anthropogenic greenhouse gas emissions (Van Dorland and Jansen, 2007, p. 12). However the future is dynamic and uncertain. One way to cope with this uncertainty is through the development of scenarios (Dessai & Van der Sluis, 2007; Dammers et al., 2011).

Climate scenarios can be defined as "consistent and plausible images of the future climate" and "(they) are intended as support for climate impact studies and adaptation measures." (Klein Tank & Lenderink, 2009, p. 7). In 2006 a set of scenarios was published by the KNMI on how the climate in the Netherlands is expected to change during the 21st century. In this publication Van den Hurk et al. (2006) present four scenarios which include changes in precipitation, temperature, potential evaporation and wind centred around the year 2050, and sea-level rise centred around the year 2100 (Van den Hurk et al., 2006; Klein Tank & Lenderink, 2009, p. 7). The four scenarios were established by combining information from a wide range of global and regional models (Global Circulation Models and Regional Circulation Models). Observations were used to test which of the models were best at describing the climate in north-western Europe (Van den Hurk et al., 2006; Klein Tank & Lenderink, 2009).

Figure 1 is a schematic overview of the four climate scenarios as published by the KNMI. Four different scenarios were developed, depending on changes in global temperature and air circulation patterns. The *Gematigde* (moderate) scenarios describe a rise in average global temperature of 1°C for G and G+ and a change in air circulation patterns over the Atlantic Ocean and Western Europe for G+. The *Warm* scenarios describe a rise in global average temperature of 2°C for W and W+ and a change in air circulation patterns over the Atlantic Ocean and Western Europe for W+. Changes in air circulation patterns are expected to cause warm and wet winters and hot and dry summers (Van den Hurk et al., 2006; Klein Tank & Lenderink, 2009, p. 7).

In 2009 KNMI published a report with supplements to the 2006 scenarios. In this publication Klein Tank & Lenderink (2009) conclude that: "the climate scenarios published by the KNMI in 2006 show that changes in extreme weather events will probably be different than changes in the average weather." (Klein Tank & Lenderink, 2009, p. 7). Extreme weather events are by definition low probability, high impact events and are defined by the IPCC as: "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or above) ends of the range of observed values of the variable." (IPCC, 2012, p.3).

As described above, in every KNMI 2006 scenario the temperature increases in summer and in winter time with respect to the current climate. This leads to a greater likelihood of occurrence of heat waves. Precipitation during the summer in the scenarios with more westerly circulations decreases, whereas unchanged circulation leads to wetter summers. In all scenarios the amount of rainfall per event will increase, leading to more extreme rainfall events. No changes in extreme storm activity have been found. The expected sea-level rise for 2100 is between 35 and 85 centimeters (Van den Hurk et al., 2006; Klein Tank & Lenderink, 2009). The changes in the severity and frequency of extreme weather events, changes the risks that the climate system imposes on the electricity sector and its different components. Since the electricity sector plays such a large socio-economical role in the Netherlands, it should to be protected from the effects of a changing climate. How the changes in weather extremes affect the Dutch electricity sector is the subject of the next section.

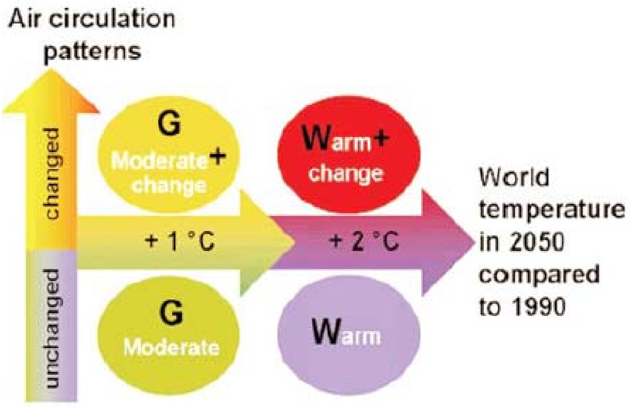


Figure 1: Schematic overview of the KNMI'06 scenarios (source: Van den Hurk et al., 2006)

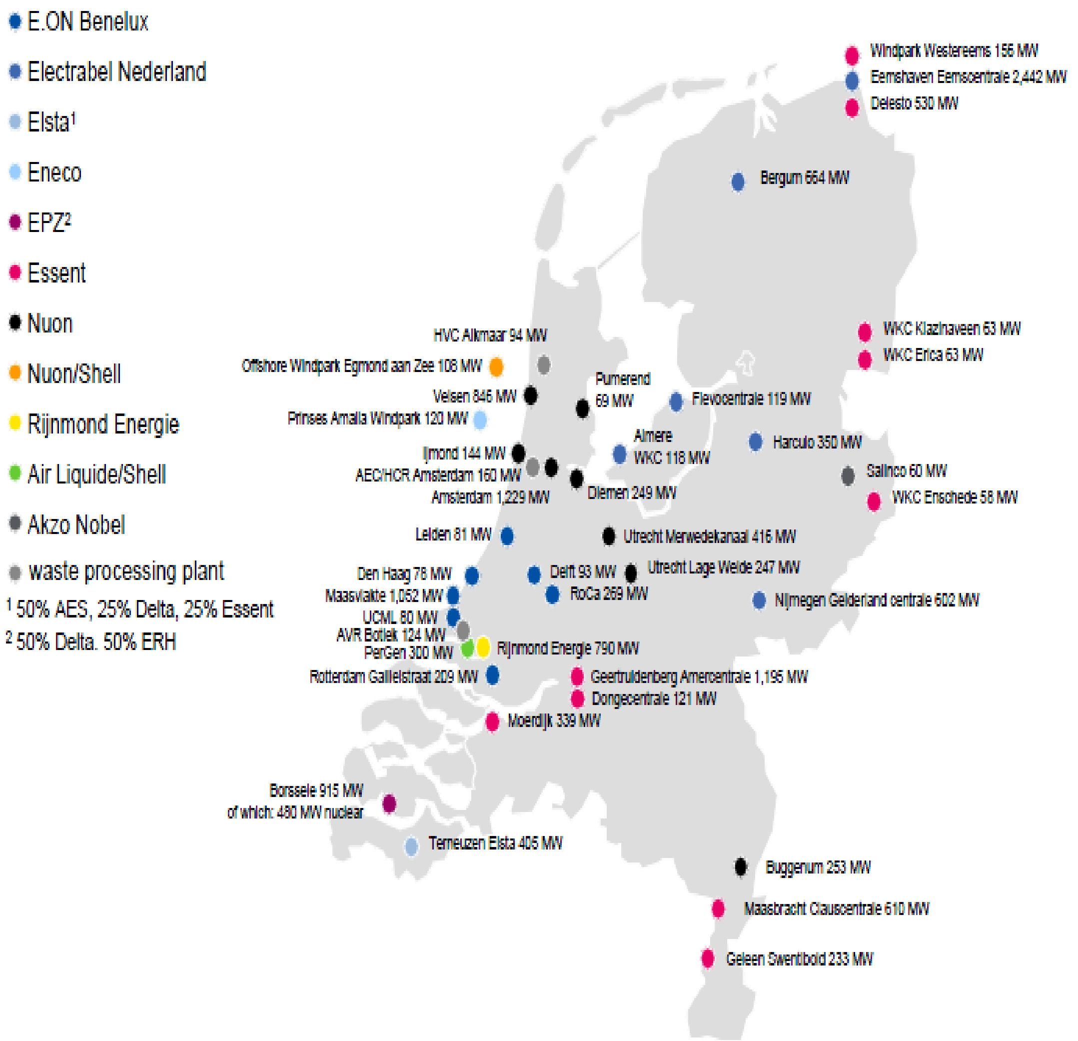
2.2 The Dutch electricity sector

Since July 1st, 2004 the Dutch energy market has been completely liberalized. This meant the separation of electricity supply and network operation. The liberalization of the electricity market is set out in the *Electricity Act 1998* (Electriciteitwet 1998) (Wenting 2002; Energie-Nederland, 2011). Moreover, in order to strengthen the competitiveness of the Dutch electricity sector, and because the electricity sector plays a key role in the economy of the Netherlands, the sector has been marked as an 'economic leading sector'. This highlights the importance of the sector for the Netherlands and therefore the need to make it climate-proof. Furthermore, it is the ambition of the Dutch government to make the energy supply more sustainable and strive for a climate-neutral economy in 2050. Also, the government wants to make the energy supply less dependent on increasingly scarce fossil fuels, while providing end-users with reliable energy at competing prices (Ministry of Economic Affairs, 2011, p. 2-3; Ministry of Infrastructure and Environment, 18-11-2011). These changes create a window of opportunity for a more (climate) resilient electricity sector. The focus of this research is on the electricity generation and (national and regional) transport grid, because these components are the most vulnerable to the impacts of extreme weather events.

