Karina Gabrielsen

Climate change and the future Nordic electricity market - Supply, demand, trade and transmission

Statistisk sentralbyrå • Statistics Norway
Oslo–Kongsvinger

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ISBN 82-537-6847-8 Trykt versjon
ISBN 82-537-6848-6 Elektronisk versjon
ISSN 0806-2056

Emnegruppe
01.03.10

Design: Enzo Finger Design
Trykk: Statistisk sentralbyrå/183

Standardtegn i tabeller	Symbols in tables	Symbol
Tall kan ikke forekomme	Category not applicable	.
Oppgave mangler	Data not available	..
Oppgave mangler foreløpig	Data not yet available	...
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Abstract

Karina Gabrielsen

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Reports 2005/24 • Statistics Norway 2005

The aim of this study has been to analyze the effects of climate changes on the Nordic electricity market. Concentration of greenhouse gases in the atmosphere influences the climate, which then alter the amount of primary energy for countries or regions where hydropower and wind power constitutes important parts of the energy supply. Besides, the demand effect of increased temperature may be large in economies where heating makes a large share of total energy demand. In this report we apply climate change calculations from natural science and detailed inflow data from the authorities to estimate the change in primary energy supply for the hydropower dominated Nordic electricity market. The estimated inflow model shows an increase in primary inflow in the following 40 years of 6-15 per cent in the Nordic countries. An estimated temperature model shows a 2-4 per cent initial drop in demand in the same time period, due to increasing temperature. Within the context of a perfect competition electricity market model, we simulate the total market outcome. As primary supply increases, the production cost decreases, prices drops and the total demand increases as the price effect dominates the temperature effect. Since the hydropower plants are located differently from large consumer groups, the stress on the transmission networks is dramatic for some regions, which in the next face may trigger new investments in transmission network capacities

Sammendrag

Karina Gabrielsen

Klimaendringer og det fremtidige nordiske elektrisitetsmarkedet - tilbud, etterspørsel, handel og transmisjon

Rapporter 2005/24 • Statistisk sentralbyrå 2005

Formålet med denne rapporten er å undersøke hvordan klimaendringer påvirker det nordiske elektrisitetsmarkedet frem mot 2040, og da med særlig fokus på tilbud og etterspørsel, samt handel og overføring av elektrisitet. Temaet er relevant både for produsenter og konsumenter i deres valg av fremtidige investeringer i form av konsum, produksjon og kapasitet. Det teoretiske grunnlaget for analysen er Førsunds optimeringsmodell (1994) for et vannkraftsystem. Modellen brukes som et rammeverk for å diskutere mulige skranker på kapasitet som følge av klimaendringene. Prinsippene i Førsunds teori er formalisert i markedsmodellen Normod-T (Johnsen, 1998). Denne modellen inkluderer regionale og nasjonale forskjeller i tilsig, temperatur, etterspørsel, transmisjonsnett, mulige skranker og skyggepriser på elektrisitet. Klimaendringene er i denne rapporten avgrenset til betydningen på simulert tilsig, temperaturavhengig etterspørsel og vindhastighet i perioden 2001-2040.

Vi har utviklet og estimert en modell for å simulere tilsig. Modellen er basert på historiske tilsigsdata fra NVE og dataserier på regn og snø (vannekvivalent) fra RegClim . Snøsmeltingen er inkludert ved å lage multiplikative dummyer for hver uke i snøsmeltingsperioden. I denne perioden har regn en annen rolle enn i resten av året; hvis det regner mer i denne perioden, vil smeltingen øke. Det er derfor multiplikative dummyer for regn hver uke i samme periode. RegClims data på temperatur ble benyttet i en temperaturmodell (Johnsen mfl, 2005) for å simulere den temperaturavhengige etterspørselen etter elektrisitet. Tilsigsmodellen simulerte en økning i tilsig på 6-14,5% i de nordiske landene. Finland, samt vestlige og nordlige deler av Norge vil ha størst økning. RegClims dataserie på vindhastighet viser en økning på 1-2 % i Norden. Temperaturmodellen simulerte en 3-4% reduksjon i temperaturavhengig etterspørsel, ettersom temperaturen er forventet å øke med 0,5-1,5 Co. Resultatene fra tilsigsmodellen og temperaturmodellen, samt data på vindhastighet, ble inkludert i Normod-T. Det er viktig å understreke usikkerheten av klimamodellering, og resultatene må behandles deretter.

Ved hjelp av Normod-T produserte vi et basis scenario (uten de simulerte klimaendringene) og et klimascenario der de simulerte endringene i tilsig, vind og etterspørsel var inkludert. Sammenlikning av scenariene viste at effekten av klimaendringene er en forventet økning i nordisk tilbud av elektrisitet på 1,8 % (8,1 TWh). I utgangspunktet kan dette virke som en beskjeden økning, tatt i betraktning hvert lands økning i tilsig i perioden. Men ettersom vannkraft bare utgjør om lag 50 % av den totale elektrisitetsproduksjonen i Norden, vil ikke økt tilsig alene forklare endringen i nordisk tilbud. Analysen viste at økt produksjon av vannkraft, særlig i Norge, og økt eksport til de andre Nordiske landene, erstatter marginal produksjon i Sverige, Danmark og Finland. I tillegg vil prisene falle i klimascenariet ettersom tilbudet av vannkraft øker, og dette medfører lavere investeringer i ny kapasitet over perioden (jf. stigende marginalkostnader). Vi forventer en økning i nordisk etterspørsel etter elektrisitet på 1,4 % (6,3 TWh), til tross for den reduserende effekten av økt temperatur. Ettersom tilbudet øker og prisene faller med rundt 2,4. øre i Norden, vil etterspørselen øke. Altså er priseffekten større enn temperatureffekten, og heller ikke all etterspørsel er temperaturavhenging. Vi forventer at klimaendringene medfører at netto eksport fra Norden til resten av Europa vil være 22 % (1,8TWh) høyere i 2040. Denne økningen er begrenset av effektive skranker på overføring av elektrisitet.

I Norge forventes det at tilbudet øker mer enn etterspørselen i klimascenariet, og det medfører en økning i eksporten til de andre nordiske landene og til resten av Europa. Både Sverige og Finland ser ut til å utsette investeringer i ny kapasitet på grunn av mulighet for økt import av rimelig kraft fra Norge. Danmark vil redusere kullproduksjonen og importere mer fra Norge og Sverige, men samtidig øker eksporten til Europa noe.

Når det gjelder overføringskapasitet, er det to viktige effekter av klimaendringene. Effektive skranker på overføringsnettet kan oppstå oftere på grunn av mer handel, og ettersom presset på nettet øker vil skyggeprisene på overføring øke mer i klimascenariet. I følge Førsund (1994), vil skyggeprisen på overføring komme i tillegg til elektrisitetsprisen. Det er effektive skranker innad i hvert land og mellom landene, men skrankene trenger ikke være effektive i alle sesonger eller lastperioder. I Norge vil klimaendringene medføre et sterkt press på overføring mellom nordvestlige og østlige deler av landet i vintersesongene frem mot 2040. Dette er en konsekvens av en sterk økning i tilsig og dermed produksjon i vestlige og nordlige deler av Norge. I de nordlige delene av Sverige vil det produseres mer vannkraft, og kablene mellom nord og sør i landet vil være overbelastet i vintersesongene fremover. Det er ingen overføring innad i Danmark eller Finland (i Normod-T).

I klimascenariet vil det være effektive skranker på overføring fra Norge til Danmark, Sverige og Finland i alle sesonger fra 2010 og frem til 2040. Dette er et par år tidligere enn i scenariet uten klimaendringene, og skyggeprisene er høyere. Det vil være effektive skranker på overføring mellom Sverige (SW2) og Danmark (DEN1) i alle sesonger hele tidsperioden, og skyggeprisene er høyere i klimascenariet. Mellom Finland og Sverige (SW2) vil det også være en effektiv skranke fra 2030-2040. Også her vil skranken bli effektiv et par år tidligere. Flere andre kabler i det nordiske overføringsnettet vil være overbelastet i løpet av perioden. Det er i tillegg skranke på overføring av elektrisitet fra hvert av de nordiske landene og til resten av Europa i deler av tidsperioden. Klimaendringene medfører lengre perioder med effektive skranker på overføring og høyere skyggepriser. Dette kan indikere at det er lønnsomt å investere i ny kapasitet, men dette overlater vi til videre studier å undersøke.

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1. Introduction

This thesis is part of a project called "Climate change and the energy market", carried out at Statistics Norway in 2005[1]. We will evaluate the integrated supply- and demand side effects of climate changes on the Nordic electricity market in 2001-2040. The background for our thesis is the relevance of this subject to both producers and consumers in their choice of future investment regarding electricity production, consumption and capacity. The future energy balance in the Nordic countries depends on the development of new production and transmission capacity and the future demand for electricity. This is likely to be affected by climate changes (Nordel, 2003). We will for simplicity focus on national changes, but also devote some attention to important regional differences within each country. To limit the extent of this thesis, climate change indicators will include observations of temperature, snow, rain, runoff[2], evaporation and wind. We have developed three research questions:

- How will supply and demand of electricity in the Nordic region be affected by climate changes?
- What is the effect of climate changes on the electricity trade in the Nordic region?
- How is a changing climate going to affect the capacity of transmission between the Nordic countries, and within each country?

Research has suggested that there have already been climate changes in the Nordic countries (Kuusisto, 2004). Earlier studies have concentrated on the effect on the energy supply, which is expected to increase based on more wind, precipitation and increased temperature (Bergstrøm et al., 2003, Kuusisto, 2004, Beldring et al., 2005). Some highly relevant projects will be described in more detail in chapter 2.

[1] I want to thank Torstein Bye at SSB for giving me the opportunity to be involved in the climate project at Statistics Norway, and for always being encouraging and a source of inspiration during this time. I also want to thank Jan Erik Haugen at the Norwegian Meteorological Institute (DNMI) for providing data from the RegClim project. In addition, I wish to thank Finn Roar Aune and Bård Lian at SSB, together with Tor Arnt Johnsen and Nils Spjeldnæs at NVE, for their contributions to the Master thesis at which this report is based upon.

[2] Runoff includes the amount of precipitation and snow melting that is not absorbed by the ground

The theoretical framework in our thesis is Førsund's optimisation model (1994) for a hydropower system. Førsund derives the optimal running scheme for a hydropower system based on the aim to maximize consumer and producer surplus under given conditions. When capacity is limited, the market clearing mechanism induces shadow prices on the constraints. The principles of Førsund's theoretical model are formalized in the electricity market model Normod-T (Johnsen, 1998). Normod-T includes regional and national differences in inflow, temperature, demand, and transmission networks between the traders, all possible bounds and shadow prices on electricity. The input to Normod-T will be seasonal inflow, temperature dependent demand and wind speed from 2001[3]-2040. We will estimate a climate model for inflow based on historical data on inflow from NVE and precipitation, snow water equivalent, runoff and evaporation from RegClim. The climate model will simulate regional inflow from 2001-2040. We will use a temperature dependent model by Johnsen and Spjeldnæs (2005) to simulate the demand for electricity in 2001-2040. The temperature model isolates the effect of temperature on the demand for electricity. Wind is added directly to Normod-T's supply side, as wind speed (m/s). The theoretical framework and models will be described in chapter 3.

Chapter 4 covers the discussion of the results from the climate model, the temperature model, RegClim's data series on wind and Normod-T. We will focus on the total Nordic and national effects of climate changes on production and consumption of electricity, the price weighted with consumption, trade and shadow prices on transmission. Some regional changes will be discussed as well. Chapter 5 presents the conclusion, in terms of a response to the research questions.

It is important to emphasize the uncertainty of climate modelling. A climate scenario is not a predictor of the future climate, and the scenarios are not given a probability of occurrence. It is therefore necessary to handle the results from climate modelling with some care.

[3] 2001 is the base year in Normod T.

2. Background and previous studies

The background for our thesis is the relevance of this subject to both producers and consumers in their choice of future investment regarding electricity production, -consumption[4] and capacity. The result from this thesis will give information about capacity limitations and regional variations, which can be used when planning expansions in the transmission system.

After the liberalization of the Nordic energy market in the 1990s, excess production reserves resulted in reduced energy prices and old production plants were shut down. From 1992 till 2002, the energy consumption increased by 17 % while new installed capacity amounted to only approximately 2 % (excluding wind power). There is a transmission capacity of 10.000 MW between the Nordic countries, and bottlenecks appear frequently on the transmission net. The energy balance in the Nordic region has declined since the 1990s, making the area a net importer (Nordel, 2003). The future energy balance in the Nordic countries depends on the development of new production capacity and the future demand for energy. Climate changes are likely to affect both the supply and demand side of the energy market. There are several challenges to consider, regarding the future Nordic and regional energy balance. It is uncertain whether or not the Nordic area can meet the energy demand based on new regional production capacity, or if extensive expansion of the transmission net is necessary. For an expansion of the net to be profitable, the electricity price needs to be higher than the marginal cost of developing the new grid. There is uncertainty involved when evaluating these matters (Nordel, 2003).

Climate changes and the projected effects on the energy market have been studied in several earlier and ongoing projects. It has been suggested that climate changes have already occurred in the Nordic countries (Kuusisto, 2004). The Nordic countries are in an exceptional geographic position. The North Atlantic Oscillation (NAO) is recognized as a major feature of the global climate system. It describes the atmospheric behavior in the North Atlantic sector, especially during the winter season. NAO is defined as "the difference in sea level pressure between the Azores and Iceland" (Førland et al., 2000 p.69). A low NAO-index indicates that low-pressure systems move south in the winter, whereas a high index indicates many low-pressure systems in the Nordic area. The NAO index has increased since the 1960s, resulting in many low-pressure systems and mild, stormy winters (RegClim 3). The result is regional differences in seasonal climate and both national and regional challenges when it comes to production capacity, storage and transmission of energy.

Earlier studies (Bergstrøm et al., 2003, Kuusisto, 2004, Beldring et al., 2005) are mainly concerned with the effects on the supply side of the energy market. The supply is likely to be enlarged as inflow, temperature and wind speed is predicted to increase. However, it is important to emphasize the uncertainty of climate modelling. A climate scenario is not a predictor of the future climate. There are several scenarios with an equal probability of occurrence. The global models that are developed have a coarse spatial resolution, which means that they are not capable to include regional differences. The existing climate models can't account for all processes in the climate system as there is uncertainty regarding these processes and the driving forces of climate changes (Førland, 2002). There is unpredictable natural variability and it is argued that part of this variability is externally forced by for example solar activity or landscape changes. Hence, climate models, which predict changes based on emission data, will not capture these changes (Beldring et al., 2005). It is therefore necessary to handle the results from climate modelling with some care.

We have studied several earlier reports as a theoretical background for this thesis. The RegClim project has provided the data material used in this thesis and their reports describe the development of Nordic climate research. Climate, Water and Energy (CWE) offer

[4] The electricity share of energy consumption amounts to 48 % in Norway (Statistics Norway, 2003), 32 % in Sweden (Statistiska Sentralbyrån, 2005), 25% in Finland (Energia, 2002) and 19 % in Denmark (E-mail from Lisbeth Petterson in Dansk Energi).

knowledge of the current status of research in this field, and is based on RegClim's data series. The Norwegian Water Resources and Energy Directorate (NVE) and the metrological institute of Norway (DNMI) have cooperated in an extensive climate project in Norway. These projects have provided important background information and will be described in more detail in the following sections.

2.1. RegClim

RegClim is a coordinated research project concerning development of scenarios for climate change in the Nordic region, the surrounding maritime zone and parts of the Artic zone from global warming. The following institutions participate in RegClim: The metrological institute of Norway (DNMI), the Institute of Marine research, Nansen Environmental and Remote Sensing Centre, the Geophysical Institute in Bergen, the Institute for Geography in Oslo and Bjerknes Collaboration for Climate Research (RegClim 1). During 1997-2002, RegClim has worked to prepare for impact climate change studies, by downscaling global climate scenarios in the Nordic region[5]. RegClim used ECHAM4/OPYC3[6] and HadCM2[7]. There are now three available models for climate modelling; two global models being the Bergen Climate Model (BCM) and GCM-Oslo, and one model for atmospheric dynamic downscaling, HIRHAM. RegClim has published a research report from the first simulations with HIRHAM in the Norwegian part of the RegClim project. This report describes the results from an experiment of comparing the periods 1980-99 and 2030-49 with regards to certain climate indicators. RegClim reports an increase in temperature of 1-1.5 C° over central Europe. There seems to be an increase of 5-10 % in precipitation in large parts of Scandinavia, and this is highly correlated with the temperature. There are significant seasonal variations in Scandinavia, and western parts of Norway can expect up to 30 % more precipitation in the next 50 years. The wind speed shows increasing values all over Scandinavia. As there are systematic errors in the global model, the results are considered with some care (Bjørge et al., 2000).

RegClim is currently working to develop a model with reduced uncertainty in the Nordic region's climatic development, by investigating the role of the Nordic seas and regional pollution. The results will be produced in the third phase of the project, in 2002-2006 (RegClim 2).

2.2. Climate, Water and Energy (CWE)

CWE from 2003 is a result of effective co-operation of Nordic hydrological and meteorological institutions and the Nordic energy sector. The Swedish simulations are based on the HadCM2 and ECHAM4/OPYC3 global models, whereas the Danish and Norwegian HIRHAM are run from the ECHAM4/OPYC3 global model, but different emission scenarios are applied (Rummukainen et al., 2002). The data simulations belong to RegClim in Norway and SWECLIM in Sweden. The project applied long-term observations from the Nordic countries to study climate changes in the 20th century (Kuusisto, 2004).

The aim of CWE was to describe the present status of research and to identify the needs and key priorities in the energy sector for the future. According to CWE there has been a rise in the mean temperature during the 20th century in Norway, Sweden, Finland and Denmark. There are some differences among the countries with regards to periods with somewhat colder weather, and with respect to statistical significance. Sweden, Finland and Denmark experienced different degrees of increased annual precipitation in the 20th century. In Norway, annual precipitation increased all over the country except in the southern part. Change in snow storage is interesting from a hydropower point of view. In the southern parts of the Nordic countries the snow storage has declined, due to mild winters. However, there is a higher water equivalent of snow in the north of Norway, Sweden and Finland. There was no long-lasting observation series of evaporation (Kuusisto, 2004).

The work of the CWE- group will continue in an ongoing research project "Climate and Energy: Impacts of Climate Change on Renewable Energy Sources and their role in the Nordic Energy system". The project's objective is to do a comprehensive assessment of the impact of climate change on Nordic renewable energy resources including hydropower, wind power, bio fuels and solar energy (CE, 2003-2006). There are not available data series from this project yet.

2.3. The Norwegian Water Resources and Energy Directorate (NVE)

NVE has together with DNMI carried out a comprehensive project on the long-term variability of temperature and precipitation on future stream flow (synonymous with inflow) in Norway. The project is based on data series from the ECHAM4/OPYC3 model with the emission scenario IS92a and the HadleyAm3-model with emission scenario A2[8] and B2[9]. Altogether there are 40 SRES scenarios developed, which are equally valid as there is no probability of occurrence assigned to any of the scenarios. The project compares

[5] Email from Haugen, DNMI

[6] ECHAM4/OPYC3 is a global model the from Max Planck Institute (Førland et al, 2004)

[7] HadCM2 is a global climate model from the Hadley Institute (Førland et al, 2004)

[8] A2 describes a heterogeneous world with increasing population. There is a regional orientation with slow economic growth and technological change (IPCC 2000).

[9] B2 shows less population growth than A2. Intermediate levels of economic growth and technological change (IPCC 2000).

the period 1980-99 to the period 2030-49 in terms of temperature, precipitation and inflow (Beldring et al., 2005).

The objective of the NVE report was to detect historic variability in stream flow and compose scenarios for the future stream flow in Norway. RegClim gives the observations used in the project. The results are presented in several reports. According to NVE, the temperature in Northern Europe is expected to increase by 1-1.5 C° when using the ECHAM4/OPYC3 models. A2 has a higher emission scenario for CO_2 than B2, and this scenario shows even higher temperatures. Precipitation seems to be correlated with temperature and changes of + 5-10% can be found in large parts of the Nordic area. The major increase will be during autumn, and the western part of Norway will experience the largest increase. The stream flow will, according to NVE, increase by most in the winter and decrease by most in the summer. The annual increase varies from 3.7 – 16.5 % in Norway. The results are a little different depending upon the model applied. This underlines the aspect of uncertainty in climate modeling (Beldring et al., 2005). In the NVE reports, there are 4 seasons per year and Norway is divided into 13 regions. By having that many regions, NVE can detect regional changes in the climate. This split up is important to consider if we want to compare the results (Førland et al., 2000).

The work of NVE and DNMI is likely to be continued this year, to approach specific problems. This work will also proceed in the Nordic project "Climate and energy".

3. Theoretical frameworks and modelling

The theoretical basis for evaluating the effect from climate change on the electricity market is Førsund's optimisation model (1994) for a hydropower system. Førsund's model is used as a framework for discussing possible shadow prices on restricted capacity. Førsund's model will be extended to include international trade, increased inflow from climate changes and increased international supply of electricity, as other energy sources (e.g. wind) are included. The concepts of Førsund's theory are formalized in the electricity market model Normod-T (Johnsen, 1998). Normod-T includes regional and national differences in inflow, temperature, demand, and transmission networks between the traders, all possible bounds and shadow prices on energy.

The input to Normod-T will be inflow, temperature dependent demand of electricity and wind speed from 2001-2040. We apply a climate model to simulate future inflow. This model is estimated for historical data on inflow, precipitation, snow water equivalent, runoff and evaporation. We will use a temperature dependent model developed by Johnsen and Spjeldnæs (2005) to simulate the demand for electricity in 2001-2040. The temperature model isolates the effect of temperature on the demand for electricity. Figure 3.1 shows the relationship between theory and the three models applied in this thesis. Wind is added directly to Normod-T's supply side, as wind speed.

Figure 3.1. The relationship between the theory and models applied

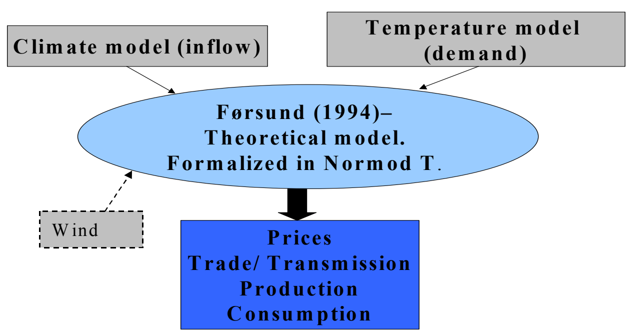
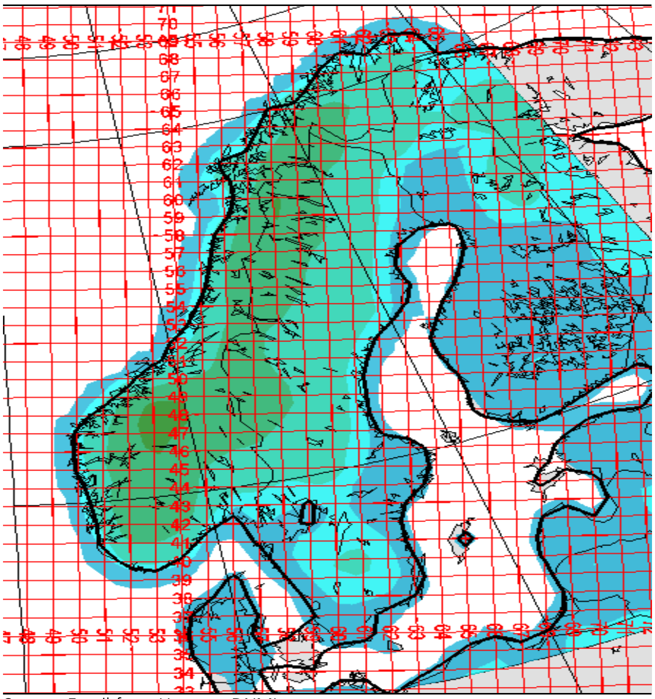


Figure 3.2. The observation points in the dataset from RegClim



Source: Email from Haugen, DNMI

3.1. The climate model

We will estimate a climate model for inflow based on historical values (1980-99) on inflow, precipitation, snow water equivalent, runoff and evaporation. The model will be used to simulate inflow in 2030-49.

NVE data covers weekly inflow in the period from 1931-2004. This inflow series show the amount of water that would have been available in today's water reservoirs for the whole period 1931-2004. We will utilize data from 1980-1999, as this is the time period of the available RegClim data series. RegClim has provided data series concerning precipitation, accumulated snow storage, daily snowfall, runoff and evaporation for the periods 1980-1999 and 2030-2049[10]. The data series originate from an experiment

[10] See appendix 1 for description of each variable in terms of unit of measurement

where RegClim compares the periods 1980-99 and 2030-49 with regards to certain climate indicators (Bjørge et al., 2000). As the values in one specific year are random, we use average values and let 1980-99 represent the current time and 2030-49 the prospective time. The data series are based upon observations at 444 geographical points in the Nordic region. The map in figure 3.2 shows how the observations are described by the climate model's redlined grid system.

The Nordic region is limited by the black rectangle. The colored area indicates observations where more than 40 % of the area is above the ocean level. The southeast corner of the map is not included in the analysis, as it is outside the Nordic region. Every grid in the system represents an area of 55*55 km^2, which indicates that it is a coarse description of the terrain. Each grid intersection indicates one observation point, and is described by latitude and longitude[11]. All variables have daily observations in each point. As inflow is described on a weekly basis, observations on precipitation, temperature, evaporation and accumulated snow will be aggregated to weekly numbers. The data material from RegClim includes 30 days each month, resulting in the last week of every year being only 3 days. To get an approximation to a normal week, this week of the year is multiplied by 7/3. Evaporation, precipitation, snowfall and runoff are described as the total amount during each week. Aggregation from daily to weekly observations is done in the following manner:

$$X = \sum_{i=1}^{7} X_{i,j,k} \quad i = 1,..7 \quad j = 1,..52 \quad k = 1,..20$$

Accumulated snow, temperature and wind are described as an average weekly observation. The average of each week's observations is calculated in the following way:

$$X = \frac{\sum_{i=1}^{7} X_{i,j,k}}{7} \quad i= 1,..7 \quad j = 1,..52 \quad k = 1,..20$$

According to Normod-T, the Nordic area is split into 14 regions (see map in figure 3.9). The 444 points will be divided into these regions as carefully as possible. Any observation measured along the coast, is given less weight than an inland observation, as it gives less inflow to the reservoirs. If more than 50 % of the observation point is below ocean level, the observation gets a 50 % weight. Otherwise, the observation is weighted 100 %. The data material will be presented as seasonal observations. Season 1 is week 1-17, season 2 is week 18-35 and season 3 is week 36-52 (comparable to the market model, Normod-T).

The climate scenario from RegClim is based on the global model ECHAM4/OPYC3 from the MaxPlanck Institute. The IPCC scenario IS92a forces this model (RegClim 2). This scenario implies that the CO_2 emissions will increase annually with 1 % from 1990 (IPCC, 2000). This indicates a doubling in CO_2 concentration by 2050. The IS92a scenario is not necessarily the most likely scenario, as there is no objective way to assign likelihood to any of the scenarios developed by IPCC (Nakicenovic et al., 2005). According to RegClim, the model gives a realistic picture of the current climate and is therefore chosen as the basis for dynamical downscaling (Bergstrøm et al., 2003 p.17).

The global climate models typically have a coarse spatial resolution, and they are not capable to include regional differences, and give a realistic description of the region (Benestad, 2003 p.90). RegClim achieved the regional climate scenario by using a model for atmospheric dynamic downscaling, HIRHAM. The climate scenarios obtained from HIRHAM, will be better suited to attend to geographical differences (mountains, fjords, forest etc) in the Nordic region (RegClim 2). There are differences between the computed data and the observed average variables. This is partly due to the coarse spatial resolution, but also inadequacies in the regional model. The results from this analysis is based on one of many scenarios, meaning that the model data for one historical day cannot be directly compared to the observed weather situation that specific date[12].

We will estimate a climate model for expected inflow based on historical data on total inflow in Norway, as we didn't obtain data on inflow in the other Nordic countries. However, we assume that the estimated coefficients can be used to simulate inflow in regional Norway, Sweden and Finland. Denmark is excluded in the analysis of inflow, as it has almost no hydropower. By doing this simplification, we assume that the climate indicators will have the same relative effect in all regions. This will not provide accurate predictions of inflow in each region, but we assume that the model will predict trends and give approximate changes in inflow in each region.

The formation of the model:
Water inflow into the hydropower reservoirs is the basis for hydropower production. The inflow varies because of rainy seasons in the spring and the autumn, cold weather and snow accumulation during winter, and snow melting in the spring, etc. We assume that inflow at time t, It, is influenced by the direct effect of rain at that time Rt, the runoff into the reservoir, Pt, which may be due to accumulated snow and rain in the surrounding ground. We deduct evaporation Et, following Bergström et.al. (2003). Our model is linear in the variables:

[11] Email from Haugen, DNMI

[12] Email from Haugen, DNMI

(3.1) $I_t = \beta_0 R_t + \chi_0 P_t - \eta_0 E_t$

and there is no constant term as there is no inflow without rain and runoff . The runoff is explained by rain as an indicator of the humidity in the soil and snow melting from the storage of snow, St.

(3.2) $P_t = \nu_0 R_t + \nu_1 S_t$

In the seasonal pattern of inflow, the effects from snow and rain differ. Rain will contribute to increased inflow with almost no lag, but will depend on the water content of the surrounding soil. The snow needs to melt before it is measured as inflow, i.e., the n1 parameter is zero for most of the year except for the melting period. During winter, almost all snow accumulates. When temperature increases in the spring, the snow starts melting. The melting speed is also influenced by the amount of rain during the melting period, i.e., the rain has different impacts on inflow during the melting period and during the rest of the year. If the temperature is high while the weather is rainy, the melting could also become overflow, i.e., all the inflow may not be captured in the reservoirs. According to the data series from RegClim, the typical melting period in Norway and Sweden, which constitutes the largest share of the hydropower capacity in the Nordic countries, is weeks 17–23. To include the effect of snow melting, we create a multiplicative dummy for every week of the average snow-melting period, with a one-week lag. Each dummy accounts for the melting in one particular week in the period. To account for the particular effect of rain on inflow in the snow-melting period, we add multiplicative dummies (D) for rain in the same weeks.

(3.3) $\nu_1 S_t = \kappa_1 S^*{}_t + \sum_{i=17}^{23} \kappa_i S_{t-1} D + \sum_{i=17}^{23} \beta_i R_t D$

The variable accounts for the effect of daily snow directly into the reservoirs. Putting equation (3.2) and (3.3) into equation (3.1) and rearranging and redefining the coefficients results in:

(3.4)

$$I_t = \beta^* R_t + \chi^* S_t^* + \sum_{i=17}^{23} \kappa_i^* S_{t-1} D + \sum_{i=17}^{23} \beta_i^* R_t D - \eta_0 E_t + \varepsilon_t$$

where we have added a normally distributed stochastic term et with a constant variance . Temperature is only included in the inflow model by its effect on rain, snow melting and runoff. If the temperature is high, more snow is melting, but as the ground might be dryer, the inflow can be somewhat reduced.

We apply OLS to estimate the parameters in chapter 4. See Gujarati (2003) for details. The climate model will simulate the effect of climate changes on inflow in the period 2030-2049.

RegClim has provided both historical data (1980-99) for the estimation of the climate model, and projected values for the period 2030-49. The estimated model is used to simulate inflow into the reservoirs based on data from 2030-49. We will estimate the linear trend in inflow from 2001-2040. As the RegClim values in one specific year are random, we need to use average values. We will estimate weekly inflow in 1980-1999, and the average inflow in this period represents the current state of time (1990). The climate model will simulate inflow from 2030-2049. The average of this time period represents the future state of time (2040). The linear trend is found by calculating the weekly growth rate from 1990-2040.

Growth rate per year 1990 – 2040 =

$$\left(\frac{\sum_{2030}^{2049} Inflow_{week} / 20 yrs}{\sum_{1980}^{1999} Inflow_{week} / 20 yrs} \right)^{1/50}$$

We only analyse the simulated inflow from 2001-2040, as 2001 is the base year in the electricity market model, Normod-T. Inflow doesn't behave linearly year by year, but the development of inflow can be described by a linear relationship, which is of our main interest.

3.2. The temperature model

Changing temperature due to climate changes may influence the demand for electricity in the Nordic countries. The cold climate indicates that a significant part of the electricity consumption concerns heating. We will use a model developed by Johnsen and Spjeldnæs (2005) to evaluate the demand for electricity. The purpose of their method is to estimate the impact of temperature on ordinary consumers weekly electricity demand. The model is meant to fit an aggregate of households and non-energy intensive industries. The weekly fuel-oil consumption is unknown, as it may be stored for a long time by the end user. To isolate the effect of temperature, the model includes other factors that may influence demand for energy.

The expression for the weekly electricity demand in this model is $E = f(P_E, P_F, Y, W, D, H)$

Where

E = electricity demand Y = activity level

T = temperature

P_E = electricity price W = wind speed

H = holiday dummies

P_F = price of alternative fuels D = day length

HDD = heating degree days

The estimations are based on an error correction model specification, where a change in the natural logarithm of weekly consumption is the dependent variable. The demand for electricity is presented in equation (3.6) (Johnsen & Spjeldnæs, 2005. p.4)

(3.6)

$$\Delta ln(E_t) = \alpha_0 + \alpha_1 \Delta ln(p_t^E) + \alpha_2 \Delta ln(p_t^F) + \alpha_3 \Delta ln(Y_t) + \alpha_4 \, ln(W_t) + \alpha_5 \Delta ln(D_t) + \alpha_6 \Delta(HDD_t) + \alpha_7 \, ln(p_{t-1}^E) + \alpha_8 \, ln(p_{t-1}^F) + \alpha_9 \, ln(Y_{t-1}) + \alpha_{10} \, ln(D_{t-1}) + \alpha_{12}(HDD_{t-1}) + \alpha_{13} \, ln(E_{t-1}) + holidayerrors + \varepsilon$$

HDD is temperature calculated as heating degree-days. Heating degree-days are defined as the sum of the difference between 17°C and the average daily temperature for all days colder than 17°C. Holiday dummies are included as 19 individual dummy variables, and the error term, ε, is assumed to behave as white noise. Demand equation (3.6) was estimated simultaneously with a price equation (3.7),

$$(3.7) \quad \Delta ln(p_t^E) = \beta_0 + \beta_1 \Delta ln(E_t) + \beta_2 \, ln(E_{t-1}) + \beta_3 \, ln(Z_{t-1}) + \beta_4 \, ln(p_{t-1}^E) + \varepsilon$$

where Z is the hydrological balance. We are interested in the effect of changing temperature on the future electricity demand. Johnson and Spjeldnæs' simultaneous model can be utilized to simulate the temperature effect by assuming all other variables to be constant. To make sure our *HDD* values can be used in combination with this model, we calibrate Johnson and Spjeldnæs' equation, with all its actual variables, for each week in 2001 and replace their *HDD* values with our *HDD* values (from RegClim). The estimated electricity demand proves to be very similar. Johnsen and Spjeldnæs' model is estimated for an area similar to our region 1[13], but we assume that the coefficients for *HDD* can be used in all the Nordic regions. In high frequency data, a simultaneous model is necessary to identify demand elasticity, see Hansen and Bye (2005) for detailed discussion. However, we will only consider the first order effects of changing temperatures. Equation (3.6) indicates that demand for electricity is reduced when the temperature increases. Equation (3.7) shows that the price will fall when demand decreases, consequently prices falls when the temperature increases. The temperature effect on price is included in Normod-T. By excluding equation (3.7), we try to avoid double calculation. We will simulate a linear trend in demand for electricity from 2001-2040. The procedure is explained for inflow in chapter 3.1.

3.3. Førsund's optimisation model

Førsund (1994) has developed an optimisation running model for a hydropower system. Norway is almost a 100 % based on hydropower, whilst Sweden has 45 % and Finland 15 % hydropower (Kuusisto, 2004). In Norway, if being an autarky or congestion restricted area, this implies that one can ignore variable cost of production, as they are close to zero in a hydropower based system. The value of the water alone represents a variable cost. The water value is the opportunity cost of producing electricity from a given amount of water in different periods. The value of the water is positive if there is a shortage of supply in a period. Without shortage, the optimal use of water results in the willingness to pay being zero (Førsund, 1994).

In this thesis, Førsund's model is used to describe how and where different bounds can become effective and create a shadow price on electricity. The model will be presented schematically with the most important equations and conditions (Førsund, 1994).

The Lagrange function for the optimization problem

(3.8)

$$L = \sum_{i=s,v} \left\{ \begin{array}{l} \int_{xi=0}^{E} P_i(\chi_i)\delta_{\chi_i} + P_i^{XI} E_i^{XI} - c_v\left(E_i^v, \overline{E^v}\right) \\ - c_m\left(\overline{M}\right) - c_{\overline{E}}\left(\overline{E}\right) - c_\Delta(\Delta) - c_{\overline{E^V}}\left(\overline{E^V}\right) - c_K(K) \end{array} \right\}$$

- $\lambda s(Ms - Mo - Vs + Us)$

$\lambda =$ Value of the water

- $\lambda v(Mv - Ms - Vv + Uv)$

- $\sum_{i=s,v} \mu i(Mi - \overline{M})$

$\mu i =$ Shadow price, max limit of reservoirs

- $\sum_{i=s,v} \gamma i(-Mi + \underline{M})$

$\gamma i =$ Shadow price, minimum limit of reservoirs

- $\sum_{i=s,v} \beta i\left(Ei - \frac{1}{a}Ui\right)$

$\beta i =$ Shadow price, converting water

$-\sum_{i=1}^{T} \kappa_i^U \left(U_i - \bar{U}\right)$

$\kappa_i^U =$ Shadow price, effect of water tapping

- $\sum_{i=1}^{T} \rho_i\left(E_i - E_i^H + E_i^{XI}\right)$

$\rho_i =$ Shadow price, trade

- $\sum_{i=1}^{T} \nu_i\left(E_i - E_i^H - E_i^v\right)$

$\nu_i =$ Shadow price, electricity balance

[13] See map in figure 3.9 for details on regional split up

- $\sum_{i=1}^{T} \kappa_i^v \left(E_i^v - \overline{E^v}\right)$

κ_i^v = Shadow price, max limit thermal power

- $\sum_{i=1}^{T} \sum_{j=1}^{u} \tau_{i,j} \left[E_{i,j} - T_{i,j}\left(E_{i,j} .....E_{i,u}\right)\right]$ τ_{ij} = Shadow price, transmission

Under the following assumption

(3.9) $E_i = T_i\ (E_{i1,...}E_{in})$, $\frac{\delta Ti}{\delta Eij}$ E[0,1], $\frac{\delta\hat{}2Ti}{\delta Eij\delta Eik}\begin{pmatrix}\geq 0 \\ \leq 0\end{pmatrix}$, j, k = 1,..n , i = 1,....T

The objective function (3.8) maximizes the sum of consumer and producer surplus and the income from trading, and then subtracts the costs from thermal production, investment in reservoirs, effect, inflow, thermal power and transmission grids. Førsund's optimization model shows where there might be bounds that can turn out to be effective (>0). When a bound is effective, its belonging shadow price is positive and affects the electricity price. The conditions show that a bound can arise from several reasons. When transmitting electricity, there will always be a transfer loss. Equation (3.9) shows that the customer will not receive the amount of electricity that was sent to him in the first place, because of the transmission losses. Table 3.1 explains the symbols used in the Lagrange function.

Table 3.1. Explanation of symbols in equation (3.8) and (3.9), and the resulting conditions

Symbol	Explanation	Symbol	Explanation
$P_i(E_i)$	Marginal willingness to pay for electricity in period i	$P_i(X_i)$	Income (price*quantity)
M_o	Water storage at start	E_i^H	Hydro power production
M_i	Water storage in period i	E_i^I	Imported electricity
$\overline{M}$	Maximum reservoir	$\overline{E^v}$	Capacity of thermal power
$\underline{M}$	Minimum reservoir	E_i^X	Exported electricity
V_i	Inflow in period i	E_i^{XI}	Electricity traded
U_i	Tapping in periode i	P^{XI}	Price (trading)
E_i	Electricity in KWh	K	Investing in transfer grid
E^v	Electricity produced by thermal power	a	Water coefficient
$\overline{E}$	Maximal effect	Δ	Investing in inflow

(Source: Førsund, 1994)

The different bounds will be effective at different times and in different situations. For example, if climate changes imply a dryer autumn/winter, there might be a shortage of water and a positive water value. The bound on the lower limit of the reservoir γ_w may turn positive and increase the electricity price and the willingness to pay. Reduced supply of electricity will lead to more import from neighboring countries. This might result in an effective bound and a positive shadow price on transmission, τ . If there is a shortage in the effect of tapping water, the shadow price κ_i^U will come in addition to the water value when determining the shadow price of using water for electricity production. Førsund's model assumes that only thermal production yields a cost to the producer, as the hydropower plant already exists. The capital cost for hydropower is sunk and variable cost is close to zero.

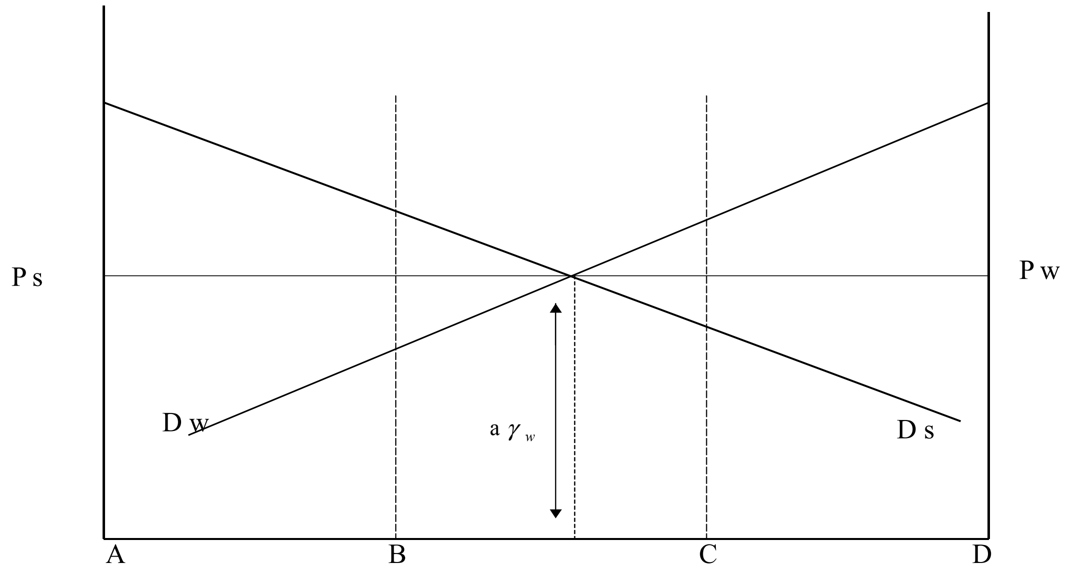
In this thesis we use a hydropower-based market as an illustration of how the electricity market might react to climate changes. Førsund's model is also recognized as the bathtub model, due to the physical illustration of the hydropower based market. The following sections are devoted to illustrating how international trade and climate changes affect the Norwegian hydropower-based market.

3.3.1. Autarky in a hydropower market

We assume an autarky market. When there are no effective bounds in such a market, the price of electricity should be equal at any time. To simplify the illustration, the year is divided into one summer (S) and one winter (W) period. Figure 3.3 illustrates a hydropower market in Norway.

Figure 3.3 shows total inflow in summer and winter on the horizontal axis. The inflow is assumed to be greater in the summer than in the winter. AC represents inflow in the summer and CD in the winter. The demand functions are measured along both vertical axes. The storage capacity in the reservoirs is BC. In the case of figure 3.3, the assumption is that there is a shortage of water in the winter. This indicates a positive value of water in the winter, λ_w >0. There will be a maximum transfer of electricity between the periods, to obtain the same price in the two periods. The bound on water in the winter will set the price.

Figure 3.3. A hydropower autarky market without reservoir limitations



Førsund (1994, p.8) shows that for an autarky model the Lagrange function is

(3.10) $L = \sum_{i=s,w} \left\{ \int_{xi=0}^{Ei} p_i(\chi_i)\partial\chi_i \right\}$

(3.11) $- \lambda s(M_s - M_0 - V_s + U_s)$

(3.12) $- \sum_{i=s,w} \beta_i \left(E_i - \frac{1}{a} U_i \right)$

(3.13) $- \sum_{i=s,w} \mu_i (M_i - \overline{M})$

(3.14) $- \sum_{i=s,w} \gamma_i (-M_i + \underline{M})$

(3.15)- $\lambda_w (M_w - M_s - V_w + U_w)$

Equation (3.10) maximises the consumer surplus by summing the price and quantity of electricity for both periods. Equations (3.11) and (3.12) describe which variables that decide if the value of water, λ, is positive or negative in each period. The shadow price on the upper and lower level of the reservoir is μ_i and γ_i, and is determined by the level of water in the reservoirs (3.13 and 3.14). Equation 3.15 determines the shadow price on the conversion of water, β_i, dependent of the energy level, tapping and a water coefficient, a[14].