2.2.1 Electricity supply in the Netherlands

Electricity in the Netherlands is mainly supplied through large-scale production. This is in most part done by five electricity generation companies: Electrabel Netherlands (Electrabel GDF Suez from 2012), E.On-Benelux, Essent (part of RWE), Nuon (part of Vattenfall) and EPZ (Energie-Nederland, 2011, p. 23). In 2009 these companies (EPZ excluded) owned 64% of the total installed capacity. Essent and Nuon had a share of 57.5% in the retail electricity market for households and 49% in the business-to-business market (Essent, 02-06-2010. See also annex A). Besides the high percentage of large-scale production, the Netherlands has a large share of electricity produced by cogeneration plants (CHP) employed by the industrial (10% of total electricity production) and horticultural sector (13% of total electricity production) (Essent, 02-06-2010 and annex A; Energie-Nederland, 2011, p. 23). The share of sustainable electricity, coming from solar, wind, hydro-power and biomass, in final electricity consumption was 9.1% in 2010 (Energie-Nederland, 2011, p. 23), but has risen to around 10% in 2012 (Van Dril et al., 2012).

Figure 2: Production sites with installed capacity greater than 60 MW owned by electricity producers (from Energie-Nederland, 2011).



The electricity transportation network in the Netherlands has been split in two levels: a national grid of voltages levels of 380 and 220 kilovolts (kV), managed by the Transmission Service Operator (or TSO) Tennet, and a regional grid which ranges between 150 and 50 kV that is managed by regional network operators (Energie-Nederland, 2011, p. 17-18). From the regional network bulk-users are supplied. Households are supplied via the low-tension network (Energie-Nederland, 2011, p. 35). Besides the national transportation of electricity, there are also flows of electricity coming in and going out of the Dutch electricity market through interconnections with Belgium, Denmark, Germany, Norway and the United Kingdom (Van Dril et al., 2012. See figure 3).

Figure 3: Electricity transportation network in the Netherlands (from Van Dril et al., 2012, p. 68).

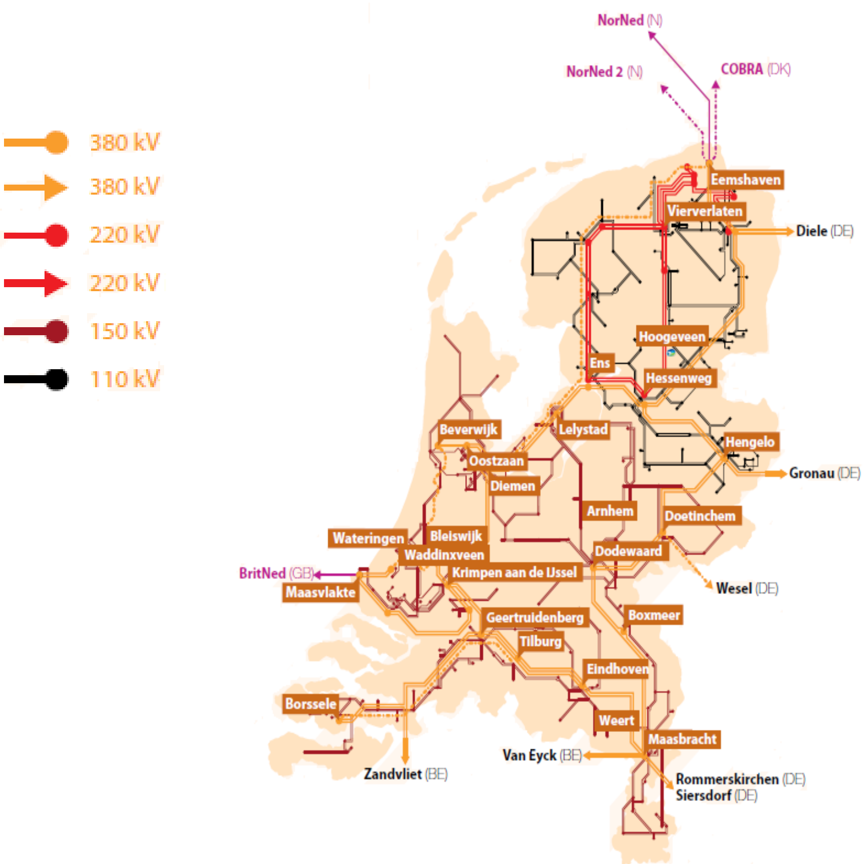


Figure 4: Regional electricity network operators (from Energie-Nederland, 2011, p. 19).

	AANSLUITINGEN gas / gas	CONNECTIONS elektriciteit / electricity	nummer op kaart pagina / number on map page
Cogas Infra en Beheer B.V.	138.000	53.000	1
Delta Netwerkbedrijf B.V.	187.000	207.000	2
Endinet***	451.000	106.000	3
Enexis B.V.	1.908.000	2.631.000	4
Intergas Energie B.V.****	148.000	-	5
Liander N.V.***	2.156.000	2.914.000	6
RENDO Netbeheer B.V.	102.000	32.000	7
Stedin B.V.	1.946.000	2.054.000	8
Westland Infra Netbeheer B.V.	52.000	55.000	9

On the electricity market a balance needs to be maintained between supply and demand. This is done by balance responsible or BRs. BRs are market parties that retail electricity. Any market party can assume this role, but it is mostly fulfilled by suppliers and/or traders (Energie-Nederland, 2011, p. 80). The role of the BR is to inform Tennet daily on the transactions for the following day with other BRs, by setting up programs for production, transport and electricity use in their 'energy programs'. The BR party then has the responsibility to abide by the program (Wenting, 2002).

Relevant stakeholders for this research are companies that are responsible for the production of electricity and the supply of electricity to end-users; electricity generation companies, companies responsible for the transport of electricity over the different networks levels of the system and parties that are responsible for keeping balance between supply and demand, because they own the supply infrastructure and production units were the direct damages are inflicted upon. The next section deals with scenarios for future demand and supply in Dutch electricity market.

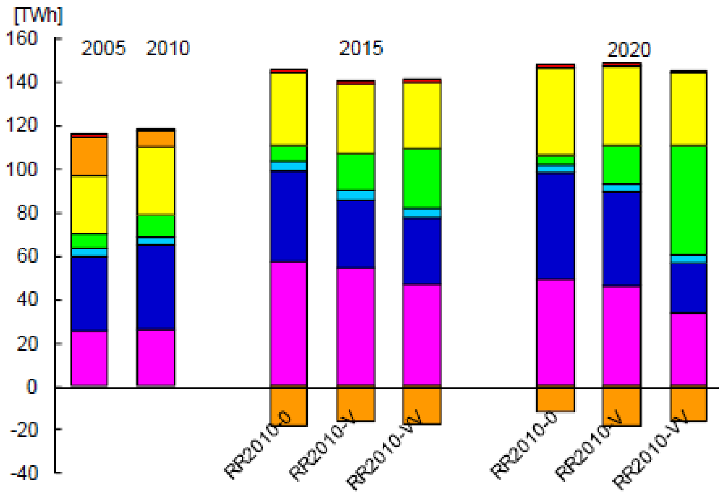
2.2.2 Electricity scenarios for the Netherlands

Energy Centre the Netherlands (ECN) and the PBL Netherlands published a reference projection for energy consumption and CO_2 emission developments in the Netherland until 2020. They made their projections based on three policy alternatives: (1) a variant without national or European policy since 2007 (RR2010-0); (2) currently set national and European policies (RR2010-V) and (3) intended national and European policies (RR2010-VV). As national policy for the Netherlands the program *Schoon en Zuinig* (Clean and Economical or S&Z) is used (Daniëls & Kruitwagen, 2010). The S&Z program is the work program for energy and climate policy until 2020 put forward by the Dutch government in 2007.

Total electricity demand in 2008 in the Netherlands was 120 Terawatt hours (TWh). The projected electricity demand in 2020 with set policies will be 131 TWh and 130 TWh with intended policies. Interconnectivity between north-western European countries will increase and from 2012 and onwards the Netherlands is expected to become a net-exporter of electricity. This is mainly caused by the increase in production capacity and comparative advantage of the coastal locations (cooling-water and relatively low transport costs for coal). Moreover, average electricity prices in the wholesale market are mainly determined by fuel and CO_2 prices; as the German electricity production park has higher average CO_2 emissions due to a large share of brown-coal in the production mix, it is more sensitive to fluctuations in CO_2 prices.

This gives electricity produced in the Netherlands a price advantage. In all scenarios therefore, the Netherlands will become a net-exporter of electricity. In the third scenario, that projects the implementation of intended policies, export is expected to be 19 TWh and for the scenario with intended policies 16 TWh (see figure 5) (Daniëls & van der Maas, 2009; Daniëls & Kruitwagen, 2010, p. 66 and p. 71-72; Seebregts et al., 2009).