The necessary first order conditions for the endogenous variables; electricity production, tapping and reservoirs, are (Førsund, 1994, p.8):

(3.16) $\frac{\partial L}{\partial E_i} = p_i(E_i) - \beta_i \qquad \begin{pmatrix} = 0 \\ \leq 0 \end{pmatrix} for \begin{pmatrix} E_i > 0 \\ E_i = 0 \end{pmatrix}$

i= s,v

(3.17) $\frac{\partial L}{\partial U_i} = -\lambda_i + \beta_i \frac{1}{a} \begin{pmatrix} = 0 \\ \leq 0 \end{pmatrix} for \begin{pmatrix} U_i > 0 \\ U_i = 0 \end{pmatrix}$

i= s,v

(3.18) $\frac{\partial L}{\partial M_s} = -\lambda_s + \lambda_w - \mu_s + \gamma_s = 0$

(3.19) $\frac{\partial L}{\partial M_w} = -\lambda_w - \mu_w + \gamma_w = 0$

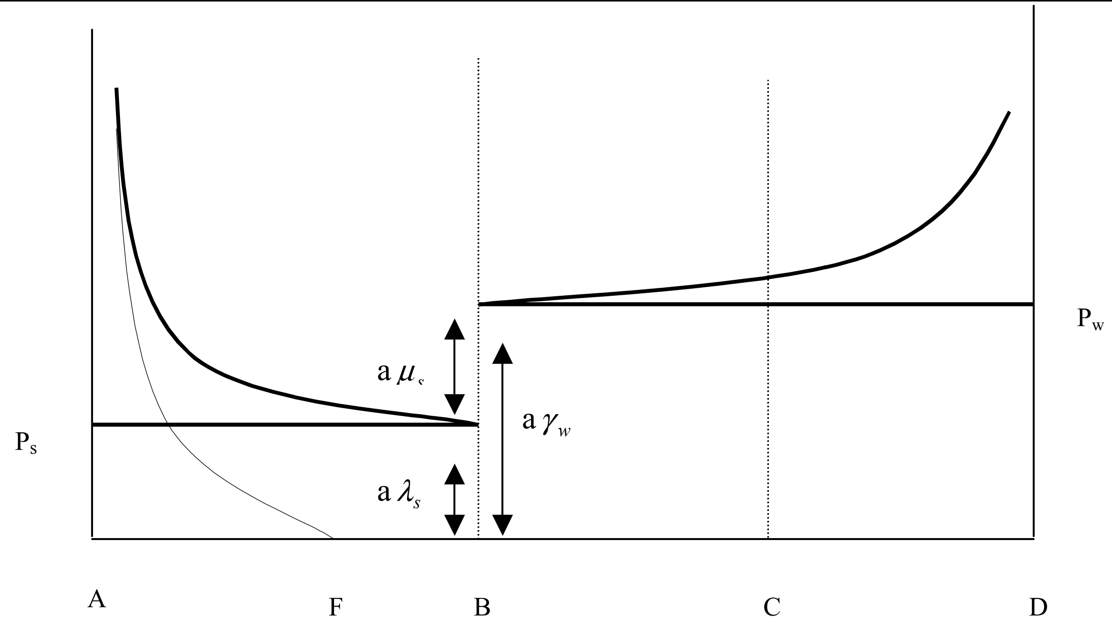
We assume that there is a positive demand for water and a positive amount of water being used. This assumption results in the following relationship between the willingness to pay for electricity and the value of water:

(3.20) $p_i(E_i) = \beta_i = a\lambda_i$

In the situation of autarky in figure 3.3, the electricity price is determined by the first order conditions above. The shadow price γ_w will be positive when there is shortage of water in the winter. There are no effective bounds in the summer period, which results in $\lambda_s = \lambda_w$ from equation (3.18), and no effective bound on the upper level of reservoir capacity, meaning $\mu_w = 0$. Equation (3.19) shows that $\lambda_w = \gamma_w$ and according to equation (3.20), the electricity price in figure 2 is $p_s = p_w = a\lambda_i = a\gamma_w$

[14] The water coefficient is a measure of the amount of water needed in the production of electricity.

Figure 3.4. A hydropower market with reservoir limitations



Source: (Førsund, 1994, p. 16)

In figure 3.3 there was no problem regarding the storage capacity. This is however a situation that easily may occur. In an autarky situation, redundant water will go to waste, as there are no export possibilities. An example is a situation with shortage of water in the winter, and flooding in the summer. If the inflow of water is larger than the electricity demand and reservoir capacity in the summer, the shadow price on the upper limit of the reservoir capacity, μ_s , will be positive as long as the stored water can be used in the winter period, and has a positive value in the summer. The shadow price on the lower level of reservoir capacity in the winter, γ_w , will be positive as there is a shortage of water (Førsund, 1994). Figure 3.4 illustrates this situation.

Shortage of water in the winter, results in transfer of as much water as possible from summer to winter. The storage capacity BC will be used during winter, resulting in a winter consumption of BD and the marginal willingness to pay, p_w.

The demand curve for the summer period is drawn in two curves. The upper curve illustrates a situation where the usage of water exactly equals the supply; there is no overflow. The value of the water will be lower than in the winter, as the difference will be the shadow price on the upper level of the reservoir in the summer. The lower demand curve illustrates a situation of flooding. An amount represented by FB will overrun the reservoir. This results in a marginal willingness to pay of zero during the summer period. Equation (3.18) and (3.19) shows that $\lambda_w = \mu_s$, and $\lambda_w = \gamma_w$. This result in the shadow price on the upper level in the summer equals the shadow price on the lower level in the winter, $\mu_s = \gamma_w$ (Førsund, 1994). The shadow price of water in the summer period is less than the shadow price of water in the winter period.

Equation (3.18) shows that $-\lambda_s + \lambda_w - \mu_s = 0$

Equation (3.19) shows that $\lambda_w + \gamma_w = 0 \rightarrow \lambda_w = \lambda_s + \mu_s$

Equation (3.20) shows that $P_s = a\lambda_s = a(\lambda_w - \mu_s) = a(\gamma_w - \mu_s)$

$P_w = a\lambda_w = a(\lambda_s + \mu_s) = a\gamma_w$

3.3.2 International trade in a hydropower market

In this section, we will extend Førsund's model by including international trade. We will not consider bounds on transmission in this simple illustration. The illustration in figure 3.5 shows the Norwegian hydropower market and the international market for electricity. The international supply curve is a step-by-step curve due to different cost levels of production. AD is inflow in period 1, and DF is inflow in period 2. CD is the storage capacity in the Norwegian market. The international price in period 1, P_1*, will be the Norwegian price as there is trading between countries. Total usage of water in period 1 is AD, whereas AB is used to satisfy domestic demand. Export will be BD, indicating no storage for period 2. The international demand in period 2 is lower, D (int) $_2$, leading to a lower price on electricity. The domestic demand increase as the price is lower. There is no water storage from the previous period, which creates a gap between the demanded electricity and the domestically produced electricity, ED. The amount ED will be imported. In the case of autarky, there would have been storage as there was no possibility of exporting.

When international trade is introduced, there is no storage for future shortage. Instead, the electricity is sold where it yields the highest return.

Figure 3.5. International trade in a hydropower based system

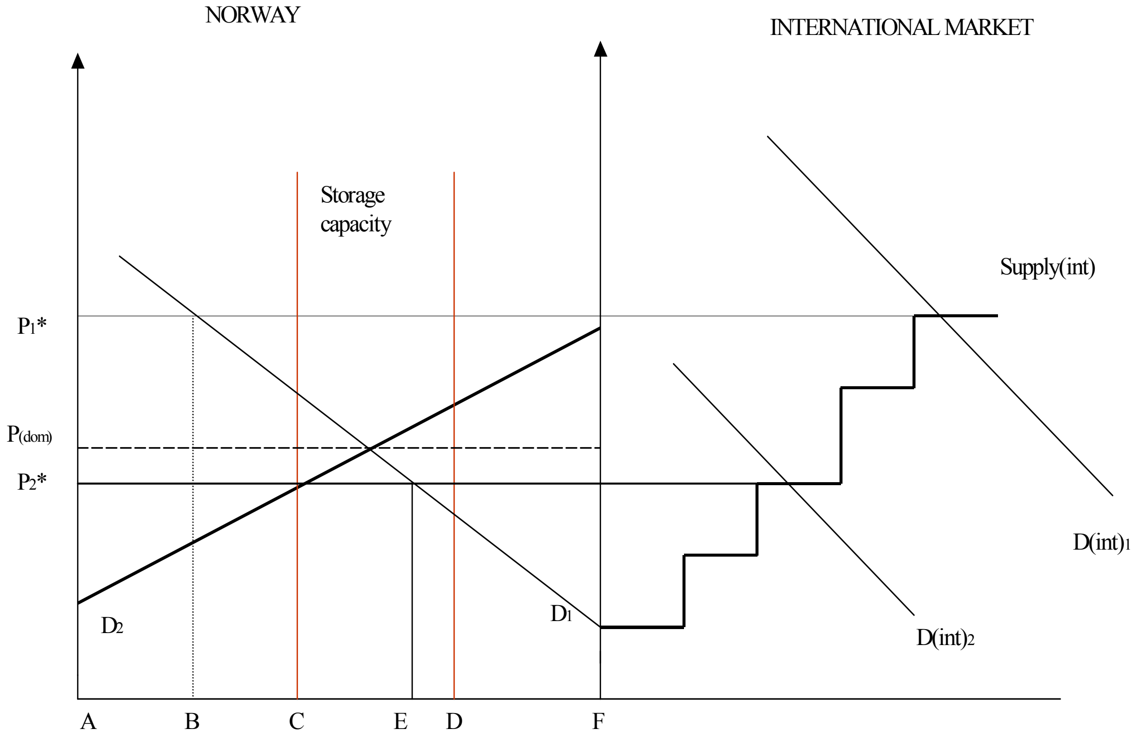
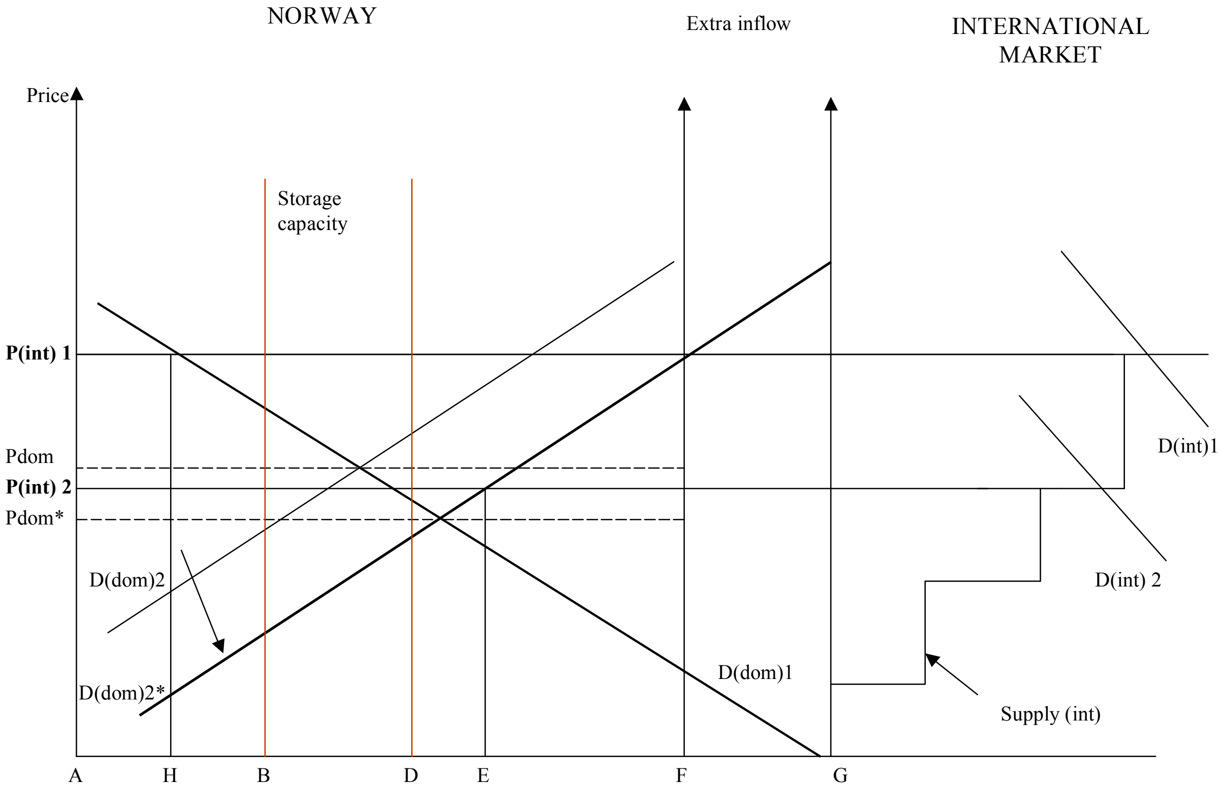


Figure 3.6. International trade in a hydropower based system with increased domestic inflow



3.3.3 Introduction of climate changes in a hydropower market

One consequence of climate change is expected to be increased inflow. Førsund's model can be expanded to involve the increased inflow. However, the effect on the electricity price will depend upon when the increased inflow occurs. It can be evenly distributed through out the year or mainly in one period. Another variable is the international demand and price for electricity in the two periods. Increased inflow in Norway increases the supply of electricity and the amount of export from Norway. To illustrate the case of increased inflow, we assume that the extra inflow comes in period 2. We will not consider restrictions and possible effective bounds in the illustration. Figure 3.6 is an illustration of this situation.

i) The increased inflow is within the limits of the production capacity.
In this case, the amount of export from Norway is increased. The inflow in period 1 is AD. The storage capacity BD is the same as before. Increased inflow in period 2, results in an expansion of the model. The area FG extends the horizontal axis, and total inflow in period 2 is GD. The increased inflow enlarges the bathtub and demand in period 2 shifts rightwards, from $D_{(dom)\ 2}$ till $D_{(dom)\ 2}*$. In period 1, the international demand sets the electricity price P(int)1, resulting in export of electricity from Norway. An amount reflected by AH satisfies the Norwegian demand, and HD is exported. There is no storage of water in this period. In period 2, lower demand results in the world price, P(int)2. The increased amount of inflow makes the Norwegian market self sufficient of electricity in period 2. The domestic demand is EG, and the export is ED.

When the increased Norwegian export doesn't affect international supply and demand, there will be no price changes. In figure 3.6, this situation is reflected by the international demand curve intersecting the horizontal part of the international supply curve.

The increased export in period 2 may result in an effective bound on the transmission capacity between the trading partners. The effective bound will create a positive shadow price on transmission, with a higher price on the exchange of power. The need for investment in new capacity should be considered. However, the electricity price needs to be higher than the marginal cost of developing a new capacity, for the investment to be profitable.

ii) The increased inflow exceeds the capacity limitations.
We assume a situation where the inflow increases more than the existing capacity can utilize. This situation will lead to an effective capacity bound for the reservoirs, and the shadow price μ will become positive. As the cost of storing water is high, the domestic electricity price will be reduced. If there is a situation of flooding, the value of the water is zero. Initially we assume that Norwegian exports don't affect international prices. However, in this case we let the Norwegian export be significantly large to affect international prices. This is illustrated by reduced electricity prices as the demand curve intersects the vertical part of the supply curve. (In our calculations later on, increased Norwegian inflow does reduce Nordic prices. The international prices are assumed to be constant in the market model, Normod-T). Figure 3.7 illustrates this situation.

The inflow in period 1 is AE, and the storage capacity is BD. The result is some water (DE) being unexploited. The international price P(int)1 results in export in period 1 equal to HD. If the reservoirs had increased by DE, the export would have increased by the same amount. When there is a capacity constraint, the redundant water goes to waste and the value of water is zero. In period 2, the inflow of water into Norway is GE and the electricity price is P(int)2. The domestic demand in this period is GI, which means that IE needs to be imported to satisfy demand.

3.3.4 Introduction of other energy sources in the international electricity market

In this section, we will look into a market with supply of both water and other electricity sources, for example wind power. The domestic inflow is extended as in example 3.2.3. The introduction of wind power will not affect the principle of Førsund's model, as it is a hydrological one. However, the international supply of electricity will increase and lead to lower electricity prices. Eventually, increased demand may offset this effect, but not in the first two periods considered. Figure 3.8 illustrates this situation

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Figure 3.7. International trade in a hydropower based system with increased domestic inflow that exceeds the capacity constraints

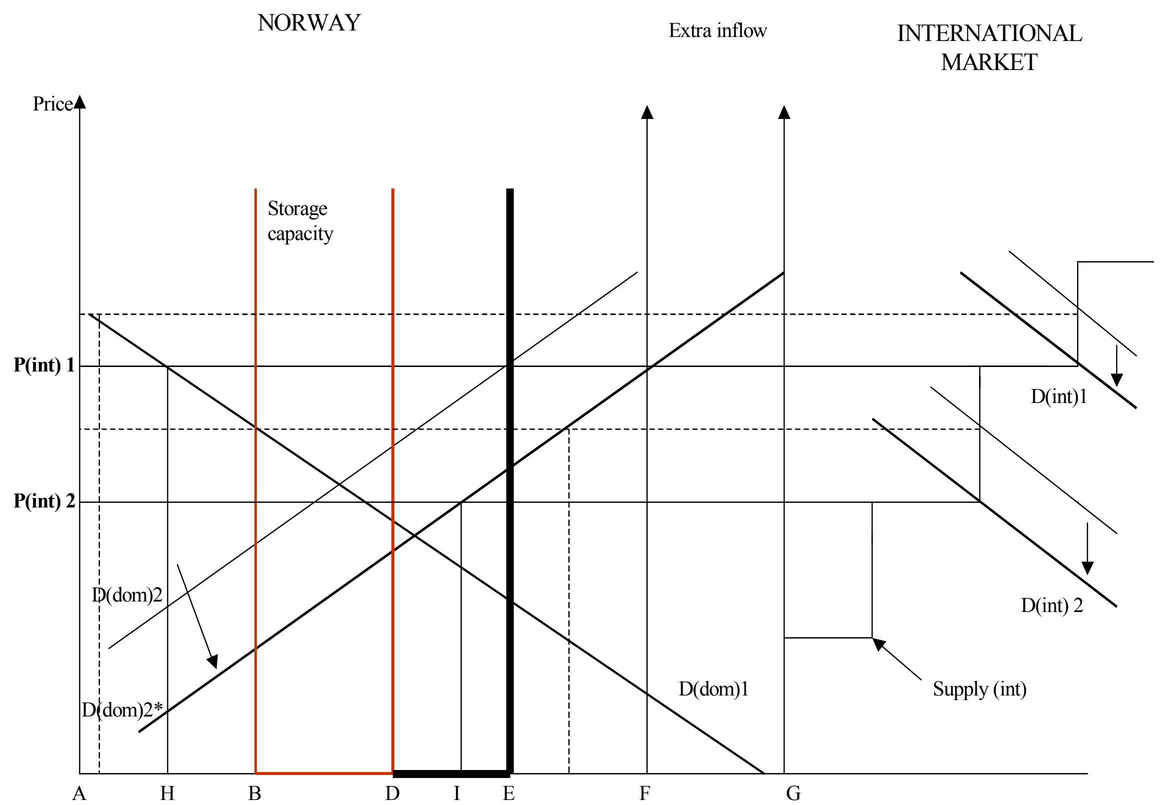
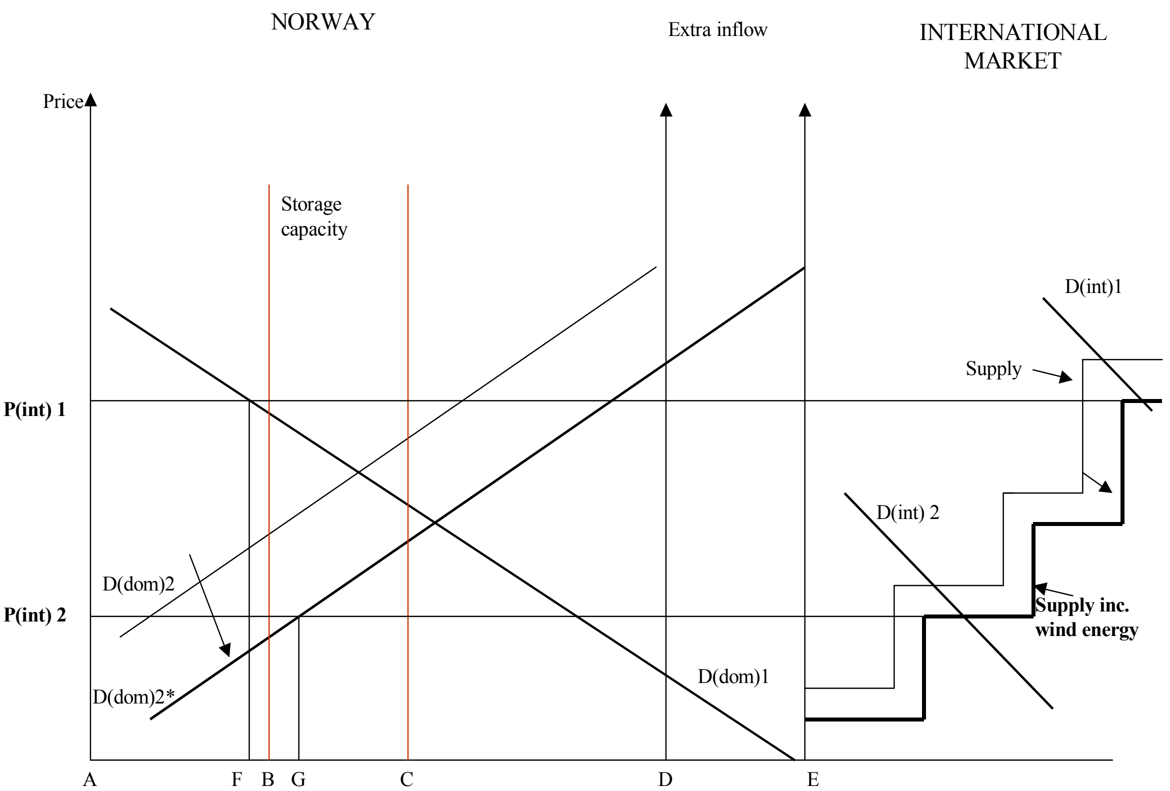


Figure 3.8. International trade in a hydropower based system including increased domestic inflow and wind power



i) The increased inflow is within the limits of existing capacity.
The increased supply of wind energy is comparable to a rightward shift of the "international" supply curve, with consequently lower international prices. In period 1, the electricity price is P(int)1. The total inflow in this period is AC, whereas AF covers domestic demand and FC is exported. When the international price falls, the Norwegian export is reduced as well.

In period 2 the international price is P(int)2. Figure 3.7 shows that when the price is this low, domestic demand increases to EG. Redundant water was exported in the previous period, leaving nothing stored to cover this period's demand. The inflow in period 2 is EC, which means that CG will be imported to satisfy domestic demand in this period. Without the extra domestic inflow, the need for imports would have been much larger. In this case, we assume that Norwegian exports don't affect international supply, and thereby not the electricity price. The international demand curve intersects the international supply curve in a horizontal area.

ii) The increased inflow exceeds the limits of existing capacity.
In this case, some water will not be exploited, as there is no reservoir capacity left. The amount of exports will be equal to the case where inflow is within the capacity limits. If there is flooding, the value of the water is zero. If the Norwegian exports influences international supply, the price of electricity falls. Lower prices leads to higher demand, and whether or not Norway needs to import electricity in period 2, depends on the amount of inflow in this period. In this situation, one needs to evaluate new investment in capacity. If the electricity price exceeds the cost of investing, it would be a profitable expansion.

The increased inflow is likely to result in a higher degree of export. This will possibly lead to positive shadow prices on the transfer of electricity between the trading partners. A result of an overloaded transmission grid is regional price areas with price differentials. The transfer of electricity will become more expensive as τ_i turns positive.

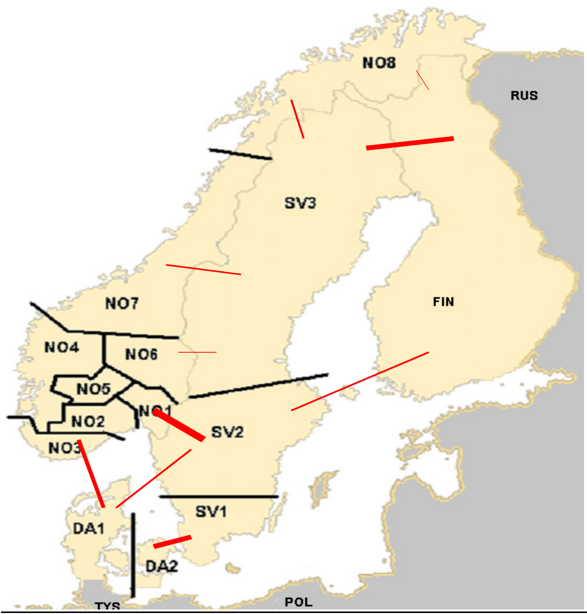
3.4 The electricity market model: Normod-T

Normod-T is an equilibrium model for regional electricity markets which is formally based on the same principles as Førsund's theory (1994). The PhD thesis by Johnsen (1998) explains the model in depth. The simulated data on inflow, temperature dependent demand and wind in the period 2001[15]- 2040 will be the input to Normod-T, to investigate total effects from these climate changes in the next 40 years. In this model existing power plants in the Nordic countries, and regionalized for Norway and Sweden, are specified by cost and capacities. The model describes the Norwegian, Swedish, Danish and Finish markets, and it's based on the assumption of perfect competition. The regional split up of the countries is based on the geographical position of the existing power plants and the transmission net.

The map in figure 3.9 shows the split up of the Nordic countries, and the transmission lines between the countries that are included in Normod. The thickness of the red lines indicates the amount of electricity that can be transmitted between countries in the short run. Norway is divided into 8 regions, Sweden into 3, Denmark into 2 and Finland is only one. The reason for this splitting up is the possible bounds from the transmission of electricity between the countries and within each country.

Normod-T separates the customers into 5 different segments. This is highly important because of the different demand and consumption patterns. All the possible bounds and resulting shadow prices are included in Normod-T. The demand side takes the following 5 demand sectors into account: metal, pulp and paper, other manufacturing, service and households. The reason for the division of demand is that different sectors use different amounts of electricity over time and the price elasticity varies between the sectors. The average price elasticity in Normod-T is - 0.3. Another reason for the division is that the size of different sectors changes at different rates over time (Johnsen, 1998).

Figure 3.9. The split up of the Nordic countries in Normod-T



Source: Johnsen et al. (2004)

[15] 2001 is the base year in Normod T.

The producers are grouped according to generation technology. Each production technology is represented by cost parameters and a number of physical and technical constraints, which restrict the system operation. Hydropower has bounds concerning the upper limit on the reservoir capacity and a lower limit of hydropower generation due to snow melting in the spring and national regulation concerning minimum water flow. Wind energy has an exogenous production pattern, and higher average production in the winter than in the summer. The model also includes bounds concerning raw materials for bio fuel. If a constraint is binding, a shadow price associated with the constraint becomes positive. See Johnsen (1998) for detailed numerical information on these functions. The time variation is taken into account by including 3 seasons, being winter 1, summer and winter 2. The three seasons are split into four periods representing different load levels[16]. Normod-T also includes all transmission capacities between regions and a specified demand side for each region. Demand for electricity is presented in equation (3.21):

(3.21) $Z_{sijt} = \beta_{0sijt} + \beta_{1sijt} PC_{sijt} + \beta_{2jt} w_{jt}$

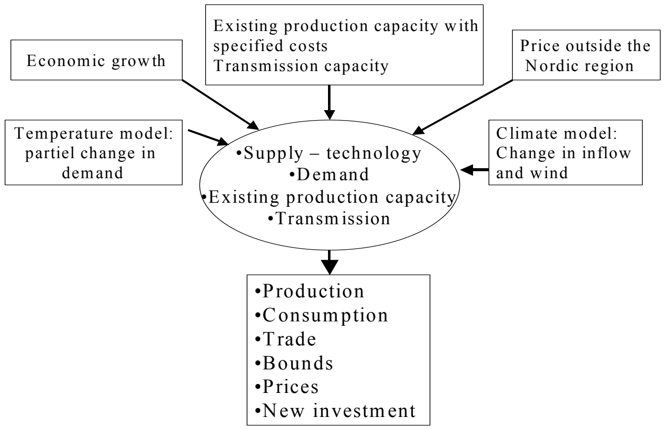
where Z_{sijt} is sector *j*'s power demand (MWh) for season *s*, load period *i* and country *t*. The end user price is *PC* (Nøre/kWh) and w indicates the income (consumers) or production (industries). Linear demand equations give price dependent elasticises. Higher price indicates higher elasticises. The end users electricity price is a sum of a wholesale price (*P*), electricity tax (*t*) and a transmission and distribution margin (*m*). Some sectors also charge a multiplicative value added tax, *v*. Equation (3.22) presents the price equation:

(3.22) $PC_{sijt} = \{P_{sijt} + t_{jt} + m_{sijt}\}(1 + v_{jt})$

When it comes to new investments in production plants, it's dependent on expected demand for electricity and the total cost that should be covered to justify new investments. Generation and transmission capacities are expanded if the investments improve the overall Nordic producer and consumer surplus in the year of consideration (Johnsen, 1998, p. 99-104).

The market solution of the model is found by maximization of the sum of electricity market consumer and producer surplus for the Nordic countries, minus the transmission costs between each pair of countries. The solution is in correspondence with the assumption of perfect competition. All electricity sellers and buyers face the same transportation corrected electricity price. The price equals the marginal cost of electricity, and the price differences across countries are a result of transmission costs and eventually shadow prices of transmission capacities (Johnsen, 1998). Figure 3.10 illustrates the main relationships in Normod-T.

Figure 3.10. The main relationships in Normod-T



Source: Johnsen (1998)

[16] See appendix 2 for details

4. Results and discussion

This chapter gives the discussion of the results from the climate model, the temperature model, RegClim's data series on wind speed and Normod-T. The focus will be on national changes, but we will devote some attention to regional changes as well, as they are important in the discussion of future patterns of trade and effective bounds on transmission.

4.1. Climate model

When estimating the climate model, some variables turn out not to be significant with a 5 % significance level. Evaporation is originally included, but due to high correlation with rain, it isn't significant in the estimation. This means that β^* indirectly explains the effect of evaporation as well. In a report by DNMI, it is stated that there are great challenges in developing models to intercept the effect of evaporation (Engeland et al., 2004). The effect from snowfall is not significant, and therefore excluded from the final model. The effect of rain in weeks 17, 18, 19 and 20 and the effect of snow melting dummies in weeks 20, 21 and 22 are not significant and are therefore excluded from the model. Our data series shows that rain and snow melting are negatively correlated, i.e., that snow melting is correlated to the negative change in the stock of snow. When there is heavy rain, there is more snow melting. The correlation between rain and snow melting is more than 0.45 in 50% of the time, and more than 0.7 in half of this observation period. Figure 4 shows the relationship between rain and snow melting in Norway in the period 1985–1995. There seems to be a lag on snow melting through runoff from soaked soil, and the model estimates showed that snow melting is significant with a one-week lag.

Equation (4.1) illustrates the final climate model.

$$(4.1)\quad \begin{aligned} I_t &= \beta_0 R_t + \beta_1 R_t D21_t + \beta_2 R_t D22_t + \beta_3 R_t D23_t \\ &+ \gamma_1 S_t D17_{t-1} \\ &+ \gamma_2 S_t D18_{t-1} + \gamma_3 S_t D19_{t-1} + \gamma_4 S_t D23_{t-1} + \varepsilon_t \end{aligned}$$

I_t = Inflow S_t = snow melting

R_t = rain D_i = dummy in week 17-23

Table 4.1 presents the results from the regression. The partial R^2 shows that rain and indirectly evaporation (β^*) will have the greatest influence on inflow. The snow dummies are negative, as a negative change in accumulated snow indicates melting. Increased amounts of melting will increase inflow. We cannot utilize the Durbin Watson indicator of autocorrelation, as some of the regressors are lagged (Durbin, 1970). However, the relationship between inflow and rain or inflow and snow melting, is characterized by causality rather than correlation.

Figure 4.1 shows the models estimated inflow in 1980-2000 and the actual inflow reported from NVE in the same period. As the data series on rain and snow from RegClim is rather stochastic, the estimated model will simulate inflow with a certain degree of uncertainty. However, figure 4.1 illustrates that the estimated inflow and the actual inflow in this period follows the same pattern

The analysis presents the seasonal changes, where season 1 describes week 1-17, season 2 describes week 18-35 and season 3 describes week 36-52.

Table 4.1 Estimation results from the regression model

	Coefficient	Std. Error	t-value	t-prob	Partial R^2
Rain					
β_0	0.89	0.02	31.7	0.000	0.535
β_1	2.01	0.25	7.95	0.000	0.067
β_2	1.93	0.204	9.44	0.000	0.093
β_3	1.43	0.167	8.61	0.000	0.078
Snow					
γ_1	–11.17	3.86	–2.89	0.004	0.009
γ_2	–18.65	4.09	–4.56	0.000	0.023
γ_3	–25.45	3.62	–7.02	0.000	0.053
γ_4	–437.91	79.47	–5.51	0.000	0.033

Figure 4.1. Observations and model fitted inflow (TWh) 1980-2000

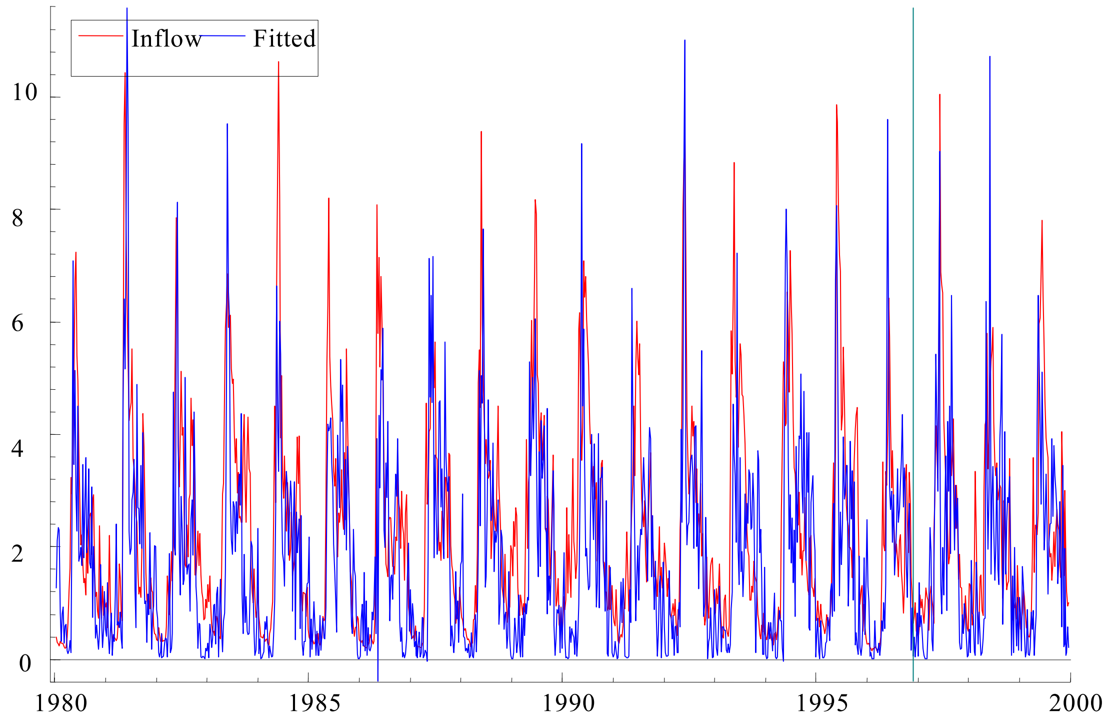
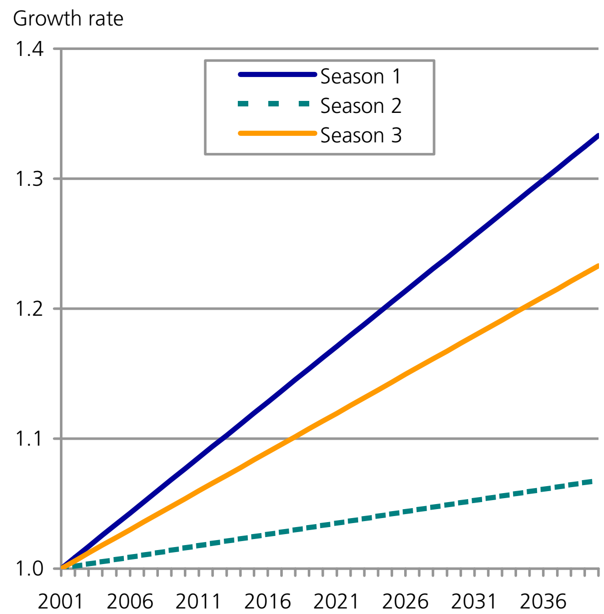


Figure 4.2. The seasonal growth rate of inflow in Norway from 2001-2040



4.1.1. Norway

For Norway, the climate model predicts that inflow will increase in all seasons from 2001 to 2040. Figure 4.2 shows that the growth rate will be largest in season 1. To calculate the aggregate increase in inflow, we use the same distribution of seasonal inflow as the market model, Normod-T. The aggregation is based on historical data on when inflow occurs in Norway. Season 1 will normally have 11%, season 2 will have 71 % and season 3 will have 18 % of the annual inflow. By using this distribution of inflow, the total effect of climate changes is less than figure 4.2 indicates. As the major share of annual inflow occurs during summer, the large percentage increases in the winter seasons in figure 4.2, do not contribute that much to the total increase in inflow. The total weighted increase in inflow from 2001- 2040, due to climate changes, is expected to be 10.3 %.

The increased inflow is explained directly by rain and snow melting, and indirectly by increased temperature and runoff. Figure 4.3 a) and b) shows the average linear development of rain and snow in Norway from 2001 till 2040. There will be a total increase of rain in Norway of 17 % in 2040, and figure 4.3 a) shows that the percentage increase is greatest in season 1. However, the volume effect is larger in season 3. Figure 4.3 b) shows that there will be less snow in the following 40 years. The accumulated snow storage (mm) will be reduced by 30 % in 2040 compared to 2001, and the volume effect is greatest in season 1. The reason for the summer season's large percentage reduction is the effect of earlier snow melting due to increased temperatures. The volume effect amounts to a reduction of 9 % in the summer (cf. the inflow share of rain amounts to almost 75 %, and snow to 25 %. See table 4.1).

Norway is divided into 8 regions in accordance with Normod-T. The regions respond to climate changes in different ways and with different magnitude. The regional distribution of inflow is based on the existing annual hydropower production capacity in each region. Table 4.2 summarizes the most important results of the regional analysis of inflow in Norway in the next 40 years.

Figure 4.3. The linear growth rate of rain and snow in Norway in 2000-2040

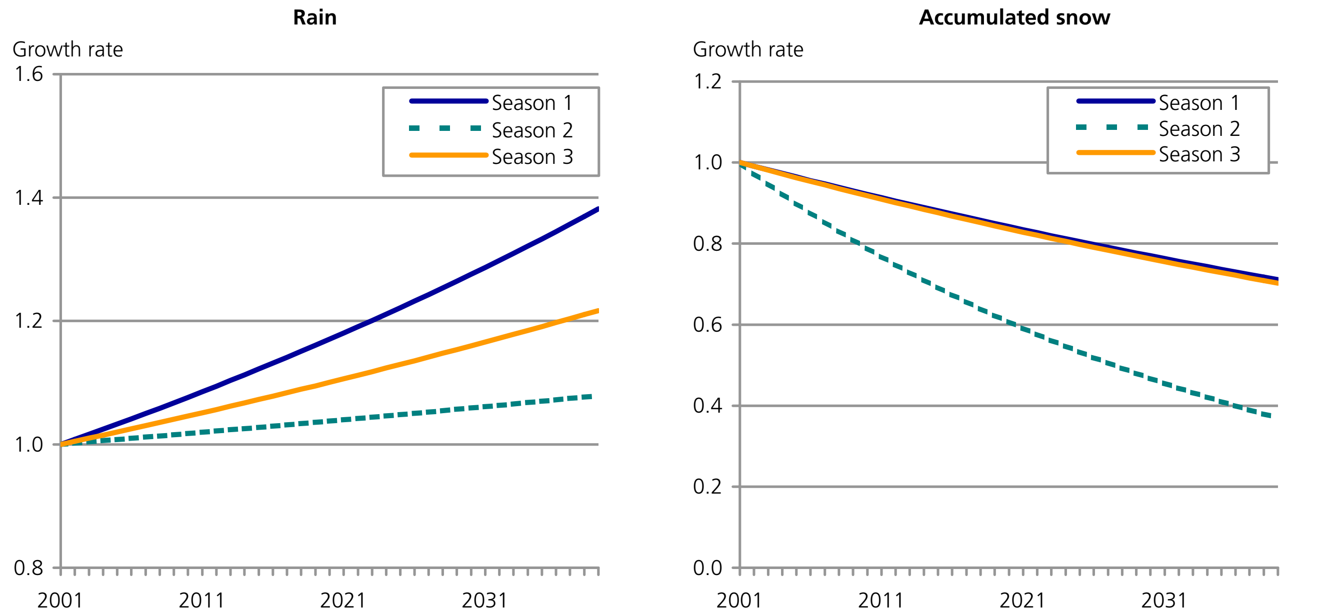


Table 4.2. Regional changes in inflow from 2001-2040

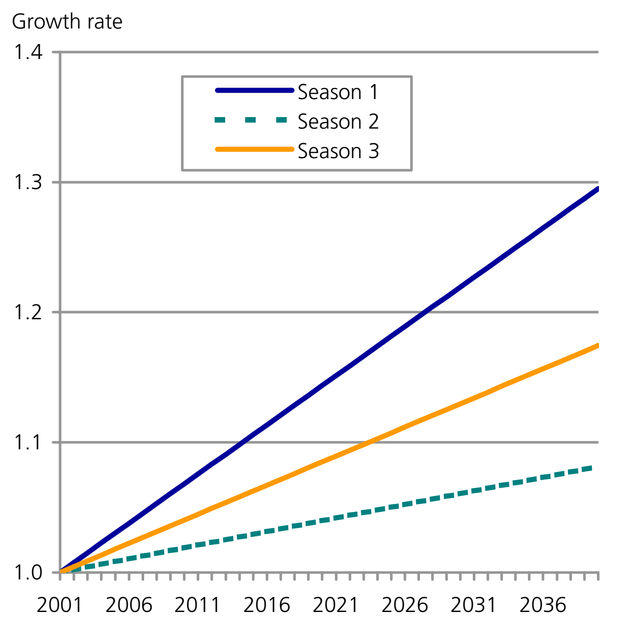
Inflow trends from 2001-2040 in Norway	Region
Increasing inflow > 15 %	7,8
Increasing inflow > 10 %	4,7,8
Increasing inflow > 5 %	1,2,3,4,6,7,8

Most regions will have an increase of more than 5 % in inflow in the following 40 years. Region 5 is the only exception, as the inflow is expected to increase by only 4.5 % from 2001-2040. In general, the western and northern regions in Norway will face the largest increase in inflow. Region 8 is expected to face an increase of 19.5 % from 2001-2040, due to climate change.

4.1.2. Sweden

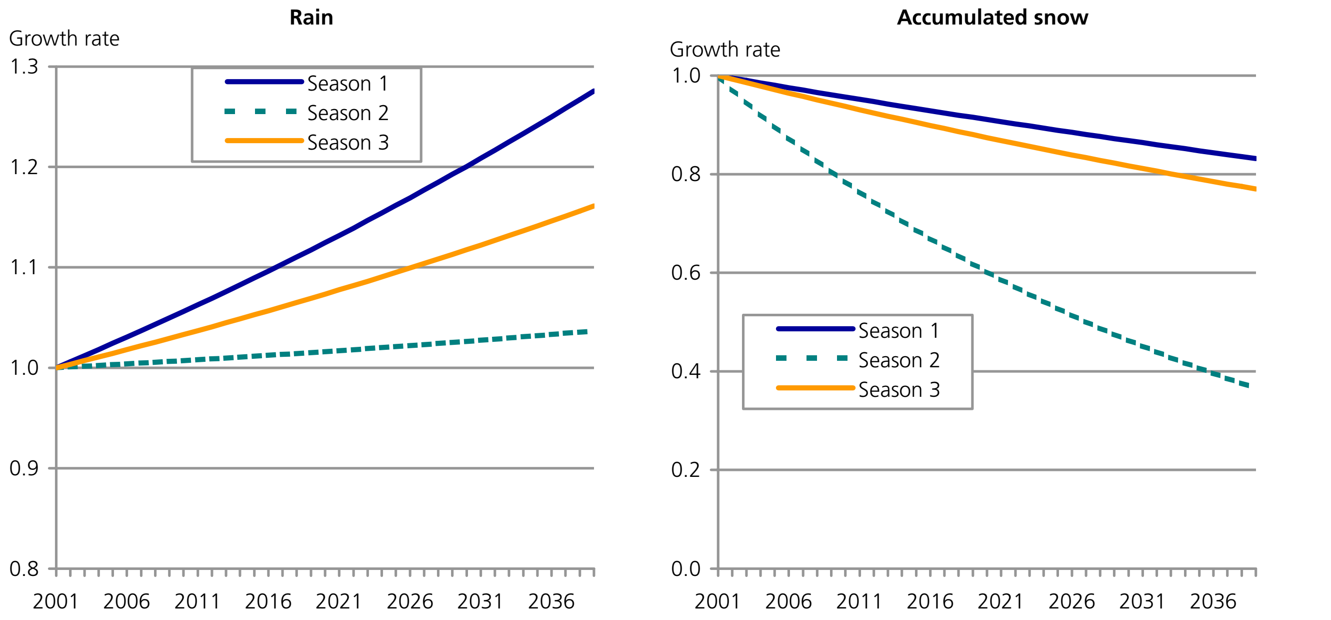
The climate model is estimated for Norway, but we assume that the same coefficients can be used when simulating inflow in the other Nordic countries. This assumption can be justified, as the climate in the Nordic countries doesn't differ too much from each other. However, the results might not be accurate but the trend indicates the development. Figure 4.4 shows that the growth rate of inflow from 2001-2040 is greatest in the two winter seasons. When we calculate the total increase in inflow from the climate model based on the historical distribution of inflow per season, the total increase is less than indicated in figure 4.3. We use the same shares of seasonal inflow as in the analysis of Norway (cf. Normod-T). The total increase in inflow in Sweden from 2001-2040, due to climate changes, is 6.1 %.

Figure 4.4. The seasonal growth rate of inflow in Sweden in 2000-2040



The increasing inflow is explained by the development of rain and snow in figure 4.5 a) and b). Figure 4.5 a) shows that there will be more rain in all seasons in the next 40 years. The annual temperature is expected to increase by 0.9 C° in Sweden, and this result in a reduction in snow storage. Figure 4.5 b) shows that there will be a reduction in accumulated snow of 20 % in the two winter seasons in 2040. The snow storage in the summer season is drastically reduced, due to increased temperature and earlier snow melting. However, the volume effect in the summer is only 10 % of the total reduction, whereas the reduction in season 1 explains 65 % of the total reduction.

Figure 4.5. The growth rate of rain and snow in Sweden in 2000-2040



In Normod-T, Sweden is divided into 3 regions. As for Norway, the Swedish regional distribution of inflow is based on existing hydropower capacity in each region. Region 3 will have the largest increase in inflow, with a change of + 6.2 % from 2001 – 2040. Region 2 will face an increase of 5.2 % and region 1 is expected to have 3.5 % more inflow in the next 40 years.