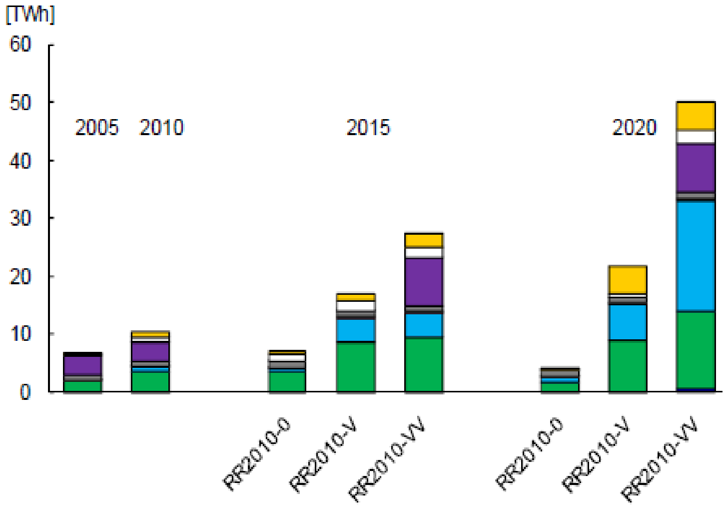
Figure 5: Production mix from coal-fired power plants (pink), gas-fired (blue), nuclear (light blue), renewable (green) and CHP installations (yellow). Electricity import/export is in orange (from Daniëls & Kruitwagen, 2010).



On the supply side the Netherlands has a relatively large growth in production capacity compared to the interconnected countries: in 2008 the Netherlands had approximately 25 gigawatts (GW) of installed capacity; this could grow to 35.6 GW in the case of set policies and to almost 42 GW with intended policies. The difference in installed capacity is caused by the intended expansion of renewable electricity, mainly wind. In the period 2015-2020 power plants with low efficiency are expected to retire. New power plants and power plants that are currently under construction are large scale facilities, ranging from 400 megawatts of electric power (MW_e) to 1600 MW_e (Daniëls & Van der Maas, 2009, p. 31; Daniëls & Kruitwagen, 2010).

The largest difference in electricity production among the three scenarios result from the electricity produced by renewable sources (see figure 6). Without national or European policies the share of renewables will drop to 2.6% in 2020. This share will increase to 6.3% in 2020 for the currently set policies and to 15.5% in the case of the execution of intended policies. The projected increase of renewables in scenarios RR2010-V and RR2010-VV is mainly due to increased wind electricity production capacity, off-shore and to a lesser extent on-shore, and the co-incineration of biomass in power plants. The latter is caused by subsidies from the Subsidieregeling Duurzame Energie (Subsidy scheme for Renewable Energy or SDE) program (Daniëls & Kruitwagen, 2010, p. 80-81). Under the influence of the increasing share of renewable electricity and increased efficiency of electricity production, relative energy savings and emission reduction decrease over time for CHP installations. In the set policies scenario the CHP production capacity grows to 8.4 GW in 2020 (Daniëls & Kruitwagen, 2010, p. 75-76).

Figure 6: Electricity production through renewable resources; off-shore (blue), on-shore (green), biomass co-incineration (purple and white) and yellow is fermentation (from Daniëls & Kruitwagen, 2010).



In any scenario there is an expected growth in supply of and demand for electricity. The largest part of the electricity supply will continue to come from large-scale, thermal production units, although there can be an expected growth in renewable and small-scale production when set and intended national and European policies are executed. The growth in size of the electricity system makes it more vulnerable to the impacts of extreme weather events; the risk of damages from the impacts of extreme weather events becomes higher as the size of the exposure is raised. Vulnerabilities to changes in extreme weather events, specified to the different components of the electricity sector in the Netherlands, are the topic of the next section.

2.3 Climate induced vulnerabilities

On the production side of the Dutch electricity market a trichotomy can be made with respect to harmful climatic effects: thermal power plants, (intermitted) renewables and the electricity transmission and distribution network. The first group can be considered as a homogeneous group with respect to climate change impacts, because thermal power plants need cooling; however, there are different impacts involved with no possibility to cool, from power shortage to dangerous meltdown (e.g. Fukushima in 2011). Intermitted renewables, on the other hand, are variable in their sensitivity. The electricity grid is the most sensitive to climate change effects (Rademaekers et al., 2011, p. 7).

Thermal power plants are vulnerable to flooding, especially nuclear power plants. Inundation can harm vital parts of the power plant and hinder electricity output. Flooding can be caused by extreme precipitation events or sea-level rise combined with a storm event (storm surges). Also, as mentioned above, thermal power plants rely on cooling-water for their electricity output, so they are vulnerable to changes in the quality and quantity of the available cooling water. Heat stress resulting from climate change raises the temperature of the cooling-water, decreasing the efficiency of the production units. Furthermore regulations on water quality limit discharge temperatures on receiving water-bodies (Klopstra et al., 2005), which could lead to shutting down of production units (Rademaekers et al., 2011, p. 57). In the case of water quantity there is insufficient cooling-water available for the cooling of power plants located at rivers, which is more likely to occur in the future as the result of increased drought stress. Besides water-related effects, an expected increase in the ambient air temperature will lead to efficiency losses. In general an increase of one degree Celsius leads to a 0.1 per cent decrease in plant efficiency, but only from temperatures above 35°C the production process is affected (Rademaekers et al., 2011, p. 61).

Renewable electricity sources are expected to have an increased share in the future energy-mix of the Netherlands (OECD/IEA, 2010; Daniëls & Kruitwagen, 2010), in particular electricity from wind-turbines, on-shore and off-shore (Daniëls & Kruitwagen, 2010, p. 81). Sea-level rise can damage the foundations of off-shore wind-turbines through corrosion and impacts from waves (Rademaekers et al., 2011, p. 8 and 66). Wind-turbines located in coastal regions are at risk, because of the increased risk of flooding. Based on the scenarios presented in figure 6, solar PV is not expected to play a major role in the future energy-mix (Daniëls & Kruitwagen, 2010, p. 81). On the other hand the co-firing of bio-mass may play an increasing role in the future energy mix, which experiences the same vulnerabilities as conventional thermal power production units.

Electricity transmission and distribution facilities suffer efficiency losses from increased temperatures and increased risks from flooding due to storm surges and (extreme) precipitation events (Rademaekers et al., 2011, p. 11). An increase in ambient air temperature affects over-head transmission lines because the resistance that is encountered by currents is positively affected by the surrounding temperature. Furthermore, higher temperatures cause transmission lines to expend and as a result hang lower to the ground which may result in risky circumstances e.g. during intense summer thunderstorms with gusts of wind when overhead transportation lines are not cleared of trees, falling trees could hit the transportation lines causing electricity supply to fail.

Demand side changes caused by climate change put higher pressure on the electricity network and may represent an extra (economic) risk for the network in the Netherlands. Wilbanks et al (2008) report on changes in energy consumption due to the warming of the climate in America. Wilbanks et al. (2008) report robust findings on electricity demand, which will most likely increase because of more extensive use of existing air-conditioning equipment and the expected penetration of space-cooling equipment in regions that traditionally have low air-conditioning density and are expected to experience longer and hotter summers (Wilbanks et al., 2008, p. 43-44). This applies to the Netherlands; the amount of hottest days has been increasing steadily. If the heat stress in the Netherlands increases, the largest effect will be experienced during mid-days when the sun is at the highest point in the sky. During this time, the demand for electricity to power cooling-appliances will be at its peak. With the increasing penetration of air-conditioning systems and heat-stress, the increased peak-demand for electricity during mid-day will put an extra burden on the electricity suppliers and transportation network.

In order to make the electricity sector less vulnerable to the impacts of current and future extreme weather events, different adaptation measures can be implemented. The identification of adaptation measures and the role of stakeholder herein is the subject of the following section.

2.4 Adaptation

Impacts from extreme weather events are the result of the severity of the events itself and the exposure and vulnerability of human and natural systems. According to IPCC (2012) exposure and vulnerabilities “are dynamic, varying across temporal and spatial scales and depend on economic, social, demographical, cultural, institutional, governance and environmental factors” (IPCC, 2012, p. 5). The exposure and vulnerability to climate extremes of the Netherlands is primarily influenced by its coastal location in a river-delta. Moreover the centre of economic and social gravity is located below sea-level; in 2009, approximately 70% of Dutch gross national product (GNP) was earned below sea-level (Kolen et al., 2009, p.43), the settlements and inhabitants are concentrated below sea-level. The latter is increasing in the coming decades by 10% or more in some areas (PBL & CBS, 12-10-2011). Besides the exposure to geographical vulnerabilities, the environmentally induced vulnerabilities that lead to the extreme weather events that were indentified in section 2.1 are of importance for adaptation. Fortunately, the Netherlands is well equipped financially and institutionally, and thus it is possible to respond and adapt effectively to projected changes in exposure, vulnerability and climate extremes (IPCC, 2012, p. 8).

Adaptation is defined by the IPCC as “the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities” (IPCC, 2012, p. 3) and by Smit et al. (1999) as “adjustment in ecological, social or economic systems in response to actual or expected climatic stimuli and their effects or impacts” (Smit et al., 1999, p. 2000). According to Dessai and Van der Sluis (2007) adaptation is often reactive and induced by observed extreme weather events and their impacts (Dessai and Van der Sluis, 2007, p. 8). On the other hand there can be anticipatory adaptation “as an essential part of the optimal response to climate change, as it is much likely less expensive than relying on reactive adaptation only” (De Bruin et al., 2009, p. 24). Furthermore, adaptation offers opportunities to handle uncertainties that are rooted in scientific models, but cannot be quantified in principle; adaptation can act as a ‘safety net’ where mitigation fails to take these uncertainties on board (Dessai and Van der Sluis, 2007, p. 11). Societies and their different sectors are often times not adapted to the present occurrence and duration of extreme weather events, let alone future extreme weather events. Research commissioned by the European Commission showed that most actors in the European electricity sector do not explicitly consider climate change in their business operations, but are focussed on implementing government imposed mitigation regulations (Rademaekers et al., 2011, p. 55-77).