4.1.3. Finland

Finland will have increased inflow in all seasons from 2001-2040. Figure 4.6 shows that the growth rate of inflow will be greatest in season 1. The total increase in inflow from 2001 – 2040, based on the same historical distribution of inflow as for Norway and Sweden, is 14.6 %. This is the largest percentage increase in the Nordic region, but the change only amounts to 1.8 TWh in 2040.

We explain the increased inflow by a warmer and more humid climate. RegClim's data series on temperature reveals that the temperature in 2040 is 1.0-1.5 C° higher in each season than it was in 2001. Finland will face the largest temperature increase in the Nordic region. The temperature affects the development of rain and snow, which is presented in figure 4.7 a) and b). Figure 4.7 a) shows that the major percentage increase in rain will come in season 1, but the voluminous effect is greatest in season 3. Higher temperatures lead to earlier snow melting, and figure 4.7 b) shows a reduction of 80 % in snow storage level in the summer season. However, the voluminous reduction in the summer season amounts to 5 % of the total reduction in snow storage. The reduction in season 1 will explain 73 % of the total reduction, as some snow will come as rain due to the increased temperature.

Figure 4.6. The seasonal growth rate of inflow in Finland from 2001 - 2040

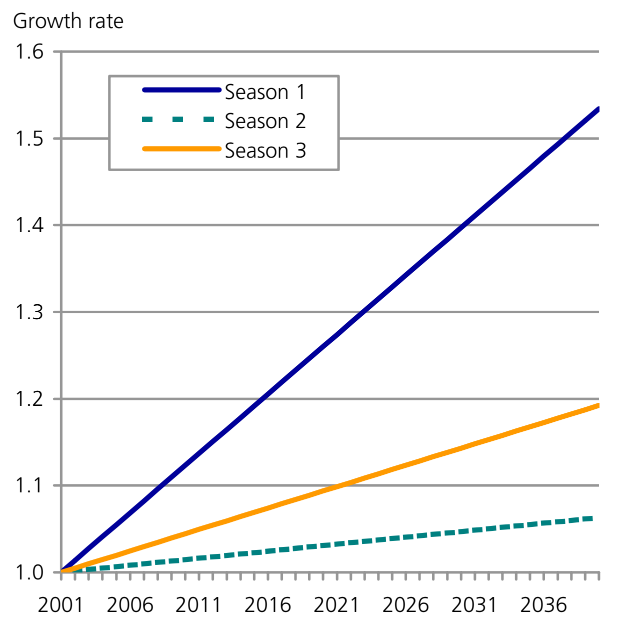
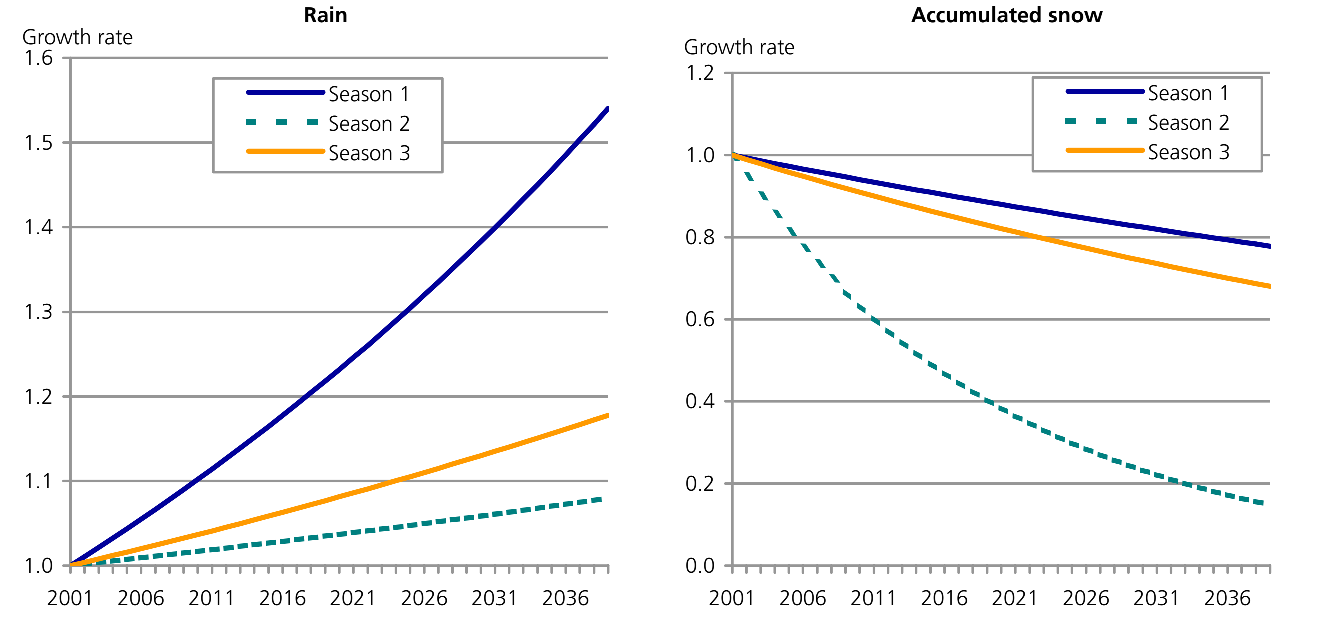


Figure 4.7. The growth rate of rain and snow in Finland in 2000-2040



4.2. Temperature model

In 2003, Norway, Sweden and Finland had the highest energy consumption per capita in the world. Danish consumers used 4 times less energy. The major reason for this variation is that Norway, Sweden and Finland have more energy intensive industry than Denmark (Pedersen et al., 2004). We simulate temperature dependent demand for electricity by using Johnson and Spjeldnæs model (2005). By keeping all variables except the temperature constant, we assume demand for electricity to be a function of temperature alone. Increasing temperature reduces demand for electricity, and vice versa.

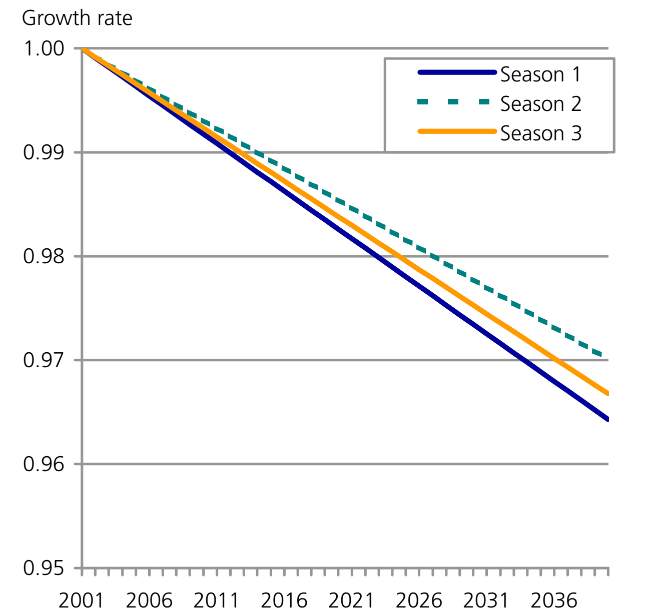
4.2.1. Norway

Figure 4.8 shows the development of electricity demand in Norway in the following 40 years. Increased temperature leads to a reduction in demand for electricity of approximately 3 %.

Figure 4.9 a) shows the average temperature per season in 2001 and 2040, and figure 4.9 b) shows the temperature change (C°) in this time period. The annual temperature in Norway increases by 0.9 C° from 2001- 2040.

The temperature changes are different in the 8 Norwegian regions. The major temperature increase will be in the northern part of the country. As the temperature model simulates demand as being dependent on temperature only, demand is reduced by most in region 8. Appendix 3 presents temperature changes (C°) per region.

Figure 4.8. The seasonal growth rate of demand in Norway from 2001 - 2040



4.2.2 Sweden

The development of electricity demand in Sweden is described in figure 4.10. Sweden will have the same pattern in demand as the other Nordic countries. The annual reduction in demand from 2001-2040 is 3 %.

Figure 4.9. Temperature in Norway. 2001-2040

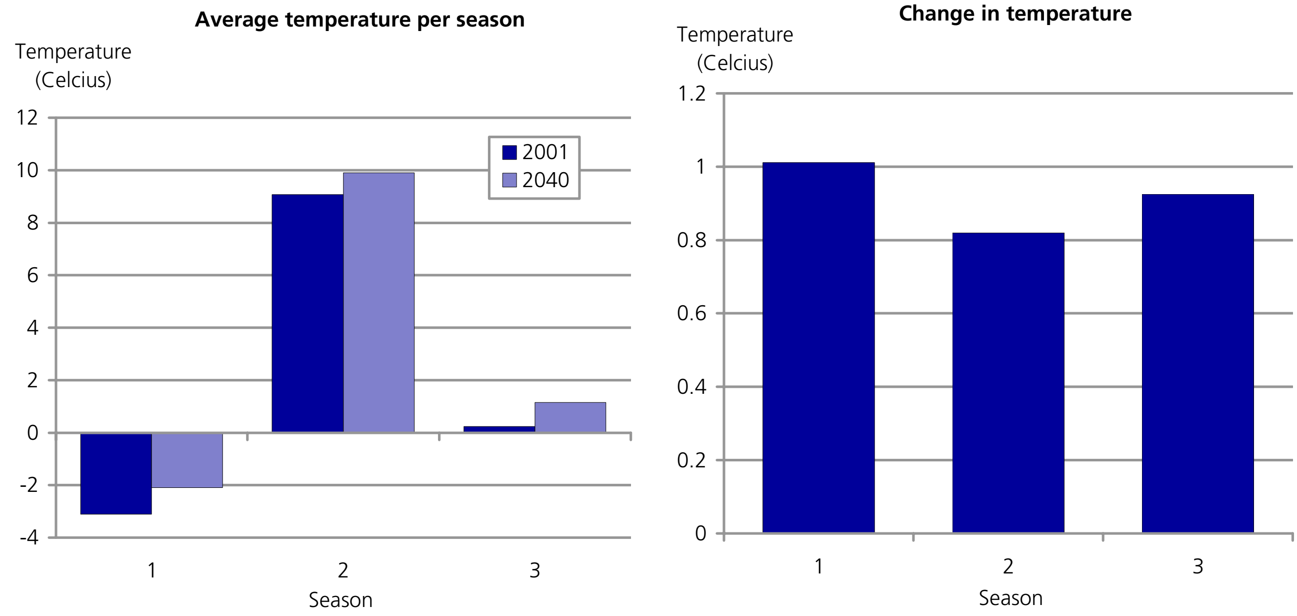
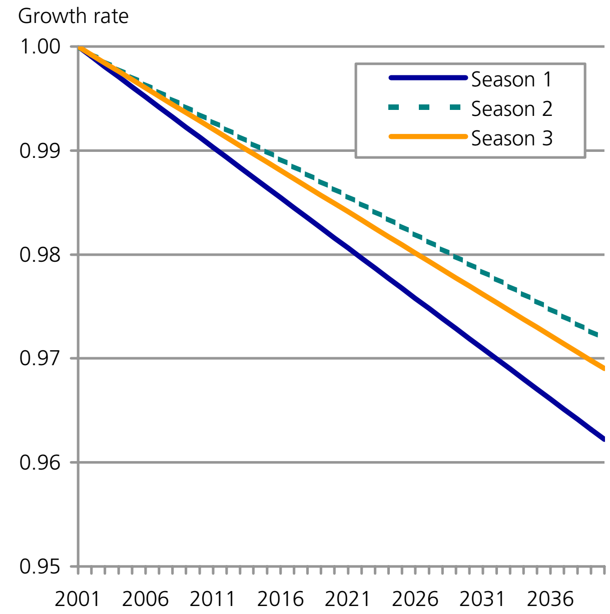


Figure 4.10. Demand for electricity Sweden – 2001-2040



Demand for electricity is a reflection of the changing temperature. Figure 4.11 a) and b) shows how the temperature is expected to behave from 2001-2040. The largest increase in temperature is expected to be in season 1, but on average, the annual temperature increases by 0.9 C° from 2001-2040. According to Normod-T, there are regional differences in Sweden. The Northern region (SW3) is expected to face a somewhat higher increase in temperature than region SW1 and SW2[17]. Appendix 3 shows the regional differences in temperature.

[17] See map in figure 3.9 for details on regional split up

Figure 4.11. Temperature in Sweden, 2001-2040

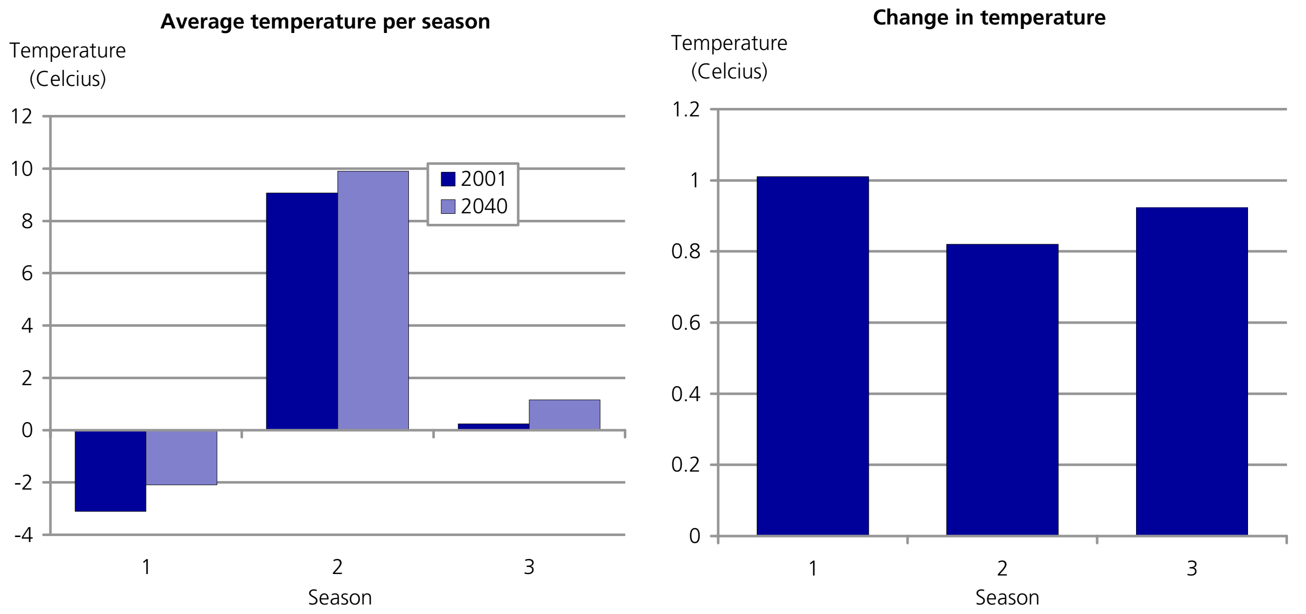
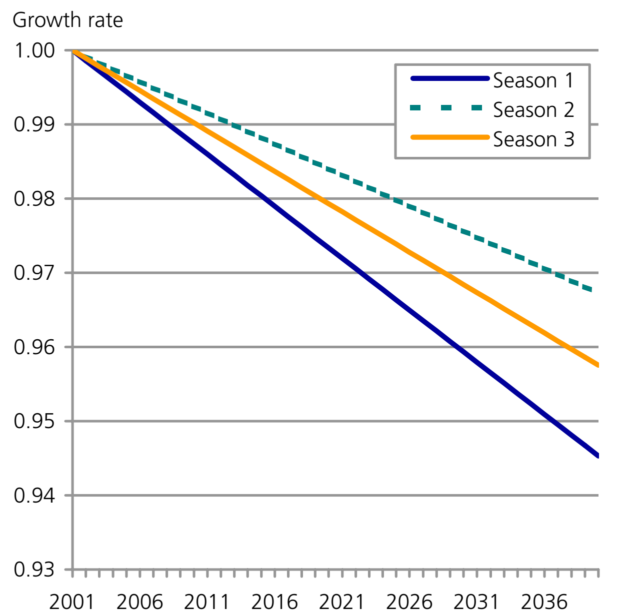


Figure 4.12. Demand for electricity Finland – 2001-2040



4.2.3 Finland

Finland will have a total reduction in demand of 4 % from 2001-2040. Figure 4.12 shows how demand for electricity will develop in the following 40 years.

The annual temperature in Finland is expected to increase by 1.2 C° in the next 40 years. Figure 4.13 a) and b) show that the major changes will be in season 1. As the temperature in season 3 increases by 1.2 C°, the average temperature in season 3 will be above zero in 2040.

4.2.4. Denmark

Denmark is expected to face a reduction in annual demand of 2.5 %. Figure 4.14 shows the growth rate of electricity demand in Denmark in the following 40 years.

Figure 4.14 shows that Denmark will have the same pattern in electricity demand as the other Nordic countries, but the reduction will be approximately 1% less due to smaller temperature changes. There will be an annual increase in temperature of approximately 0.75 C° in the following 40 years. Figure 4.15 a) and b) show the seasonal distribution of the temperature changes from 2001-2040.

There are not significant differences between the two Danish regions. Appendix 3 shows the regional changes in temperature per season.

Figure 4.13. Temperature in Finland, 2001-2040

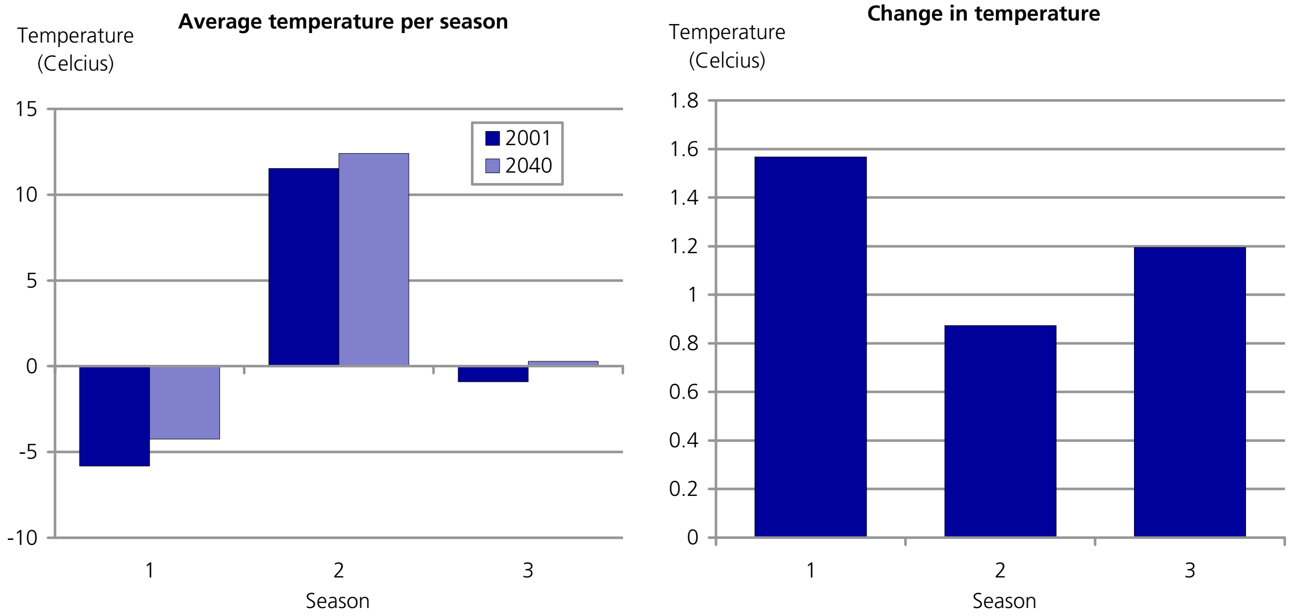
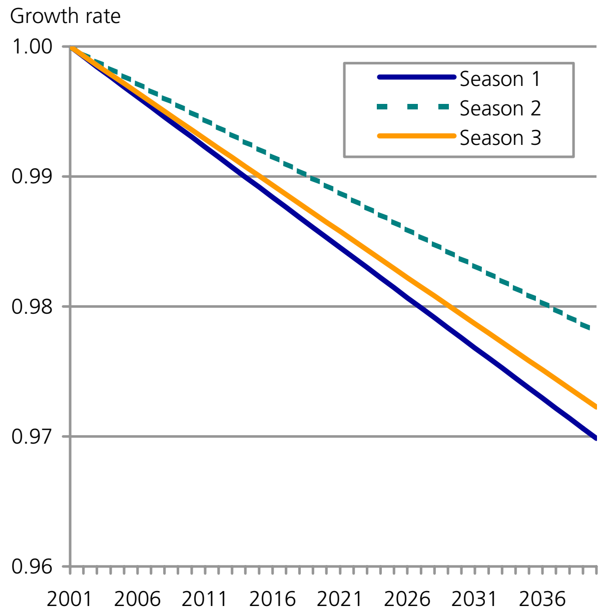


Figure 4.14. Demand for electricity in Denmark – 2001-2040



4.3. Wind

RegClim has provided observations on wind speed in the Nordic region in the two time periods. A modern wind power plant produces electricity when the wind speed is between 4 m/s and 25 m/s. About 35 % of the energy in the wind is transformed to electricity (Mandelid, 2003). Wind energy is included in Normod-T by separating the potential in different coarse groups according to costs for each region. These groups have an indirect representation of average wind speed and amplitude over the year. If there is an increasing amount of wind, the average wind speed will increase and add to the number of hours the windmill has to stop due to high wind speed. These two aspects have an incompatible effect on the production capacity from a windmill. Whether the production increases or decreases depends on the distribution function of the annual wind speed and amplitude. We will focus on the development of wind speed, as the data series from RegClim gives average wind speed, and thereby no information of the amplitude.

4.3.1. Norway

The coast of Norway is exposed to strong wind, and the development of this energy source is important when considering if and where to invest in wind power. Figure 4.16 a) and b) shows the average wind speed and the growth rate of wind speed in m/s in this period of time. There will be a little increase in the wind speed as the climate turns warmer and more humid in the period 2001-2040. The annual increase is of 1.2 % in 2040.

Some regions will experience a stronger growth in wind speed than others. The coastal regions 3, 4, 7 and 8 will have the greatest increase in wind speed from 2001-2040. The greatest increase will be in region 8 in season 3 (2.6 %) and in region 4 in season 1 (2.3 %).