There are large uncertainties in the projections of change in extreme events; the large spread in the models of the regional climate is caused by model uncertainty, natural variability and uncertainty in projected emissions. Apart from model uncertainty, society is likely to respond to climate change scenarios, which means that the scenario will change in an anticipatory mode. This reflexive uncertainty is a reason to suggest robust adaptation measures. Robust adaptation measures can only be created together with involved stakeholders, taking into account their perspectives, needs and values (Dessai & Van der Sluis, 2007; Dessai & Hulme, 2004). Stakeholders are actors who have a stake or interest in a particular issue. Identifying the perspectives and priorities of stakeholders on adaptation measures for extreme weather events is of key importance for the success of the measures because they have already dealt with the weather for ages and have developed knowledge and responses (Klein Tank & Lendrink, 2009). Furthermore the participation of stakeholders can improve the likelihood of the implementation, and a useful outcome, of the decision-making process for, adaptation plans. For this research stakeholders were included through the assessment of adaptation options for the electricity sector.

Table 1 shows the extreme weather events for the Netherlands from the KNMI climate scenarios, the resulting vulnerabilities and affected production units, and adaptation options for the Dutch electricity sector, based on an extensive literature review. The numbered options are the adaptation option that are included in the MCA, as will be discussed later.

Table 1: Identified extreme weather events, vulnerabilities, affected components of the electricity supply system and (selected) adaptation options.

Primary indicators	Extreme event	Vulnerabilities	Affected (production) units	Adaptation option (nr.)
Temperature	Increase in the occurrence and severity of heat waves[1]	Higher temperatures of cooling water reduces efficiency[2,4]	Thermal power plants	Improve cooling capacity of thermal power plants[4,5] (1)
				Installation of air-coolers[2]
		Reduced efficiency of power plants (ambient air temperature)[3,4]	Thermal power plants	Improved efficiency heat-exchange mechanisms[4]
				Increased efficiency coolant pumps[4]
		Temperature limits on cooling water outlet[2]	Thermal power plants	Adaptation of regulations to (temporally) allow higher discharge temperatures[4,5] (2)
				More deployment of decentralized electricity generation[5] (3)
		Increased peak-load demand electricity due to cooling appliances [3,4]	All	Use of off-grid heating and cooling (heat and cold storage)[3] (4)
				Installation of electricity storage facilities[3] (5)
				Increase interconnectivity EU electricity market[4] (6)
				Advanced building-designs for less need of cooling[3,5]
				Installation of a smart-grid[3]
		Increased resistance overhead transportation and transportation losses		Electricity transport under-ground[4]

[1] From Klein Tank, A.M.G. & Lenderink, G., 2009
[2] From Klopstra, D. et al., 2005
[3] From Wilbanks et al., 2008
[4] From Rademaekers et al., 2011
[5] From De Bruin et al., 2009

Table 1: Identified extreme weather events, vulnerabilities, affected components of the electricity supply system and (selected) adaptation options (continued).

Primary indicators	Extreme event	Vulnerabilities	Affected (production) units	Adaptation option (nr.)
Precipitation	Increase in the occurrence of droughts[1]	Decrease in cooling-water availability[2,3,4]	River-based thermal power plants	Build new or enhance existing sluices[5] (7)
		Disruption of barge coal delivery[3]	River-based coal-fired power plants	Diversify modes of coal delivery (train, road)[3] (8)
		Increased water pumping for irrigation and residential use[3]	All	
	Increase in the occurrence of heavy precipitation events leading to flooding[1]	Increased flood-risk due to higher river-discharge[4]	Low-laying thermal power plants	Constructing new power plants on elevation[4] (9)
				Build dikes around plants[4] (10)
	Increase in summer precipitation	Required changes in coal handling due to increased moisture content[3]	Coal-fired power plants	Diversification of energy source intake[6]
Sea-level rise	Increase in storm surges leading to flooding[1]	Flooding of thermal production units[4]	Thermal power plants at coast	Installation of extra water pumps in the area of power plant[4] (11)
				Build new power plants in the East[6] (12)
		Damage to the foundations of wind turbines[3,4]	Wind turbines	Re-enforce foundations of off-shore and coastal wind-turbines[4,5] (13)
		Loss of electricity transport equipment[4]	National and regional electricity networks	
All				Invest in research and development[7] (14)

[6] Included on behalf of the researcher
[7] Suggested during the second interview

3 Methodology

3.1 Data collection

3.1.1 Selection of interviewees

The data was collected through a series of interviews with stakeholders that are active in the production and supply of electricity (see annex A for parties that were approached for an interview). The selection of interviewees followed convenience sampling; identified participants were asked if they were prepared to participate in an interview for the research. Individuals that were willing to cooperate were included in the research. In total nine interviews were conducted (list of participants can be found in annex C). The interviews took place in November and December 2012 and they lasted approximately one hour. The interviews were recorded and transcribed verbatim.

3.1.2 Procedure

From table 1 we selected fourteen adaptation options that were the most relevant for the Dutch context. The interviewees were asked to assess the adaptation options selected in section 2 and assign scores to these options, according to four criteria: importance, urgency, no-regret and feasibility. Importance indicates the expected benefits that can be obtained by implementing an option. Expected benefits can be understood as damages avoided from the effects of extreme weather events by a specific adaptation option. The urgency of an adaptation option reflects the need to act quickly, because postponement could lead to increased costs and potentially irreversible damage. No-regret refers to the degree to which the implementation of an option is good; irrespective of changes in extreme weather events, the expected future benefits will be higher than the costs of implementation, even without the benefits of the avoidance of damages from future extreme weather events. Implementing some options is easier than others, because of technical, social or institutional restrictions. These differences are reflected in the criterion feasibility. During the interview the interviewees were asked to elaborate on and explain their scores.

These evaluation criteria have been used before by De Bruin et al. (2009), with the addition of co-benefits and mitigation. Furthermore, De Bruin et al. (2009) included a second round of scoring to assess the feasibility of the adaptation options, based on the criteria technical, social and institutional complexity. For this research the choice was made to only include the first three criteria, because it would keep the interview sizable and the scoring manageable; interviewees were asked to participate in a one hour interview (most of the interviews were completed in approximately forty-five minutes, but some lasted way beyond an hour). The reason not to use co-benefits as a criterion is because there is a considerable overlap with no-regret; they are not mutually exclusive (something that is recognized by De Bruin et al., 2009, p. 28). With regard to mitigation effects, this is something that can be determined with the knowledge possessed by the researcher and can thus be left out of the interviews. The three criteria used in the second round in study of De Bruin et al. (2009) have been put together in one criterion that determines the complexity of implementing an adaptation option, the criterion feasibility. Once again this was done to keep the interview sizable and the assessment manageable.

Table 2: Ranking of adaptation option - score table

	Score				
	1	**2**	**3**	**4**	**5**
Importance	The option has a **very low** level of importance	The option has a **low** level of importance	The option has a **medium** level of importance	The option has a **high** level of importance	The option has a **very high** level of importance
Urgency	The option has a **very low** level of urgency	The option has a **low** level of urgency	The option has a **medium** level of urgency	The option has a **high** level of urgency	The option has a **very high** level of urgency
No-regret	The net benefits are **very low**, irrespective of climate change	The net benefits are **low**, irrespective of climate change	The net benefits are **medium**, irrespective of climate change	The net benefits are **high**, irrespective of climate change	The net benefits are **very high**, irrespective of climate change

Feasibility	The option has a **very low** level of feasibility	The option has a **low** level of feasibility	The option has a **medium** level of feasibility	The option has a **high** level of feasibility	The option has a **very high** level of feasibility

Thereafter the interviewees were asked to rank the evaluation criteria; from one to four, allowing for equal placement (i.e. both importance and feasibility could be placed first). These rankings determine the weights that are assigned to each criterion in the MCA. Finally, the interviewees were asked to add adaptation options which they thought were missing and that should be included for adaptation in their sector.

3.2 Weighted summation

The ranking system put forward in this report is a multi-criteria analysis (MCA) using weighted-summation, whereby the input is acquired through stakeholder and expert consultation. Weighted-summation is used because the approach is methodologically well established, easy to explain and transparent (Janssen, 2001, p. 105). A total score for each adaptation option is calculated by multiplying the scores with its appropriate weight, followed by summing the weighted scores of all criteria using equation (1) (Janssen, 2001).

$$score(a_j) = \sum_{i=1}^{N} w_i (s_{ij}) \qquad (1)$$

where $score(a_j)$ represents the total score for each alternative a_j, N is the number of criteria used, w_i stands for the weight of criterion c_i and s_{ij} represents the score for alternative a_j with respect to criterion c_i.

A standard part of the procedure of weighted summation is a sensitivity analysis, which aims to determine the robustness of the acquired results. This is done by adjusting the weights assigned to the different evaluation criteria and assessing the impact hereof on the overall results (Janssen, 2001).