Figure 4.15. Temperature in Denmark, 2001-2040

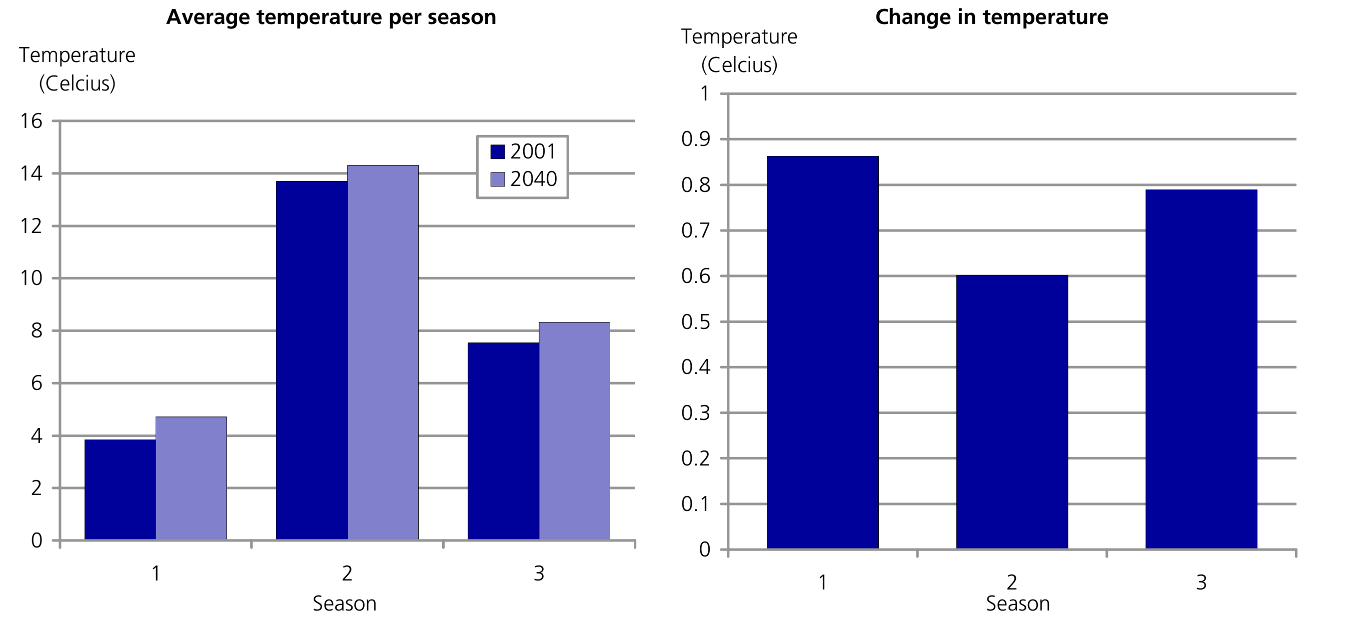
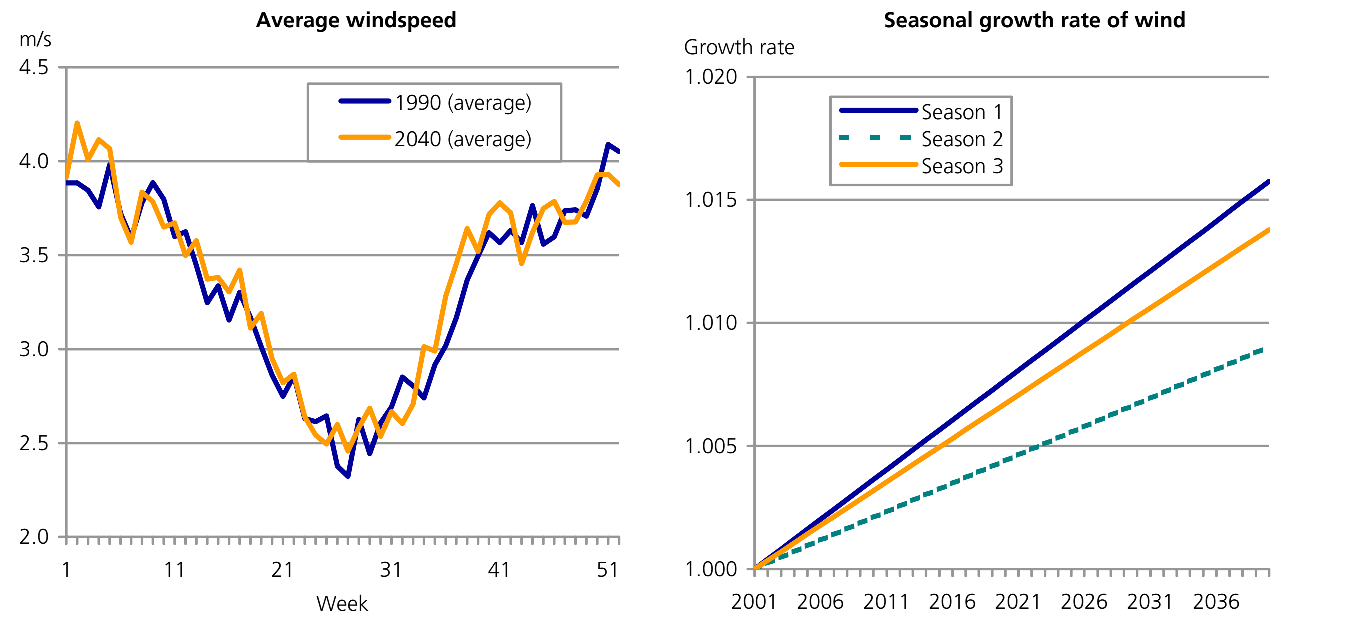


Figure 4.16. Wind in Norway from 2001-2040



4.3.2. Sweden

Sweden seems to follow the same pattern as Norway when it comes to changes in wind speed. Figure 4.17 a) and b) shows the average wind speed and the growth rate of wind speed in m/s in this period of time. Based on RegClim's data we expect more wind in all seasons until 2040. The annual increase in 2040 will be 1 % according to RegClim's data series.

The regional Sweden will respond to the climate changes with different magnitude. The wind speed is highest in region 1 with an average of 4.8 m/s in the winter seasons in 2001. Region 1 and 2 will have an increase in wind speed of approximately 1.8 % in the summer season.

4.3.3 Finland

The average wind speed in Finland is the lowest in the Nordic region. Figure 4.18 a) and b) show the development of the wind speed in Finland in 2001-2040. There will be less strong wind in season 2. The rest of the year will face more strong winds, and the annual increase in wind speed is 0.5 % in 2040.

Figure 4.17. Wind in Sweden from 2001-2040

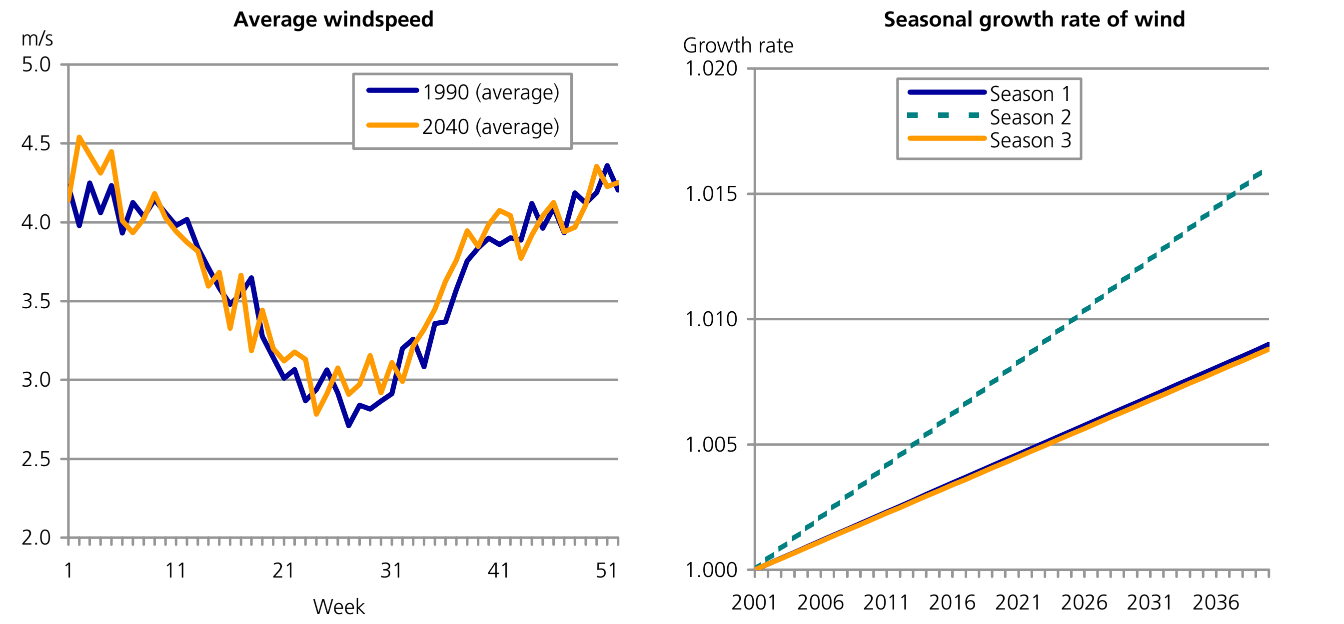
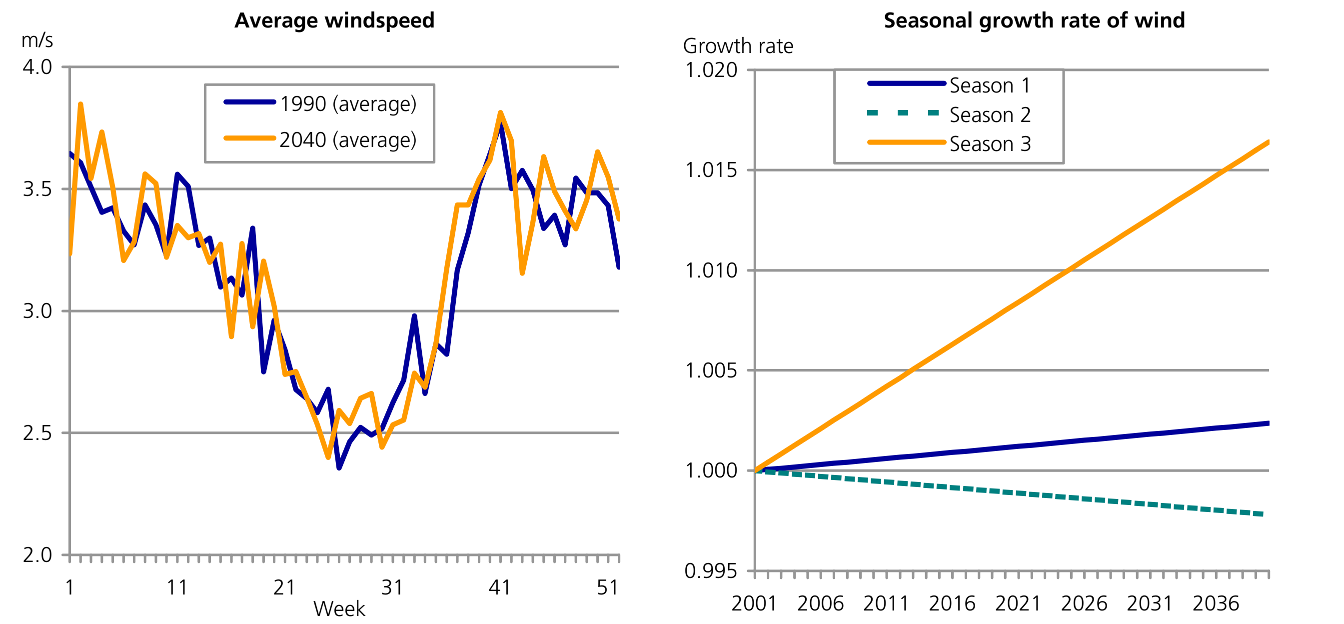


Figure 4.18. Wind in Finland from 2001-2040

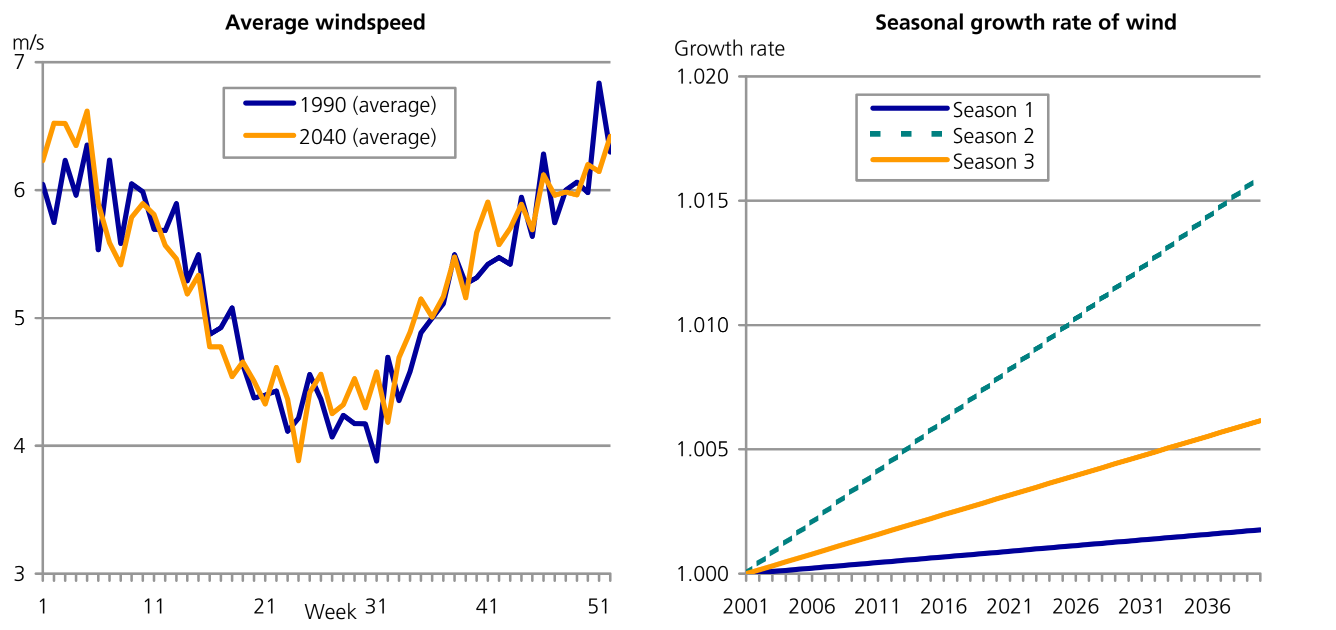


4.3.4. Denmark

Denmark has significantly stronger wind than the other Nordic countries. Both Sweden and Norway have a yearly average wind speed of approximately 3.5 m/s in 2001-2049, whereas Denmark has an average wind speed of 5.0 m/s per year in the same period. Figure 4.19 a) and b) show the annual wind speed and the growth rate of wind in Denmark in the following 40 years. The annual increase in 2040 is 0.8 %, and the wind speed will increase most in the summer season, and least in season 1.

According to Normod-T, Denmark is divided into two regions. The major increase in wind speed will be in the summer in region 1. In Denmark about 20 % of the electricity is produced by wind power mills (Pedersen et al., 2004).

Figure 4.19. Wind in Denmark from 2001-2040



4.4. Normod-T

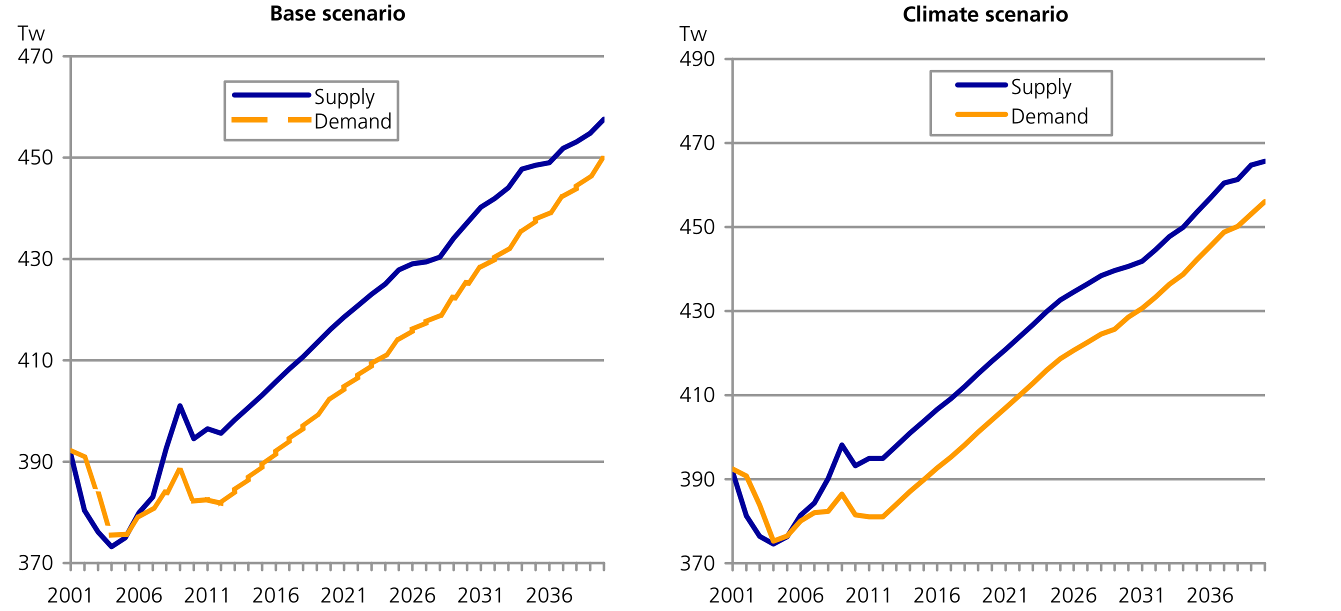
With Normod-T, we produced one base scenario for the development of the Nordic electricity market where the simulated effects of climate change were excluded, and one scenario where the changes were included. We will evaluate the effects of climate changes by comparing these two scenarios. We focus on the national effects of climate changes on production, consumption, trade and shadow prices on transmission. The most important regional differences will be discussed as well. In the base scenario, we assume the annual growth in income of the household and service sector to be 1.8 %. In terms of energy intensive industries, there is an annual reduction in production of 0.5 %. As for the rest of the industry sector, the analysis is based on a 1 % annual growth rate. The price of electricity outside the Nordic area is based on the historical price conditions in Germany in 2001/2002. This is updated during the time period. The exception is Russia, where the prices are low and generally lower than in the Nordic region. Finland is importing from Russia, and in Normod-T, the price is significantly low for Finland to import the maximum amount in the entire period. This price condition in Normod-T will eventually be updated. The CO_2 quota price is set to 125 NOK per ton in both scenarios, as we assume that the Nordic emissions are too modest to influence the international quota price (Aune et al., 2005).

4.4.1 The Nordic region

The base scenario has real numbers for the starting year 2001. There is an increasing trend in supply and demand for electricity from 2001-2040. Denmark is an exception, as the electricity supply will be 25 % lower in 2040 relative to 2001 due to less profitability of coal production. Finland, together with Sweden, is the world's largest user of bio fuels (Sweden SE, 2005). There will be least investments in electricity production in Denmark and Finland.

The electricity trade between the Nordic countries will be somewhat different in 2001 and 2040, but the major pattern will be the same. The west and north of Norway together with the north of Sweden are the most hydropower concentrated parts of the Nordic region. There are major exports from these regions to Denmark and Finland. The south of Norway and Sweden will occasionally import electricity from Denmark, but the total national trade balance is positive. Denmark is importing from Sweden and Norway, and exporting to the rest of Europe. The total Danish trade balance is negative. Finland is exporting some electricity to the northern regions in Norway and Sweden, but as the import from Russia is large, the total trade balance is negative. Figure 4.20 shows that the Nordic region will be an overall net exporter of electricity in both scenarios, and there are only minor differences in magnitude.

Figure 4.20 Supply and demand for electricity in the Nordic region

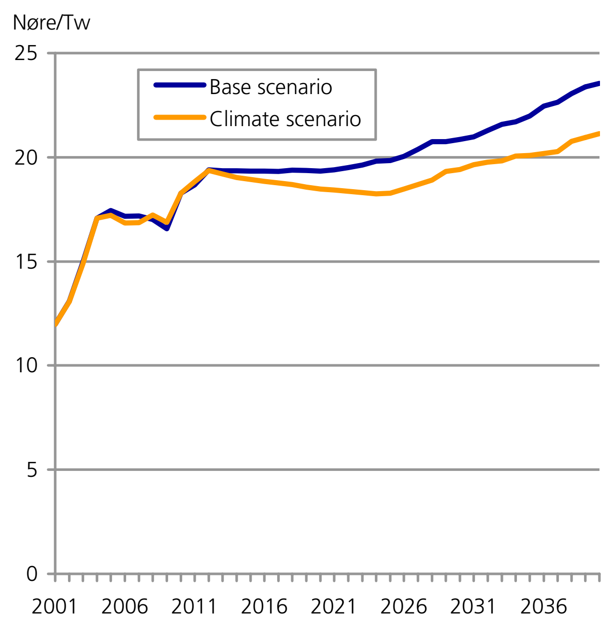


The analysis of the climate model implies more inflow and RegClim's data series on wind shows an increasing trend in major parts of the Nordic region. This will increase the supply of electricity in the Nordic region. Figure 4.20 shows that there will be approximately 8.1 TWh (1.8 %) more supply in the climate scenario than in the base scenario. This seems to be a small increase in production relative to the large increase in inflow. However, as hydropower only amounts to about 50 % of electricity production in the Nordic region, the increased inflow doesn't alone explain changes in the total Nordic electricity production. Increased hydropower production due to more inflow and enlarged import of hydropower will substitute marginal production in Sweden, Finland and Denmark. In addition, increased primary supply at low cost decreases prices in the climate scenario, which again implies lower investments in new production capacity. This does not outweigh the initial increase in production, but the increase is reduced. Normod-T doesn't consider the possible effect of different regional water coefficients (cf. Førsund, 1994). The model assumption is that all regions have a water coefficient equal to 1.

The temperature model showed that the temperature dependent demand for electricity is expected to decrease by roughly 3 % in most of the Nordic region. However, figure 4.20 shows that demand for electricity will increase by 6.3 TWh (1.4 %) in the climate change scenario. This is a result of more supply leading to reduced prices, and consequently an increase in demand that will more than offset the initial temperature effect. In addition, not all demand is temperature dependent[18]. The price effect from increased supply is captured by Førsund's theoretical model (1994) and the temperature effect is simulated in the temperature model. However, it is necessary to use a market model like Normod-T, to calculate the total effect on demand from both increased temperature and reduced prices.

Figure 4.21 shows the development of the price weighted with consumption. The electricity price is expected to increase less in the climate change scenario, as there is more supply of electricity. The figure shows that in 2040, the price is 2.4 Nøre / KWh lower in the climate change scenario than in the base scenario. The price differential occurs after 2013. This is mainly caused by enlarged hydro production in region 4 and 7 in Norway.

Figure 4.21 The average electricity prices weighted with consumption



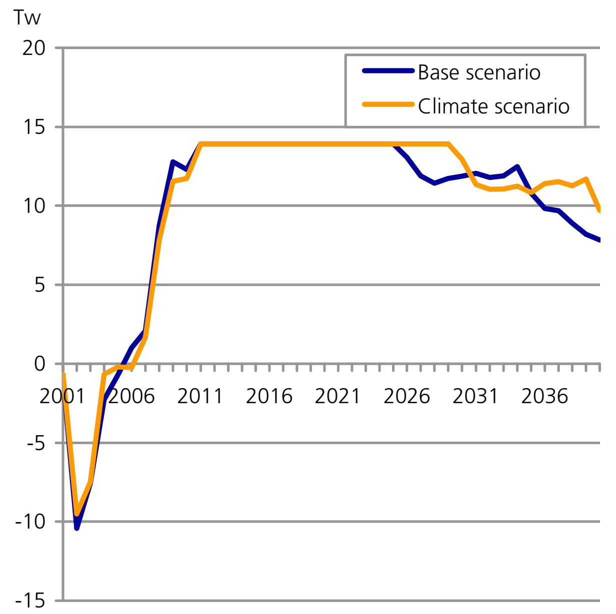
[18] The temperature influences demand for electricity from households and the service sector. The assumptions made about temperature dependence in Normod-T are documented in appendix 4.