3.3 Decision support software

To support the process of deciding on the most relevant adaptation option(s) for the electricity sector the decision support software package DEFINITE (decisions on a finite set of alternatives - or the Dutch acronym BOSDA) is used (Janssen & Herwijnen, 2007). DEFINITE has been developed to improve the quality of (environmental) decision-making. The software package contains a tool kit for a wide variety of problems; when a set of alternative solutions to a problem is identified, DEFINITE can weigh up and select the most suitable alternative(s). Furthermore the software has the ability to lead the researcher systematically through the process for a MCA as outlined in section 3.2.

4 Results

4.1 Descriptive statistics

In total 504 scores were assigned during the research; nine interviewees scored fourteen adaptation options based on four different characteristics. The total average score (M) assigned is 2.73 with a standard deviation (SD) of 1.38. Table 3 shows the average scores that were assigned to the fourteen adaptation options and the standard deviations, per criterion. In bold the highest average score for each criterion is indicated. From table 3 it can be seen that a greater deployment of decentralized electricity generation (option 3) received the highest average score for three out of the four criteria (urgency, no-regret and feasibility). The highest average score with respect to the criterion importance was received by the option to invest in research and development (option 14). Another feature that stands out from the interviews is that the option to further increase interconnectivity with European electricity market (option 6) received the second highest average score for all the four criteria used.

Low scoring options shown in table 2 are diversifying modes of coal delivery (option 8) with respect to criterion importance, followed at some distance by moving new power plants to the East (option 12). These two options are also the lowest scored options for criterion urgency, followed by adjusting the underside of wind-turbines at the coast (option 13). In the case of criterion no-regret, the option to install extra water pumps in the area of power plant (option 11) received the lowest average score out of the fourteen options. The lowest scoring option in terms of feasibility is moving new power plants to the East (option 12). The second lowest average scores are for installation of electricity storage facilities (option 5).

Standard deviations shown in table 3 are an indication of controversy; the higher the spread in the answers given by the interviewees, the more controversial an adaptation option is, because the interviewees did not agree with each other. This gives an indication of political feasibility, a criterion that was not included in the interviews. The most controversial options with regard to importance are the installation of electricity storage facilities (option 5) and the building of dikes around power plants (option 10), followed by the adaptation of regulations to (temporally) allow higher discharge temperatures (option 2). This option is also the most controversial with respect to criterion urgency, closely followed by an increased interconnectivity with the European electricity market (option 6). The most controversial option regarding no-regret is the installation of electricity storage facilities (option 5). The second most controversial option is improving the cooling capacity of thermal power plants located at rivers (option 1). In the case of feasibility, the installation of electricity storage facilities (option 5) and constructing new power plants on an elevation (option 9) turned out to be the most controversial options, followed closely by the adaptation of regulations to (temporally) allow higher discharge temperatures (option 2).

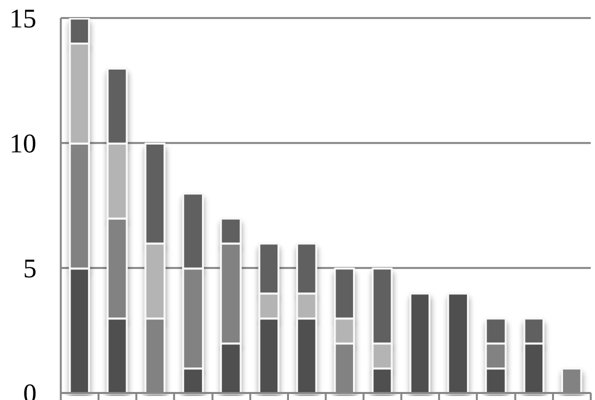
Figure 7 shows the number of times that an adaptation option received the highest score, specified per criteria. The stacked columns at the top of figure 7 show graphically what has been specified numerically in the table at the bottom of the figure; the option to have a greater deployment of decentralized electricity generation (option 3) has been awarded the highest score most frequently out of the fourteen adaptation options that were selected: fifteen times during the course of the interviews, fourteen of which were for the criteria urgency, no-regret and feasibility. Further increasing interconnectivity with the European electricity market (option 6) has scored the highest thirteen times and almost completely evenly divided over the four criteria. The option to invest in research and development (option 14) has received the highest score ten times, spread over the criteria importance, urgency and no-regret. None of the interviewees deemed it to be the most feasible of adaptation options.

The next step for the interviewees was to rank the four criteria. The results hereof are presented in figure 8 on the next page. Figure 8 illustrates graphically (top) the number of times that a criterion was ranked at a place from first to fourth (which is also shown numerically at the bottom of figure 8). Importance was the highest ranked criterion for this research: six out of nine interviewees indicated that this criterion should rank first, two interviewees ranked importance as second, and none deemed it to be the least important criterion. Urgency and feasibility are ranked intermediate, with urgency ranked slightly higher. The criterion no-regret is ranked the lowest and is thought to be the least important criterion to which the adaptation options should perform well. These rankings determine the weights that are assigned to the four criteria in the MCA, discussed in the next section. Since importance is ranked the highest during the interviews, it received the highest weight, followed by urgency, feasibility and no-regret. This ranking is in accordance with the criteria weights that were assigned by experts in De Bruin et al. (2009), where importance received 40% of the weight, followed by urgency (20%) and no-regret (15%) (See De Bruin et al., 2009).

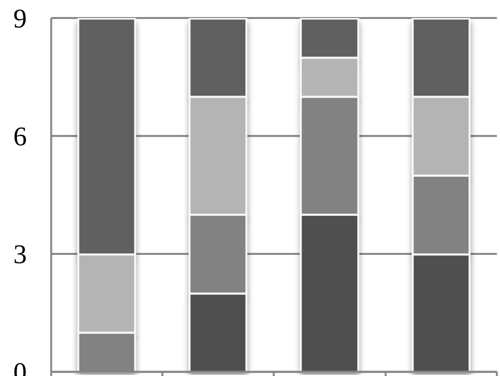
Table 3: Average scores assigned to the fourteen selected adaptation options during the research per criterion. Bold scores are the maximum average scores per criterion.

Criterion:	**Importance**		**Urgency**		**No-regret**		**Feasibility**	
Option nr:	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Option 1	2.44	1.34	2.44	1.26	2.22	1.40	2.78	0.92
Option 2	2.67	1.41	2.56	1.34	2.00	1.05	3.22	1.40
Option 3	3.33	1.15	**3.67**	**1.15**	**4.22**	**0.63**	**4.11**	**0.87**
Option 4	3.22	1.13	2.44	0.96	3.89	0.99	3.33	0.94
Option 5	3.22	1.55	2.11	0.74	3.56	1.50	2.56	1.42
Option 6	3.78	1.13	3.22	1.31	4.00	0.67	3.89	0.87
Option 7	2.44	1.07	1.78	0.92	2.78	1.23	2.56	1.07
Option 8	1.56	0.83	1.56	0.68	1.67	0.47	3.89	1.20
Option 9	3.33	1.33	1.89	1.20	1.56	0.83	3.44	1.42
Option 10	3.22	1.47	2.11	0.99	1.67	0.94	3.00	1.05
Option 11	2.11	0.99	1.78	0.79	1.33	0.47	3.67	1.25
Option 12	2.00	1.25	1.33	0.67	1.78	1.31	2.11	1.20
Option 13	2.22	1.31	1.67	0.82	1.89	0.99	3.78	0.79
Option 14	**4.00**	**0.82**	3.22	1.03	3.56	1.34	3.22	0.63

Figure 7 and 8: Number of times that an adaptation option is awarded the highest score (left), ranking of the four criteria by interviewees from first to fourth place (right).



	3	6	14	5	4	2	9	1	10	8	11	7	13	12
Importance	1	3	4	3	1	2	2	2	3	0	0	1	1	0
Urgency	4	3	3	0	0	1	1	1	1	0	0	0	0	0
No-regret	5	4	3	4	4	0	0	2	0	0	0	1	0	1
Feasibility	5	3	0	1	2	3	3	0	1	4	4	1	2	0



	Importance	Urgency	No-regret	Feasibility
1st	6	2	1	2
2nd	2	3	1	2
3rd	1	2	3	2
4th	0	2	4	3

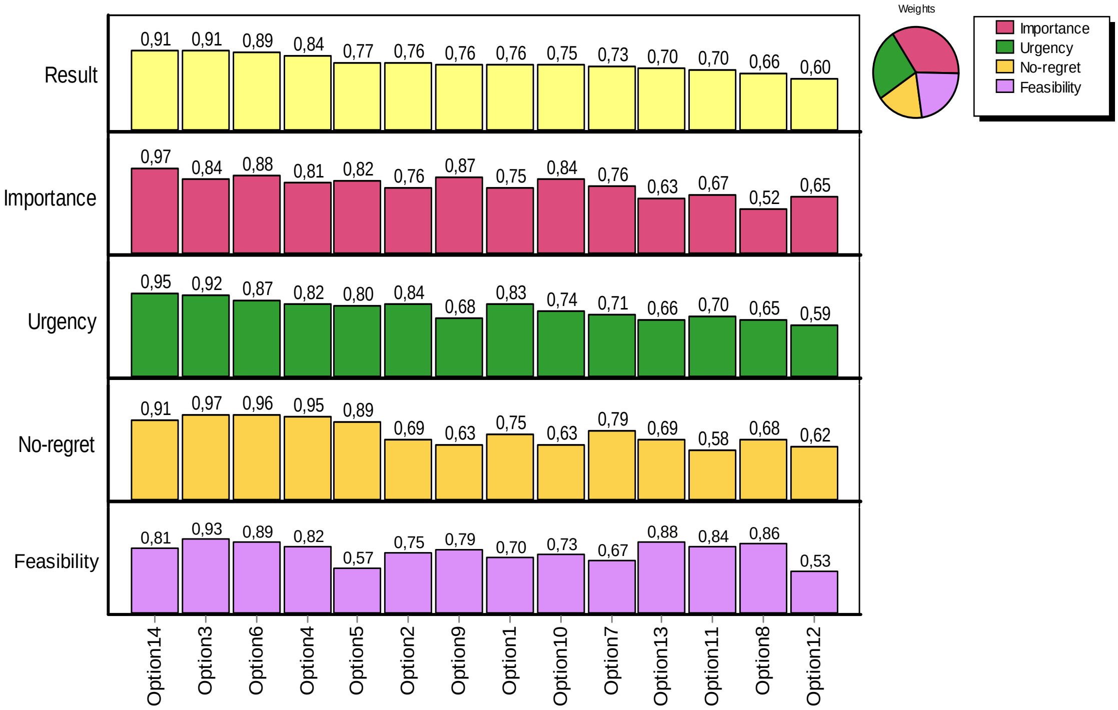
4.2 Multi-criteria analysis

4.2.1 Ranking based on evaluation criteria

Figure 9 displays the result of the ranking of adaptation options by a weighted summation of the scores based on the criteria (i) importance (weight 34%), (ii) urgency (25%), (iii) no-regret (18%) and (iv) feasibility (23%). The weights are illustrated by the pie-chart, on the top right of the figure. The first row of figure 9 shows the overall result of the multi-criteria analysis (MCA). In the following four rows the result has been split up into the contributions of the four criteria on the overall result after the weights have been applied and summed up over the nine interviewees.

The overall result shows that there is a joint highest ranking for the option to invest in research and development (option 14) and the option to have a greater deployment of decentralized electricity generation (option 3), followed by further increasing interconnectivity with the European electricity market (option 6). The lowest ranked option is to build new power plants in the East (option 12), followed at some distance by the option to diversify the modes of coal delivery (option 8). Then there is a broad range of options ranked in the middle.

Figure 9: Results of the MCA with weighted summation.



The ranking of adaptation options for criterion importance is shown in the second row of figure 9. The highest ranking with respect to this criterion is for the option to invest in research and development (option 14), followed by a further increase in interconnectivity with the European electricity market (option 6) and the option to construct new power plants on an elevation (option 9). These options are expected, by the interviewees, to yield the highest benefits (i.e. avoid the most damage caused by future extreme weather events) out of the fourteen selected adaptation option when they are implemented. The lowest ranked adaptation option for this criterion is to diversify the modes of coal delivery (option 8), followed at some distance by the option to adjust the underside of wind-turbines located at the coast (option 13).

Also in the case of criterion urgency the option to invest in research and development (option 14) was ranked highest. For this criterion the option for a greater deployment of decentralized electricity generation (option 3) was ranked second, followed by option 6 (increase interconnectivity with the European electricity market). Based on the interviews, these options should be implemented quickly, because postponement could lead to higher costs and possibly irreversible damage. The lowest ranked option with respect to criterion urgency is to build new power plants in the East (option 12). This option is followed by the diversification of the modes of coal delivery (option 8) and the option to adjust the underside of wind-turbines located at the coast (option 13).

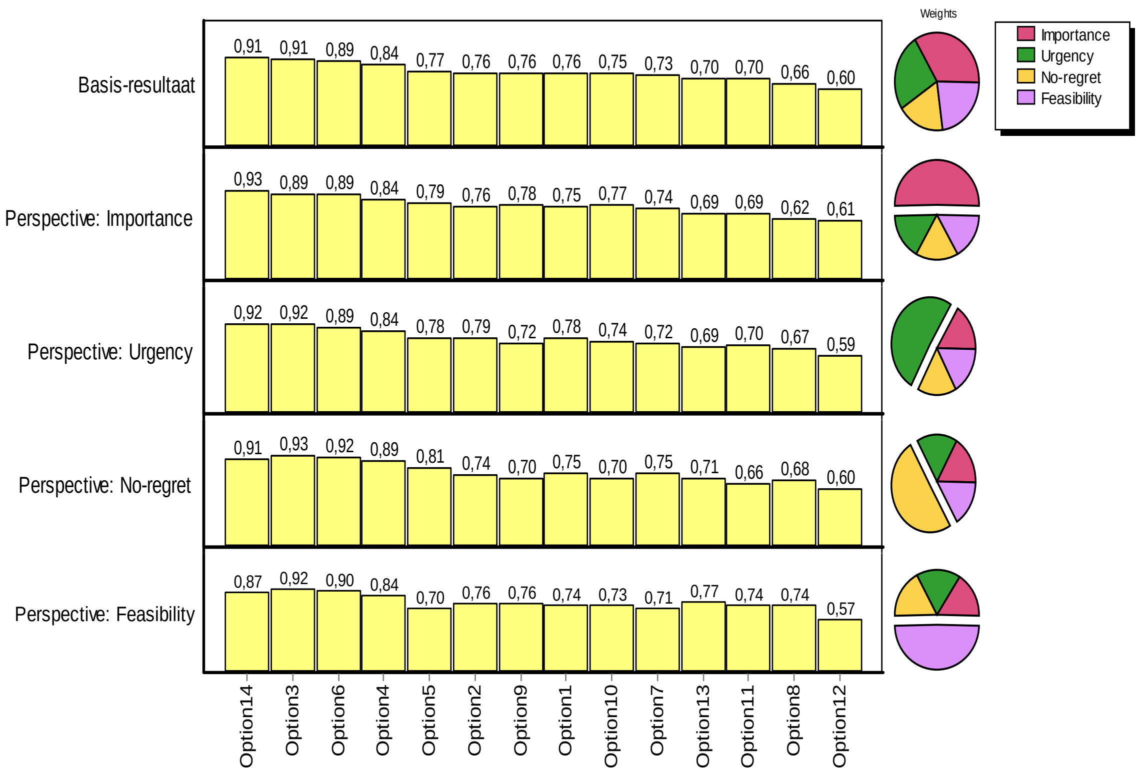
For criterion no-regret the highest ranked option a greater deployment of decentralized electricity generation (option nr. 3), closely followed by a further increase in interconnectivity with the European electricity market (option 6) and the use of off-grid heating and cooling (heat and cold storage) (option 4). These options are judged by the interviewees to be good to implement regardless of the changes in extreme weather events i.e. they expect that the chances that these options have higher future benefits than costs, without the benefits of the avoidance of damages from future extreme weather events, are relatively high. The lowest ranked option is the option to install extra water pumps in the area of power plant (option 11), followed by the option to build new power plants in the East (option 12).

The highest ranked option for the last criterion, feasibility, is again a greater deployment of decentralized electricity generation (option 3). This option is followed by a further increase in interconnectivity with the European electricity market (option 6) and the option to adjust the underside of wind-turbines located at the coast (option 13). These options are deemed to be relatively easy to implement. In contrast, the low ranked options build new power plants in the East (option 12) and installation of electricity storage facilities (option 5) are considered to be relatively hard to implement.

4.2.2 Sensitivity analysis

A sensitivity analysis was conducted to see if the results that were obtained in the MCA are robust. This was done by varying the weights assigned to the four criteria. Figure 10 shows the result of the sensitivity analysis. In the first row of figure 10, the overall result as obtained in section 4.2.1 is shown. In the following four rows in turns, extra weight is assigned to one of the four criteria. The other three criteria are each assigned equal weights. The weight for the criterion where the emphasis is placed on is equal to 50%, whereas the other criteria each receive 16.67% of the weight. The three options that were ranked highest in the overall result emerge as the highest ranked regardless of the way the criteria are ordered, because they score highly on all criteria. Changing the weights of the criteria only affects options that score better on some criteria than others. The results from the sensitivity analysis indicate that the results from the MCA that were obtained in the prior section are robust.

Figure 10: Sensitivity of the overall results of the MCA to a changed order of criteria.



4.2.3 Qualitative analysis

In addition to scoring the adaptation options, interviewees were asked to elaborate on their judgments, and in doing so provided qualitative data for the analysis of the results found in section 4.2.1. In this section the main arguments and reasons that accompanied the assessment by the interviewees will be presented for the three highest ranked adaptation options in the overall results of the MCA, as well as for the two lowest ranked options.