The trade between the Nordic region and the rest of northern Europe is mainly based on exchange between a hydropower dominated area and a thermal dominated area. As prices in the peak periods increases, the net export in peak periods also increases (cf. Førsund, 1994). Rising prices increases the value of water and reduces Nordic demand, which is dominated by peak and high-level demand. The peak prices in the Nordic region are higher in the climate scenario relative to the base scenario. The abundant electricity supply in the Nordic region will then be exported to the rest of Europe, as the increased primary supply is cheaper to develop than the backstop technology of gas power.

There is export from Sweden's region 1, Denmark's region 2 and from Finland to Europe. There will be an exogenous investment in a transmission line from Norway's region 3 to Europe from 2008 (in both scenarios). This investment is assumed to be profitable based on expected prices and demand for electricity. The Nordic export is expected to increase by 2 TWh or 22 % in 2040 due to climate changes. Increasing inflow and hydropower production capacity place a downward pressure on prices reducing the profitability of alternative production technologies. The total effect on trade is then ambiguous and has to be calculated in a complete market model, as is Normod-T. Figure 4.22 shows that the net export trend will be the same in the two scenarios, but as the supply is relatively larger in the climate change scenario, the bound on transmission will be effective in larger parts of the time period. According to Førsund (1994), the shadow price on transmission, τ , will add to the electricity price. Normod-T assumes the electricity price in Europe to be constant, but the added shadow price is endogenous.

There are two possible important consequences of climate change for the network and trade possibilities. Firstly, the transmission bounds may turn effective earlier/more often than in a scenario without climate changes as the supply increases due to climate changes. Second, the pressure on the effective bounds will be greater and the shadow prices increase relatively more. There can be differences between the seasons, and even between the load levels of demand. This will be illustrated for each country in the following chapters. The regional split up is illustrated in figure 3.9 in chapter 3. The cost of the effective bound will be the shadow price multiplied with the amount of electricity transferred. Whether or not the investment in transmission capacity is profitable, is not within the scope of this thesis.

Figure 4.22. Trade between the Nordic region and Europe

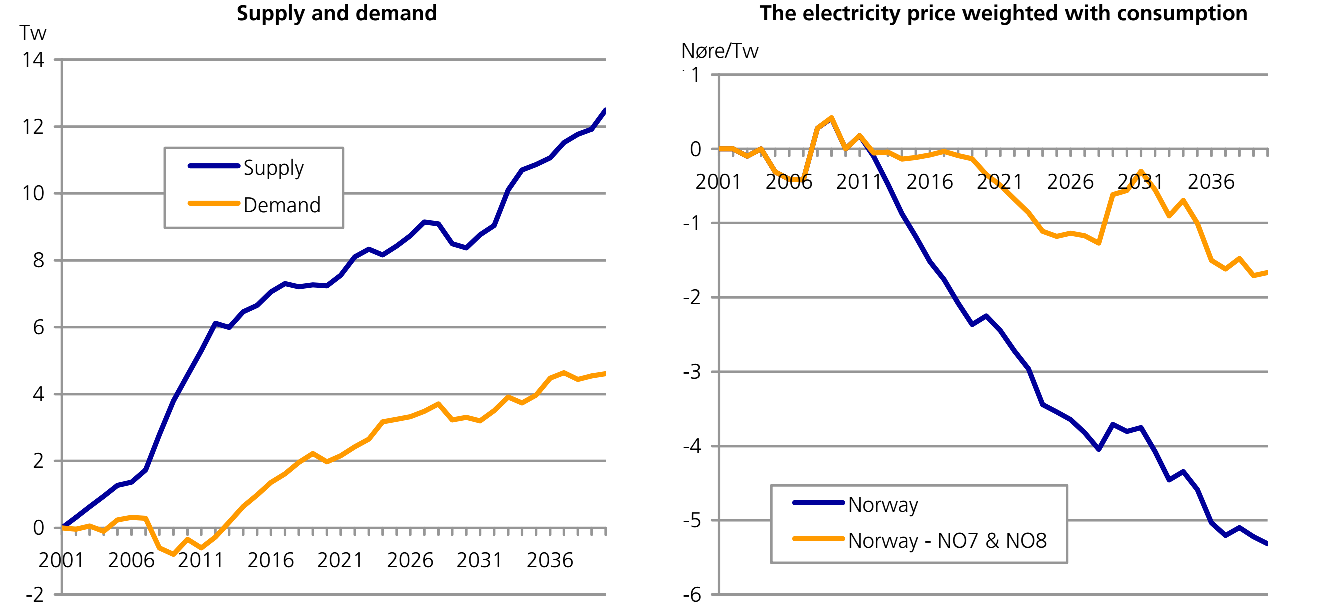


4.4.1. Norway

Norway is relying almost 100 % on hydropower in its electricity production. Our climate model shows that we can expect inflow to be 10.3 % larger in 2040 than in 2001, due to climate changes. Figure 4.23 a) shows that the supply of electricity will be about 8.4 % (12.5 TWh) larger in the year 2040 in the climate scenario relative to the base scenario. The increased electricity supply results in lower prices and thereby reduced investments in new capacity over time. This explains why the increase in production doesn't equal the increase in inflow. The major increase in production will be in region 4, 8 and 7, with an increase of 4 TWh, 3 TWh and 1.6 TWh respectively. The other regions will have an increase of 0.5-1.0 TWh in 2040. Region 7 supplies region 4, 6 and 8, whereas region 4 supplies the southeastern parts of Norway. Demand for electricity will increase despite the temperature increase following climate changes. An increase in electricity demand of 4.6 TWh or 3.2 % is explained by the reduced prices, illustrated in 4.23 b), induced by the increased water inflow, wind and other supply sources. Figure 4.23 b) shows that it is the reduced price in region 7 and 8, due to increasing transmission constraints, that contribute the most to the reduced Norwegian electricity price in 2040. The price effect on demand will more than offset the temperature effect discussed in chapter 4.2.1. In addition, not all demand is temperature dependent[19]. Region 7 and 8 will have the lowest price, as this is where the majority of inflow occurs and the transmission out of these regions is restricted by transmission bounds in large parts of the time period. This will be illustrated in figure 4.24.

[19] See appendix 4 for details

Figure 4.23. The effect of climate changes on annual supply, demand and the price of electricity



Region 7 will, in our calculations, have the greatest increase in demand in 2040 because of an increase in the metal industry from 2015. In Norway, a large part of the energy intensive industry entered into long-term energy contracts with the government as far back as in the 1950s. Even though the price is indexed and adjusted for the increase in wholesale price index, these contracts offer favourable prices for the industry even today. However, the majority of these contracts expire in the period 2005-2010. The result will be that the industry will face market prices, and probably reduce their energy demand as a consequence of the price increase (Von der Fehr, 1999). In our base scenario, these sectors have the same structure after 2010, which indicates that the expected reduction in demand from the industry is not accounted for in this analysis. However, as we assume an annual drop in production of 0.5 % in the energy intensive industry in Normod -T, we do partly intercept this effect.

As the major increase in inflow will be in the western part of the country, we can expect effective bounds on the transmission of electricity between some regions (this might be strengthened if we relax the manufacuring industry assumptions just mentioned). If an abundant region doesn't have large enough transmission possibilities out of the region, the price will be lower within the region than in the rest of the country (cf. Førsund, 1994). Normod-T reveals effective bounds on three transmission lines within Norway. Figure 4.24 a), b) and c) illustrates the development in season 1 in Norway.

Figure 4.24 a) shows that the bound on transmission between region 4 and 5 will turn effective in the peak load of season 1 in the latter years of the climate scenario. The peak load is dependent on effect, and in this case, the effective bound from region 5 to 4 might be explained by more effect and peak load production in region 5. The increased pressure on the constraint, will lead to higher shadow prices on transmission in the climate scenario relative to the base scenario. The transmission of electricity between region 4 and 7 goes both ways, but mostly from region 7, especially after 2010. Figure 4.24 b) shows that as region 7 will have increased supply of electricity due to climate changes, the bound turns effective earlier and the shadow price will be increasingly higher. At the same time, the bound on transmission between region 7 and 6 turns effective. Region 7 will have abundant electricity resources, but as it is a congestion-restricted area, the shadow price on transmission increases dramatically. This eventually put a downward pressure on electricity prices within region 7. In the case of electricity transfer from region 7 to 4 and 6, figures 4.24 b) and c) show the development in the peak load of season 1, as this is when the major changes occur. The trend will be the same in season 2 and 3, and the bound is effective in all load levels, but the shadow prices will only be 40 % of the price level in season 1. As the shadow price on transmission from region 7 is increasing dramatically from 2011, it might indicate a profitable investment in the transmission grid between region 7 and its neighbouring regions with greatest demand.

Due to increased inflow, the Norwegian export is expected to be 7.9 TWh larger in 2040 in the climate scenario relative to the base scenario. In the base scenario the total export was calculated to be 5.7 TWh, whereas the level in the climate scenario was 13.6 TWh. The increased inflow will result in increased exports as long as domestic demand is almost unchanged and there is enough reservoir- and transmission capacity. International prices on electricity make investments in production capacity profitable.

Figure 4.24. Shadow prices on transmission between regions in Norway

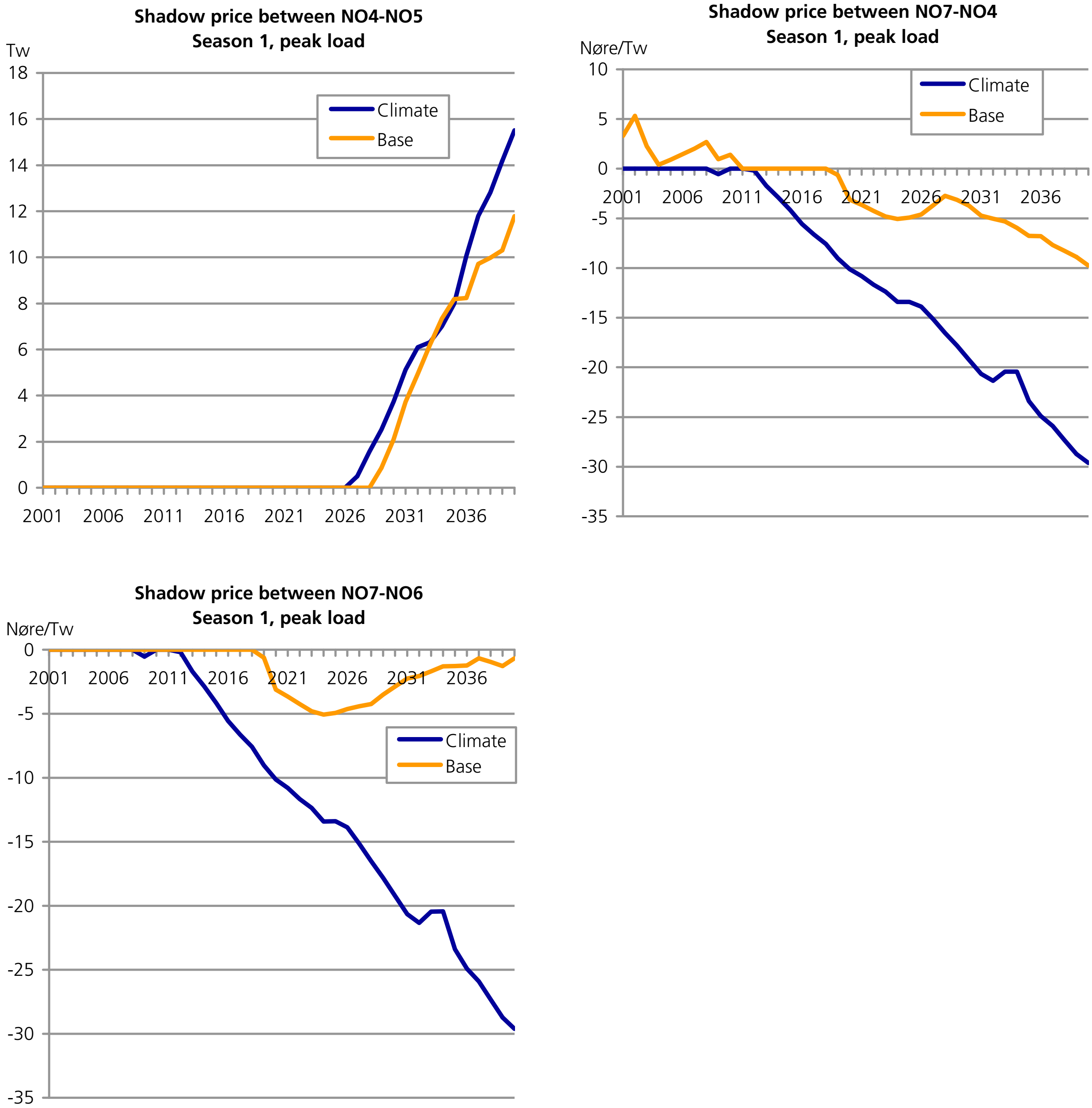
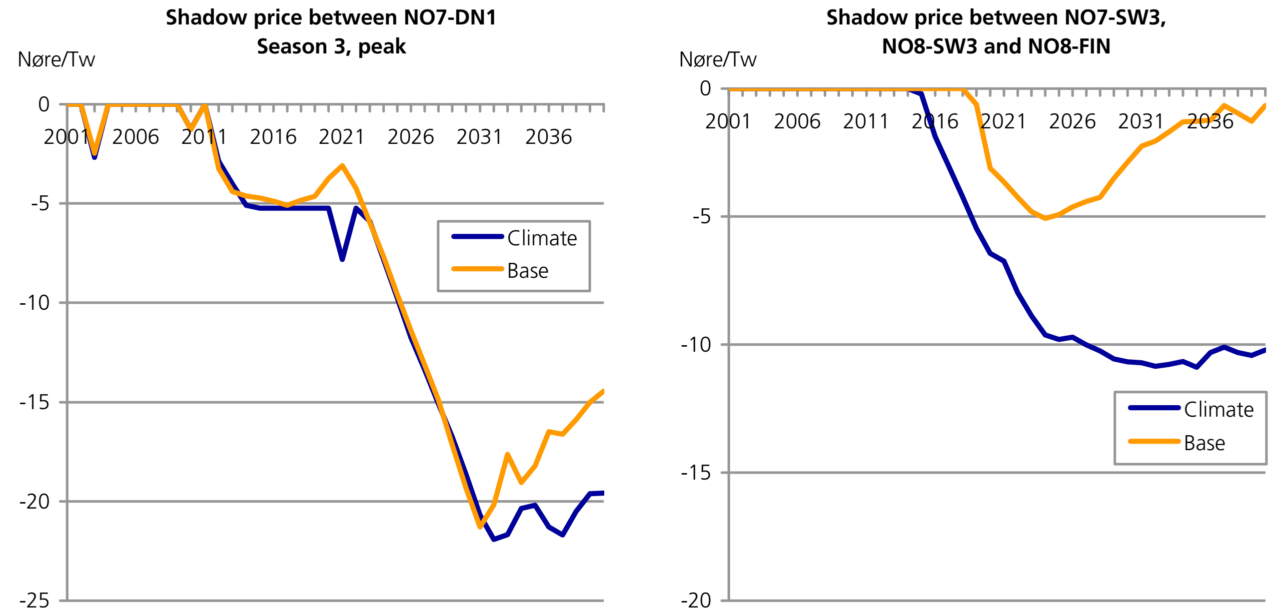
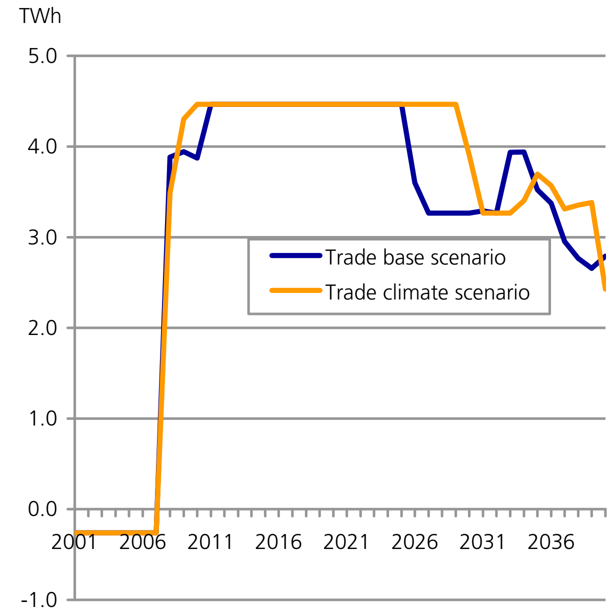


Figure 4.25. Shadow prices between Norway and other Nordic countries



There is a continuous increase of export to the other Nordic countries as the supply is greater in Norway. There will be increased exports from the south of Norway (NO3) to Denmark, as the Danish coal production is reduced further due to lower electricity prices in the climate scenario. It is more cost efficient for Denmark to import hydropower from Norway, as the coal production is the marginal production capacity in Denmark. Figure 4.25 a) shows the development in season 3. The trends will be the same in season 1 and 2, but as the pressure on the grid is less profound, the shadow prices will be lower in these seasons. There will be an effective constraint on the transmission in the peak load in all seasons. During summer, the medium load face an effective bound as well. In general, electricity flows from Norway to Denmark in all seasons when the demand is at the highest level, but the shadow prices are higher in the autumn/ winter. Climate change will lead to somewhat more pressure on the transmission grid, resulting in higher shadow prices from 2030. The Norwegian northern regions, 7 and 8, will increase exports to Sweden's region 3 and to Finland due to climate changes. Figure 4.25 b) shows that climate changes will increase the pressure on the transmission grid, which makes the bound turn effective a few years earlier than in the base scenario. The constraint will be effective in all three seasons, and there is no difference between load levels. The increased pressure results in rising shadow prices on transmission between the countries. By having effective bounds on the transmission to all the Nordic countries, Norway in general will be a congestion-restricted area with lower prices relative to the total Nordic region. This may be an argument for profitability in transboundary transmission line investments.

Figure 4.26. Trade from Norway to Europe



The transmission lines between Norway and Europe are located in region 3 and 8. In our analyses, the European prices are assumed to be constant, so we can't calculate the shadow prices on the connections to Europe. However, figure 4.26 shows that the constraint on transmission is effective seven years longer in the scenario including the climate changes. Even though Norway has abundant electricity supply, there is not enough capacity to export more than ca. 4.5 TWh per year directly to Europe via the existing transmission grid.

The shadow price on transmission, τ , will increase the price on the exchange of power. If there is a wet year in Norway, the effective bound on transmission will put a pressure on the capacity of the reservoirs and eventually the upper bound of the reservoirs, μ , might become effective. The price of storing water will be higher, and the consumer price must be reduced to stimulate increased demand of electricity. If there is flooding, the value of water and the willingness to pay is zero (cf. Førsund, 1994).

4.4.2. Sweden

Sweden had about 45 % hydropower and nuclear power, 3 % bio energy and 2 % oil based electricity production in 2001. The climate model indicates an increase in inflow of 6.1 % (4.2 TWh) and RegClim's data series show a 1 % increase in wind due to climate changes. Figure 4.27 a) shows that in 2007 – 2030 the supply of electricity will be lower in the climate change scenario than in the base scenario. This is caused by a postponement of a gas power plant investment in region SW2. The gas power plant would have produced 6.5 TWh per year, but it is postponed to 2012, and 2033 is the first year it produces more than 5 TWh. The increase in supply of electricity in the climate scenario from 2030 is explained by the gas power production and increased production of hydropower, bio energy and wind energy due to climate changes. In 2040, the level of electricity supply is 0.5 TWh or 0.03 % less due to climate changes. The effect on total supply is then smaller than in Norway, not only because the supply is less hydro dominated but also because the increased hydropower substitute the gas power plants in Sweden.

According to the temperature model, demand for electricity is expected to decrease by 3 % due to increased temperature. This effect is offset by increased Nordic supply and reduced price of electricity, illustrated in figure 4.27 b). In addition, not all demand is temperature dependent[20]. The middle and northern region, SW2 and SW3, are hydropower abundant and will face lower prices than the south of Sweden (SW1) due to restrictions on transmission out of the regions. (This is illustrated in figure 4.28.) The total effect of climate changes on demand for electricity is an increase of 0.85 TWh or 0.5 % in 2040. However, during most of the time period, reduced supply and increased demand indicates a need for more import of electricity. In the climate scenario, it is more cost efficient to import hydropower-based electricity as the increased supply has reduced the price of electricity.

As climate change implies more inflow, there will be more supply in the hydropower concentrated regions. There is transmission from the north to the south of Sweden. Figure 4.28 a) shows that there will be an effective bound on transmission from region SW2 to region SW1 in the entire time period. The figure shows the development in the peak load in season 1 and 2. There will be an effective bound during summer as well, but the shadow price will be less than 1 % of the winter level due to less pressure on the grid. The climate changes increase the shadow price, as region SW2 can't transfer enough electricity to region SW1.

Figure 4.28 b) shows the development of transmission between SW3 and SW2. Climate changes will only incur an effective bound on transmission between region SW3 and region SW2 in the peak load of season 1 from 2025-2040. SW3 will have increased production of electricity due to more inflow and a small increase in bio energy. The price of electricity is high in the peak load, forcing production even though the transmission lines out of SW3 are full. The previous chapter showed increasing shadow price on the transmission between Sweden and the north of Norway in the same time period.

Sweden is importing electricity from its Nordic neighbours from 2001-2006, but as Sweden invests in two gas power plants around 2007, it starts exporting electricity to its Nordic neighbours. The export is lower in the climate change scenario relative to the base scenario in 2007- 2030, due to the postponement of another large gas power plant in SW2. Increased production of hydropower, bio energy and wind energy increases the export until 2030. In the base scenario, new gas production capacity is developed in region 1 in 2035. This will not occur in the climate scenario, which results in reduced exports relative to the base scenario. In 2040, we expect the net export to be 1.4 TWh lower in the climate scenario relative to the base scenario.

There will be some effective bounds on the transmission between Sweden and its neighbouring countries. Figure 4.29 a), b) and c) shows where these bounds will be and the effect on the shadow price. Figure 4.29 a) shows that when Sweden is importing from Denmark, the bound will be effective in the base load of season 1 and 2, regardless of climate changes. There is no addition to the shadow price. Figure 4.29 b) shows that this is the effect of increased supply in SW3 due to climate changes. As SW3 can't transfer sufficient electricity to Norway (or to SW2 in figure 4.28 b), there is an increasing shadow price on the transfer of electricity. As the increase is rapid and significant, it might be cost efficient to invest in the transmission capacity between these regions. There will also be an effective bound between SW2 and Denmark (DEN1) in the entire time period, and figure 4.29 c) shows that the climate change will only contribute to increased pressure on the grid the latter 10 years. However, the capacity will be insufficient

[20] See appendix 4 for details.

from 2010 regardless of climate changes. Whether or not it is profitable to invest in an extension of the capacity is not a matter to be discussed in this thesis. The bound will be effective in the peak load of both winter seasons as well, but the summer will have somewhat higher shadow prices on transmission.

The only Swedish transmission line to Europe goes from region SW1. Climate changes will increase Sweden's production of hydropower, wind power and bio energy. Together with increased gas power production, this results in the bound on transmission with Europe being effective until 2030. Figure 4.29 show that the bound will be effective for five more years due to climate change. The existing capacity doesn't allow for more than 9.5 TWh per year to be transmitted between Sweden and Europe. The effective bound on transmission, τ , will increase the price of exchanging power.