Investing in research and development came out of the MCA as one of the two highest ranked adaptation options. Furthermore, with regard to importance it is the least controversial option (see table 3) and it was the highest ranked option for this criterion. This option is seen as important in avoiding damages from extreme weather events, because of the resulting techniques which are supposed to be more resilient and adaptable to extreme weather events. Also, the possibility of climate change mitigation through innovative technologies and future economic benefits were given as reasons: "We could use the money to develop techniques to adapt to climate change, but also to develop techniques to avoid it and maybe benefit from it by becoming less dependent on foreign regimes and by exporting our knowledge and techniques." (Interviewee 5, major electricity production company)

Investing in research and development, however, was ranked relatively moderate with respect to feasibility; the main reason for this is the current economic crisis. Also, the government is perceived to be reluctant to invest in innovative technologies. As interviewee 4 suggested: "The government is not at all willing to invest in decentralized electricity supply and innovative electricity solutions. We see a retracting government. For example we are working with geothermal energy, but subsidies are hard to get" (Interviewee 4, Westland Infra) Furthermore, this ranking was broadly accepted amongst the interviewees.

Greater deployment of decentralized electricity generation, is the other highest ranked adaptation option. In light of climate change and damages from extreme weather events, more decentralized electricity generation is seen as a way to spread risk and make the supply of electricity more resilient. The former reflected in the right renewable portfolio-mix because: "when we experience an extreme heat event solar PV could produce electricity while the wind production falls behind. In contrast, when there is extreme rainfall there is likely to be a lot of wind power and no solar."

(Interviewee 9, Eneco) The latter point is illustrated by Interviewee 3: “After an extreme weather event with large damages to the electricity network, decentralized production can be brought back into use very quickly as compared to centralized units. We have seen this in New York and England. Damages to small parts of the production capacity are to overcome than large interconnected systems.” (Interviewee 3, De Windvogel)

Implementation of option 3 is expected to result in positive net benefits, regardless of climate change. For instance, Interviewee 7 said that:

> *(…) as a branch organization we see the benefits from this [option] besides it making the electricity sector more resilient to climate change. On the short-term security of supply is also very important. In the context of failure of electricity supply and mixing of different supply instruments this (option) is very important and it would be very useful to combine this with climate resilience.*

(Interviewee 7, Netbeheer Nederland)

Interviewee 7 also indicated that we are reliant on Russia for our energy supply and that the electrification can play a role in reducing our dependence. In the same vein interviewee 3 said: “I see it as a part of the democracy that citizens have the right to produce their own electricity and not that those decisions on prices are made somewhere in Russia or so.” (Interviewee 3, De Windvogel) Greater deployment of decentralized electricity production is also deemed to be relatively feasible, mainly because it is technologically possible. However, some interviewees also indicated that the techniques are still costly.

Increased interconnectivity with the European electricity market (option 6) is seen as a means to make the electricity system more reliable and a way to balance the electricity market. In light of extreme weather events, when a country experiences problems with regards to electricity supply, connected countries can help and thereby limit the amount of damage. It is also recognized by the interviewees that the Netherlands is already fairly interconnected with other countries: “Even now if one-fifth of the production capacity in the Netherlands drops out, interconnected countries immediately help out.” (Interviewee 9, Eneco) According to interviewee 7: “Balance is assured when different means of electricity production, such as water, wind and sun and in between power plants are coupled, combined with consumers that buy high amounts of electricity when the price is low and little when the price is high.”

(Interviewee 7, Netbeheer Nederland) Also, interconnectivity is seen as something that the Netherlands could profit from: “Integration with other countries gives the possibilities to profit from comparative advantages, for example the Netherlands has ample cooling water because of our numerous coastal locations.” (Interviewee 9, DNV KEMA) As a corollary end-user prices could go down. However, it is also recognized that the increased interconnectivity could lead to problems; such as ensuring transport capacity, expressed by interviewees 5 and 6 (major electricity production company and Enexis), and the needed investments to overcome them. (Interviewee 5, major electricity production company)

The lowest ranked adaptation option overall is to build new power plants in the East (option 12), instead of to the coast which has been happening recently (e.g. NUON Vattenfall at the Eemshaven in Groningen and E.ON at the Maasvlakte in Rotterdam). The main reason that was given for scoring this option low was that the measure is very expensive. Moreover, the recent construction of power plants at coastal locations was done for a reason: good accessibility for bulk deliveries of fuel and ample cooling water. These characteristics make electricity production more cost-effective and circumvent the problems associated with the high temperature of cooling water from rivers. Besides the economic and network considerations, the role of the government has been put forward: “I believe that the companies receive subsidies to locate at the Eemshaven, even though it is a challenging location with the vicinity of the Waddensea, with the aim to develop the region (north-east Groningen).” (Interviewee 5, major electricity production company)

Most interviewees did recognize that there is a trade-off between the economic and network considerations and the risk from exposure to flooding. However, some interviewees indicated that they don’t expect an increase in the risk of flooding (e.g. interviewee 5, major electricity production company) or that we are already protected enough by the existing dikes (Interviewee 1, major electricity production company) Also, there were interviewees who suggested an intermediate solution: “Because power plants are becoming bigger and fewer, while summer demand for electricity increases and there is an insufficient supply of cooling water at the rivers, new power plants need to be relocated to the coast. However, smaller plants, or CHP units, with the aim of providing heating can be located inland.” (Interviewee 7, Netbeheer Nederland) This point is endorsed, from the point of risk spreading, by interviewee 9: “You would want to shrink the large clusters down to smaller ones to spread the risk for the total system, but in a way that deals with the problems with cooling water.” (Interviewee 9, Eneco)

The second lowest ranked adaptation option by the interviewees is to diversify the modes of coal delivery (option 8). The main reason that was given for the low ranking was that the new coal-fired power plants are already constructed, or planned, at coastal locations where there is ample gauge for barges. Furthermore, the future role of coal-fired production units in the Dutch electricity supply is expected to become less important or change: “Your conventional power plant needs to be used for heat production and in part for balancing the market in the future, nothing more. But we need to stop producing electricity limitlessly and throw away half of the energy in rivers.” (Interviewee 7, Netbeheer Nederland). Interviewee 7 also indicates that the problems with cooling water are more urgent and important than problems with coal delivery. Interviewee 5 has a more pragmatic approach to the implementation of this problem; arguing that it depends on the size of the production unit and its share in the portfolio, but it should only be considered for new power plants where problems with discharge levels are expected. The adaptation option is deemed to be feasible however, because the techniques to diversify the modes of delivery are available (e.g. train or truck).

4.2.4 Additional suggested adaptation options

Interviewee 6 suggested that flood risk areas in the Netherlands should be expanded, so this can be taken into account when planning the installation of infrastructure. Interviewee 6 also opted to switch overhead electricity transport lines for underground lines; then they are protected from harmful storm events, but also from transportation losses as a result from increased ambient air temperature during events of extreme heat. Interviewee 6 indicated that the effects from a rising ambient air temperature are quite extensive, especially during warm, dry periods, because, besides the losses due to increased resistance, cables expand and become longer. As a result they will hang closer to the ground, which could cause dangerous situations.

5 Conclusion and discussion

The adaptation options that were used in the MCA are for the major part not mutually exclusive; a number of adaptation options can be seen as complementary in the face of the expected changes in the occurrence and duration extreme weather events and the impacts hereof on the electricity system in the Netherlands. This is also true for the three highest ranked options, they are complementary. Investments in research and development (option 14) are supposed to lead to electricity technologies that are more resilient and adaptable to the changing climate, however: "We don't have to reinvent the wheel, because there is already a lot of research published and available. This needs to be made accessible. Make it tailor-made for users. The current research can be supplemented to contribute to the climate resilience." (Interviewee 7, Netbeheer Nederland) The option is expected to lead to new technological solutions, thereby increasing the diversity of the supply system.

A more decentralized (and diversified) electricity production portfolio (option 3) is expected to spread the risk of the impacts from extreme weather events, which can be illustrated by a statement given by Interviewee 9: "Preparing for future events means diversifying in my opinion. What we see happing in the Netherlands, however, is that we are having a tendency to cluster. For example, at the Maasvlakte and the Eemshave there are large clusters of infrastructure installed at one location." (Interviewee 9, Eneco) Moreover, decentralizing electricity production makes the electricity system more resilient and adaptable when facing (climate) uncertainties. In this sense the increased research and development efforts, in the case of climate adaptation, are a search for a more diverse and complex system with an increasing diversity in the supply sources of electricity. Decentralisation thus also aims at increasing the diversity of the supply system.

Increasing the interconnectivity between different European electricity markets (option 6) complements the two options by adding a layer of reliability and security of supply by increasing the geographic diversity of the electricity system. By interconnecting different national electricity systems, the total system becomes more diverse. A higher degree of interconnectivity means that deficits in one country and surpluses in others can be balanced. This is also important without changing impacts of extreme weather events; when in the future the electricity supply portfolio is going to contain larger shares of intermittent electricity sources. Economically, comparative advantages of national electricity systems could benefit the end-users; hydro-power in mountainous areas, solar-power in countries with high solar density, making the system more efficient. The Netherlands is already connected to other countries. It is recognized that the interconnectivity could lead to problems; such as ensuring transport capacity and investments are needed to overcome them.

This leads to the conclusion that the three adaptation options need to be pursued in tandem. They are about creating a larger diversity in the system; by increasing the complexity of the system, the system becomes more resilient to uncertainty, climate related or otherwise. This is in accordance with evolutionary economics theory: uncertainty in environmental conditions calls for a certain level of diversity of technologies and organizational structures to keep a system adaptively flexible, which allows for an easier transition to a new, changed situation. Besides adding flexibility and resilience to the electricity system, the conscious pursuit of diversity makes sense from a welfare perspective: greater diversity means more possibilities for creative combinations of different technologies. The subsequent process of (economic) selection will lead to a higher welfare level the greater the diversity in the system (Van den Bergh et al., 2007).

Implications hereof are that the most adaptation options demand a government that is actively involved by setting policy measures not aimed at short-term efficiency or cost-effectiveness, but at the long-term by stimulating a diverse energy system and protecting innovative niche technologies (Van den Bergh et al., 2007, p. 21). In relation to these conclusions Interviewee 7 said:

> *[With the current economic crisis] investments become harder to justify (...), but I still think that it has added value for society, without immediate or short-term payback, by having something in prospect. Looking at the long-term, and having the courage to do so, I think we are moving towards a society where energy is free (...), provided that the transportation is well organised.*

(Interviewee 7, Netbeheer Nederland)

These results are in conformity with the ambitions set by the Dutch government mentioned earlier in section 2.2, but the policy measures to reach them differ. One of the focal points of the Dutch energy policy, to reach the ambitions of the Dutch government, is a climate-neutral economy in 2050. In the search for a climate neutral energy system four building-blocks re-occur in different: a carbon-dioxide (CO_2)

neutral electricity supply combined with a larger role for electricity, deployment of sustainable biomass, energy conservation (mainly through energy efficiency improvements) and carbon capture and storage (CCS) (Ministry of Infrastructure and Environment, 18-11-2011). By investing in short-term measures (i.e. energy efficiency improvements and CCS technology), the lifespan of existing electricity production and supply technologies and incumbent market parties is extended. The lock-in in the current highly centralized fossil-fuel based electricity system will remain, because they make existing technologies cheaper relative to new innovative (more decentralized) technologies that are under, or will come into, development in niche-markets (Van den Bergh et al., 2007). In comparison, the three adaptation options are more long-term solutions.

Previous research on possible adaptation options against climate change in the Netherlands has been performed by De Bruin et al. (2009). Most of the results in this research are in line with their article. The article concludes that adaptation options for the Netherlands with the highest priority are in the sectors nature and water (De Bruin et al., 2009, p. 32). Amongst the adaptation options for the energy sector that were included the construction of buildings with less need for air-conditioning/heating is ranked highest in the first round, followed by the lowering of the discount factor of project appraisal and the development of cooling towers. Of these options only the development of cooling towers was included in this research, as part of the adaptation option to improve cooling capacity of thermal power plants (option 1). After the second round of scoring, the priority of implementing this option becomes medium (De Bruin et al., 2009, p. 42). This option is ranked medium in the overall results of this research as well. The other options that were included form De Bruin et al. (2009) article in this research (options 1, 2, 7 and 13) have been ranked largely similar (De Bruin et al., 2009, p. 40-43).

A major difference between the results found in this report and the results found by De Bruin et al. (2009) is in the ranking of options for decentralized electricity production. The researchers included two adaptation options that have a decentralized character: use improved opportunities for generating wind energy and solar energy. Both scored low on all criteria except for their mitigation effects, where they were scored very high, and no-regret, where they scored very low. |n contrast, a greater deployment of decentralized electricity generation (option 3) is ranked highest in the overall result in this report. Moreover, the adaptation option scored especially high with respect to the no-regret criterion. A possible explanation for the difference is the general description of off-grid production in this research: it includes more possible options. This means wind power as well as solar power, but also a range of other options. Moreover, the description of the improved opportunities for generating wind energy entails only offshore wind turbines, which will most likely not be decentralized but centralized due to its high investment costs (Van Ierland et al., 2007, p. 94).

A limitation of the research was the time constraint for the interviews; to be able to find enough participants for the research, an hour per interview was deemed reasonable. This limited time-frame meant that some identified adaptation options had to be merged or dropped. The subsequent risk of being incomplete was mitigated by allowing interviewees to add adaptation options that they felt were missing.

Supply-side adaptation options have been concerned during this research. However, interviewee 9 suggested the inclusion of demand-side options. He argued that the adaptation options that were included in the interview tend to focus solely on the supply side of the electricity market. The pressure on the electricity system can be brought down when end-users use less electricity, especially during peak-hours. Further research could focus on the possibility for implementation of demand side adaptation options, as a way to adapt the electricity system to a changing climate.

This research showed the importance, urgency and benefits of creating more diversity in the electricity supply system for the adaptation to a changing climate in the Dutch electricity sector. Interestingly, increasing diversity of the system can also lead to lower emissions of greenhouse gasses by the electricity sector, thereby contributing to mitigation. Increasing diversity and resilience may be the key to linking adaptation to mitigation efforts.

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Annex A List of identified parties for interviews

Group	Organisation	Market share
Transmission System Operator (TSO)	Tennet	100%
Branch organisation RNO	Netbeheer Nederland	
Regional Network Operators (RNO)[8]	Liander N.V.	36%
	Enexis B.V.	33%
	Stedin B.V.	26%
	Delta Netwerk B.V.	2%
	Endinet*	1%
	Westland Infra Netbeheer B.V.	<1%
	Cogas Infra en Beheer B.V.	<1%
	RENDO Netbeheer B.V.	<1%
Branch organisation producers	Energie-Nederland	
Producers[9]	Electrabel SUEZ GDF	21%
	NUON Vattenfall	18%
	Essent	16%
	E.ON	9%
	Delta	5%
	Intergen	4%
	Others (including Eneco)	4%
	Horticulture	13%
	Industry	10%
Producers renewables	Zonline	
	De Windvogel	
Technical consultant	DNV KEMA	

[8] From Energie-Nederland, 2011
[9] From Essent, 02-06-2010

Annex B Adaptation options and descriptions

Adaptation option (nr.):	Description:
Improve cooling capacity of thermal power plants located at rivers (1)	Increased cooling-water temperature and ambient air temperature lower the efficiency of power plants. By adding extra cooling capacity this loss can be overcome.
Adaptation of regulations to (temporally) allow higher discharge temperatures (2)	Heat discharge by power plants is restricted by regulations to protect the organisms living in the receiving water-bodies. If the temperatures of these water-bodies become too high, discharging is prohibited. Temporarily allowing higher discharge temperatures could ensure the continued production and supply of electricity.
More deployment of decentralized electricity generation (3)	More electricity generation using off-grid production e.g. wind power, solar-PV, CHP.
Use of off-grid heating and cooling (heat and cold storage) (4)	Storage and usage of warmth and cold in and from the ground saves electricity used for cooling and heating and temper peak-demand.
Installation of electricity storage facilities (5)	During off-peak hours extra excess electricity production can be stored with the purpose of using it during peak hours.
Increase interconnectivity EU electricity market (6)	Further integrating of the European electricity market increases the potential to absorb failure of production units.
Build new or enhance existing sluices (7)	During dry spells more water for cooling purposes can be retained for power plants.
Diversify modes of coal delivery (train, road) (8)	Coal transport via railway or road alongside the transport with barges allows continued production of electricity when river discharge levels become too low for barge transportation of fuels.
Constructing new power plants on an elevation (9)	Raising power plants to lower their exposure to the risk of flooding in flood-prone areas.
Build dikes around power plants (10)	Shielding power plants to lower their exposure to the risk of flooding in flood-prone areas.
Installation of extra water pumps in the area of power plant (11)	Extra capacity for pumping away water in the area around power plant as to lower the chance of flooding in flood-prone areas.
Move power plants to the East (12)	Moving power plants inland lowering the exposure to flooding.
Adjust the underside of wind-turbines at the coast (13)	During floods in coastal areas wind-turbines can get damaged by vulnerable parts getting submerged.
Invest in Research and Development (14)	Stimulate technological development and scientific research to gain insight into the effects of potential measures.

Annex C List of interviews

Interview number	Organisation	Position
Interview 1	Major electricity production company[10]	Gas turbine Specialist
Interview 2	Zonline[11]	CEO
Interview 3	De Windvogel[12]	Representative
Interview 4	Westland Infra Netbeheer B.V.	Asset manager
Interview 5	Major electricity production company[10]	Reliability Engineer
Interview 6	Enexis B.V.	Risk Analyst
Interview 7	Netbeheer Nederland	Manager Energy Infrastructure
Interview 8	DNV KEMA[13]	Engineer
Interview 9	Eneco	Senior Trader

[10] This organization insisted on not having its name published or connected to this research. Participants cooperated on their personal title.
[11] Zonline is an online supplier of solar PV units.
[12] De Windvogel is an association of people cooperatively producing wind power. The cooperation owns six wind-turbines (numbers from 2012).
[13] DNV KEMA is a global organization specialized in innovative solutions in business and technical consultancy, testing, inspections and certification, risk management and verification in the Electricity sector.