Figure 4.27. The effect of climate changes on annual supply, demand an the price of electricity

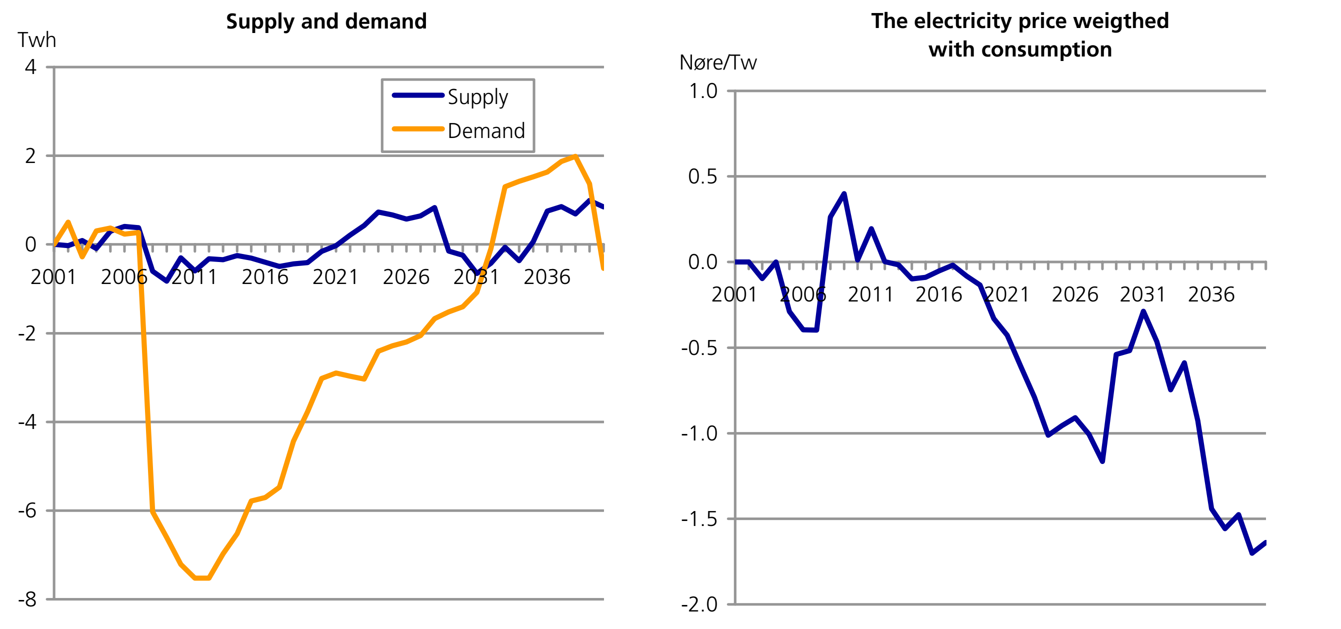


Figure 4.28. Shadow price on transmission between regions in Sweden

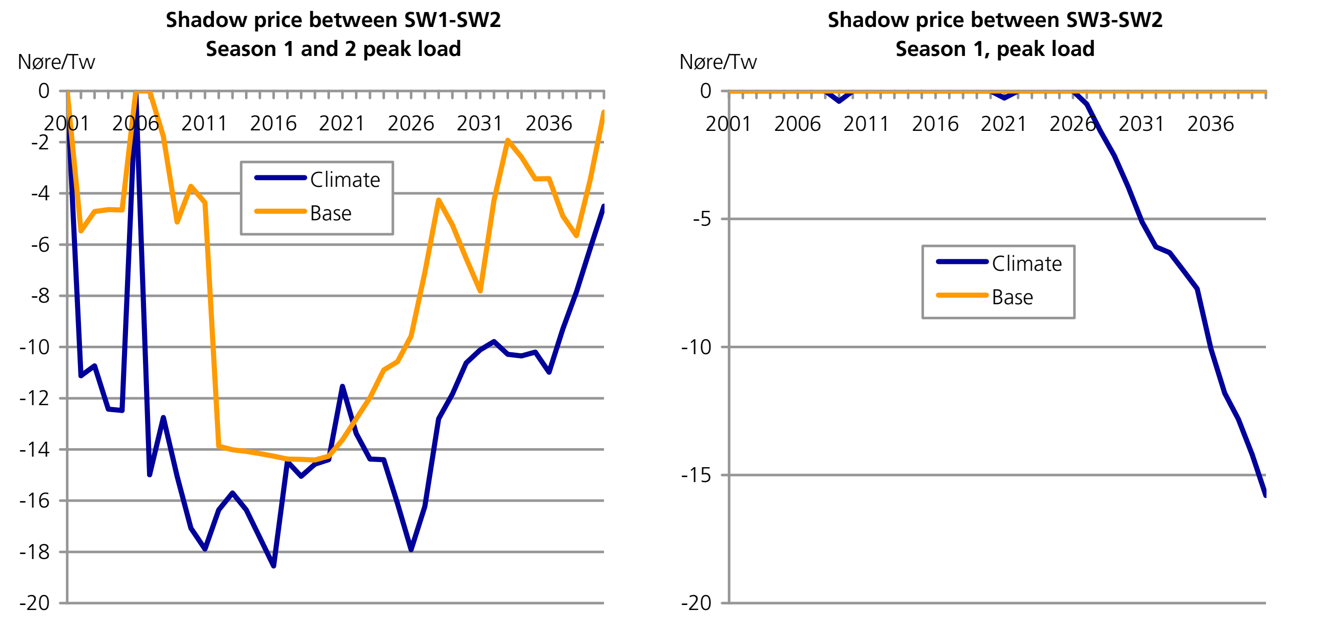


Figure 4.29. Shadow prices between Sweden and other Nordic countries

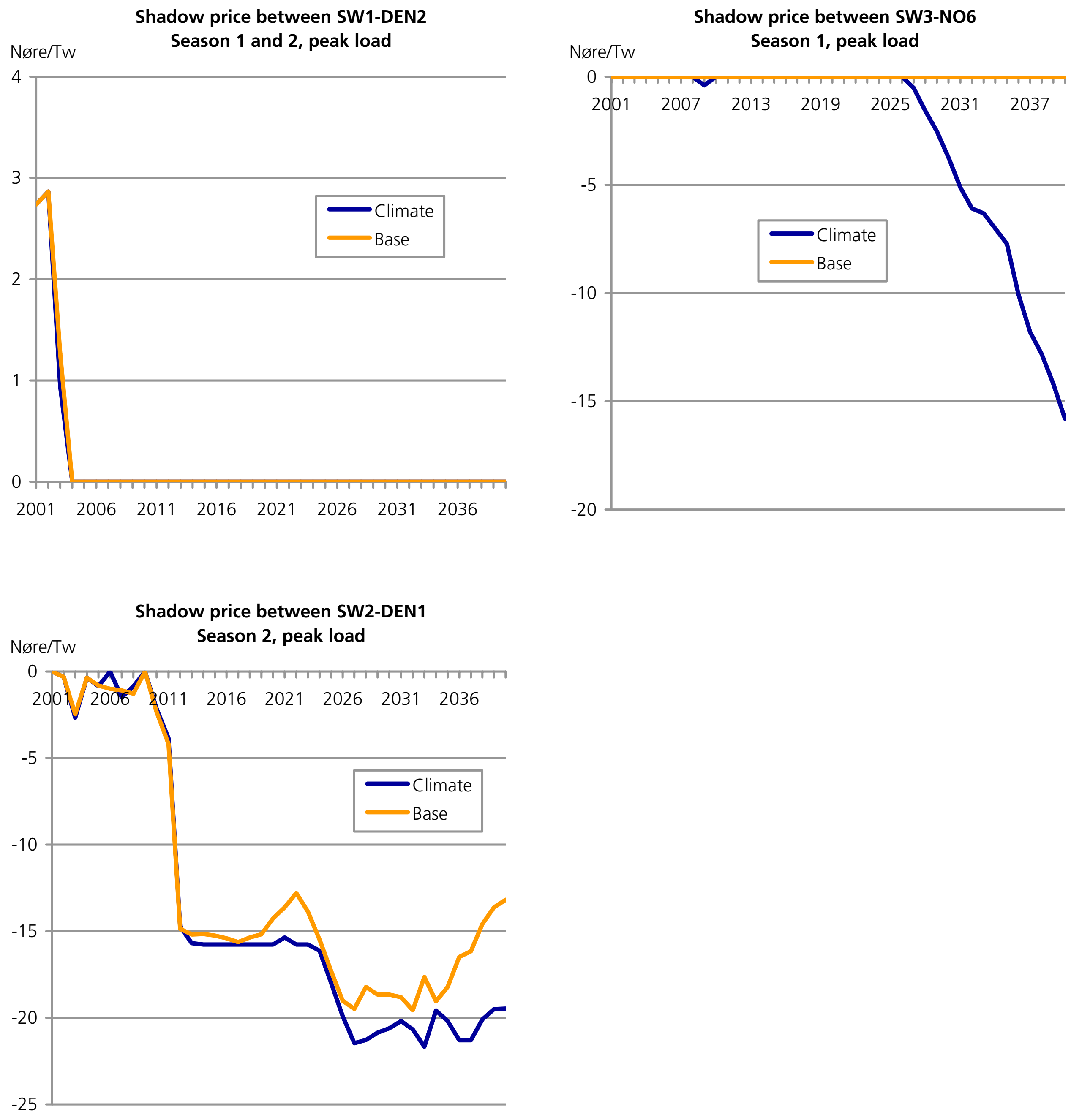
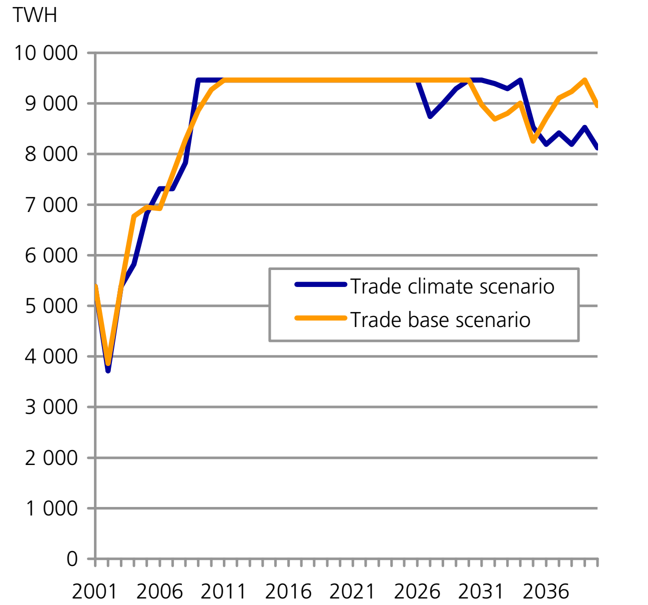


Figure 4.30. Trade from Sweden to Europe



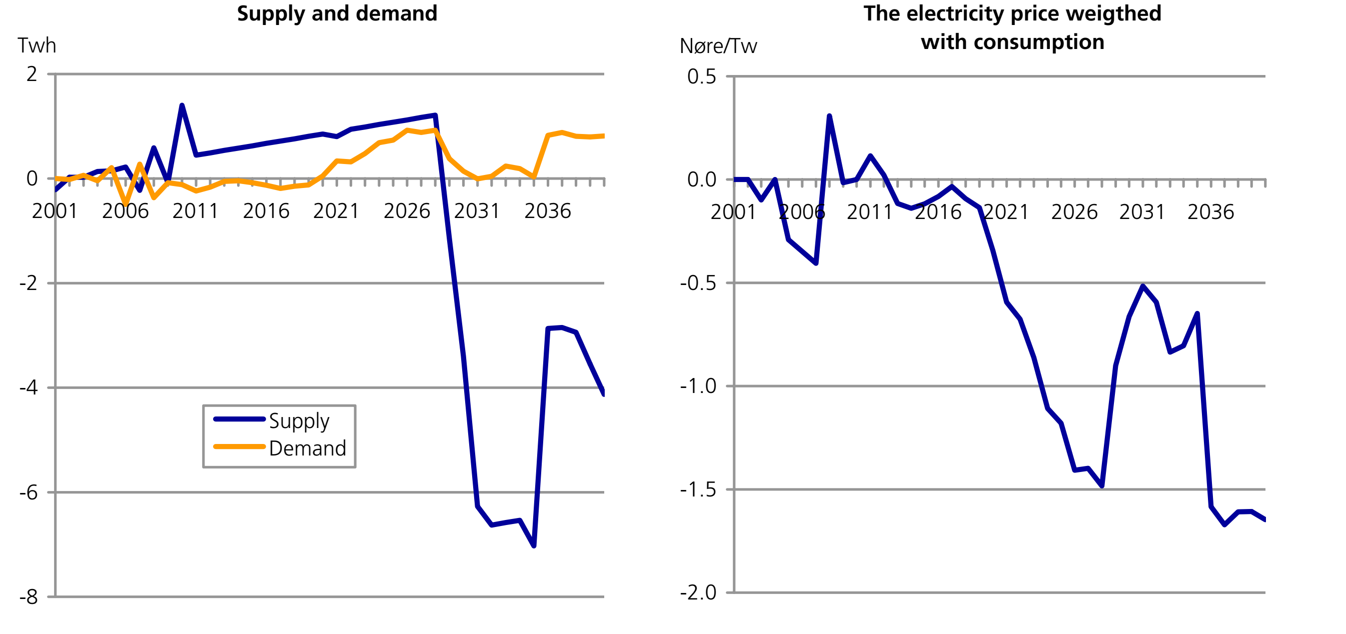
4.4.3. Finland

Finland had approximately 30 % coal and nuclear power, 15 % bio fuel and 15 % hydropower production in 2001. Even though the climate model simulates a 14.6 % (1.8 TWh) increase in inflow, this will not have a major influence on the domestic electricity production since hydropower production constitutes a minor share of the electricity production in Finland. Figure 4.31 a) shows that the supply of electricity will be a little higher in the climate scenario from 2001-2028, due to increased hydro power production of approximately 2 TWh. In 2028, the supply is reduced by almost 7 TWh. This is a result of a gas power plant being built in the base scenario in 2028, which will be postponed till 2036 in the climate change scenario, meaning that supply in the climate scenario will be lower than in the basis scenario. The gas power plant in the climate scenario will produce about 4 TWh less than the gas power plant in the base scenario. This development is caused by a minor increase in hydropower production in Finland and more imports of electricity from Norway and Sweden. It is more cost efficient to import electricity and postpone the investment in the gas power plant. In 2040, the supply of electricity is expected to be 4 TWh or 5 % less due to climate changes.

The temperature model showed that increased temperature will reduce demand for electricity, but this effect is more than offset by the increased supply and consequently reduced price. Figure 4.31 b) shows that the price will be 1.5 N øre/kWh lower in 2040 due to the climate changes. In addition, demand for electricity is not very temperature dependent[21] in Finland, and the total effect will be an increase of 0.9 % in 2040 due to climate changes.

Finland is in general an exporter in the Nordic region. However, there is a major change in the trade balance in 2028, due to the postponed investment in a gas power plant. Finland will import electricity from its Nordic neighbours from 2028. In 2040, the net import to Finland is 4.7 TWh larger in the climate scenario relative to the base scenario. Figure 4.32 a) shows that the climate changes will remove the otherwise effective bound between Finland and Sweden. This is a result of

Figure 4.31. The effect of climate changes on annual supply, demand and the price of electricity



21 See appendix 4 for details

a relative larger decrease in export than increase in imports between Finland and Sweden. Figure 4.32 b) shows that climate changes will induce an effective bound on transmission between Finland and mid-Sweden a few years earlier, and as the pressure on the transmission grid increase, the shadow price will be relatively higher in the base load of season 1. The increasing shadow price from 2030 may open for a profitable investment in the transmission grid between mid-Sweden and Finland.

Finland is only importing electricity from Russia. Figure 4.33 show that in both scenarios the import is about 11 TWh per year from 2003. This indicates that there is an effective bound on the transmission grid between Finland and Russia, and the shadow price on transmission is positive.

Figure 4.32. Shadow prices between Finland and other Nordic countries

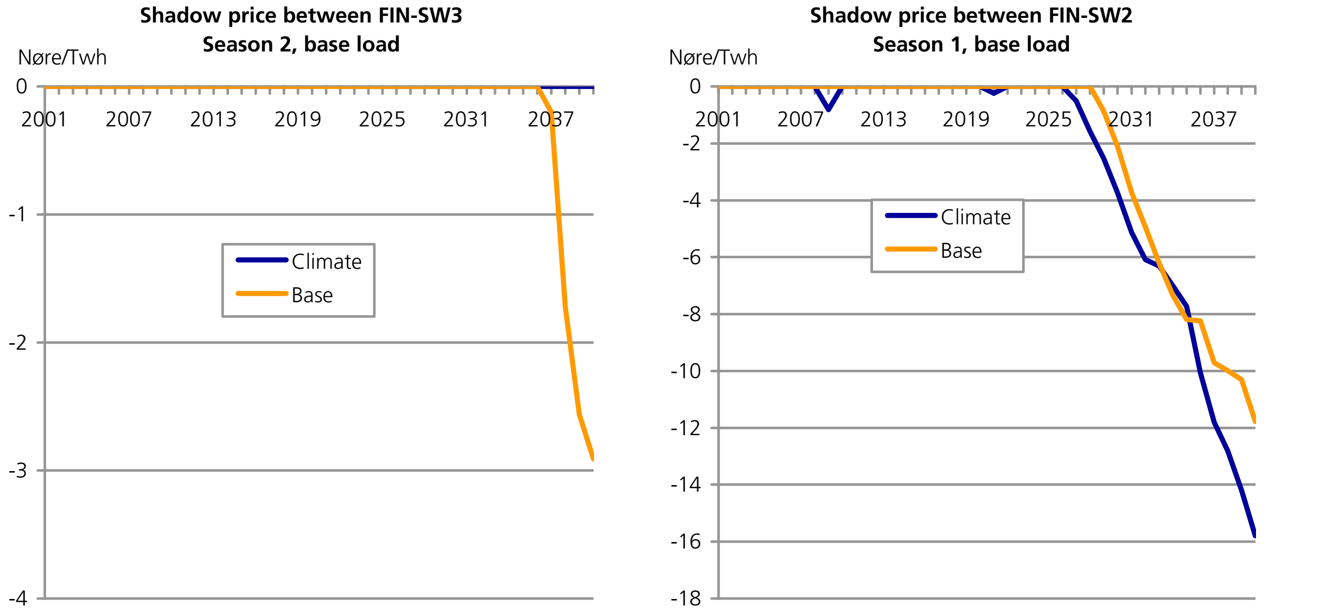
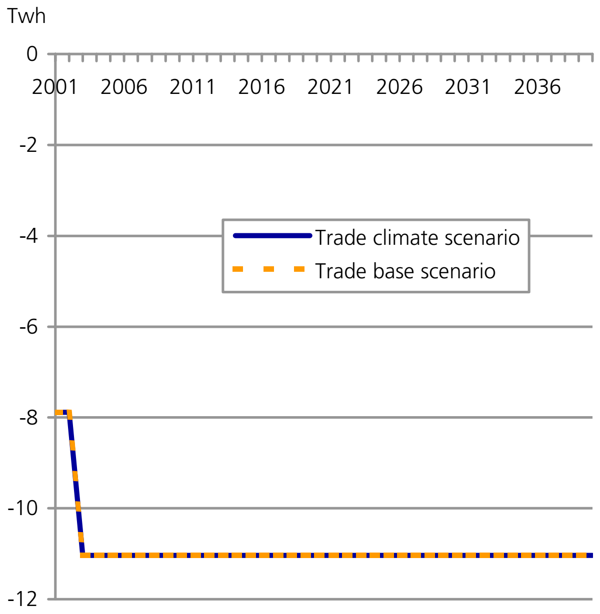


Figure 4.33. Trade from Finland to Europe

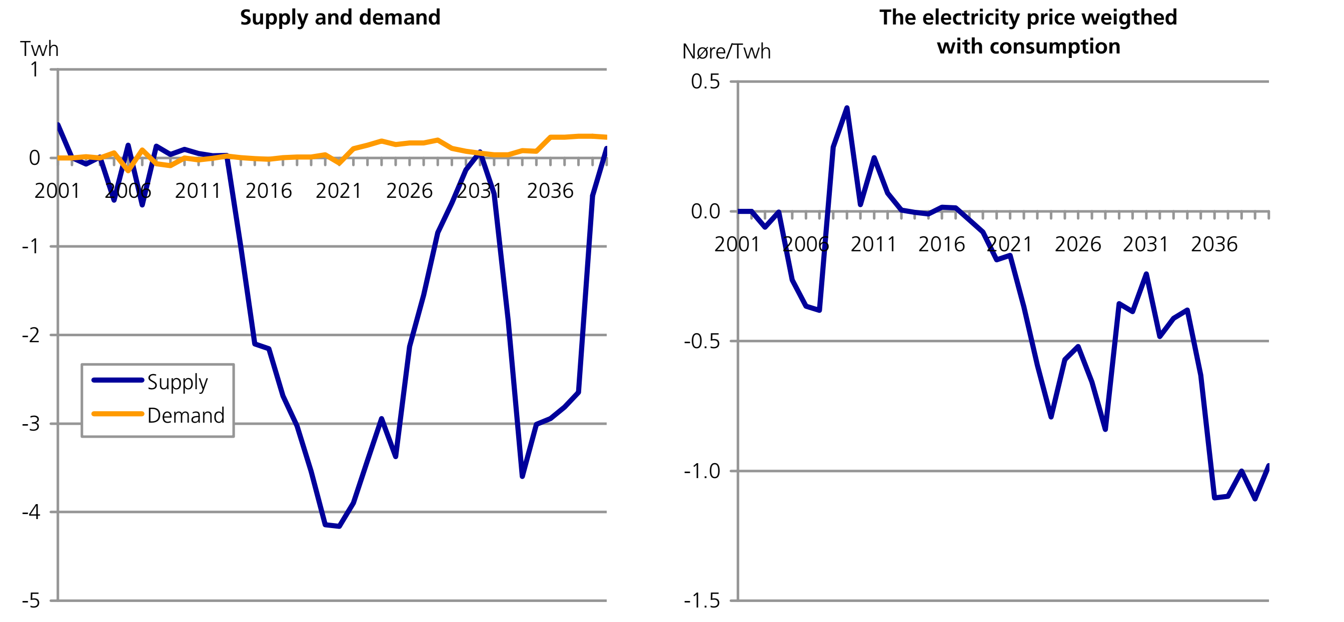


4.4.5. Denmark

Denmark had about 80 % coal power production, 10 % wind energy and 10 % gas power production in 2001. Figure 4.34 a) shows that Denmark will reduce domestic production from 2007 in the climate change scenario. RegClim's wind data shows an increase of 0.8 % in wind speed in 2040, and this result in a minor increase in TWh from wind power. The effect of climate changes is a reduction in the coal production in region DEN2 from 2010-2022. The increased inflow in the rest of the Nordic region will affect Denmark in two ways, even though it has almost no hydropower. First, the Nordic electricity market is integrated, and market signals in one country will affect the other markets through export and import. Secondly, as Denmark relies heavily on wind power, which is a stochastic electricity source, it is dependent on import of hydropower from its neighboring countries (Bye, 2002).

In 2031, the coal power production in the base scenario increases by 2.5 TWh per year. This increase is postponed to 2039 in the climate scenario. In region DEN1, an increase of 1 TWh from gas power production will be postponed from 2032 to 2034 in the climate scenario. In 2040, the supply of electricity is 0.1 TWh or 0.3 % larger due to climate changes.

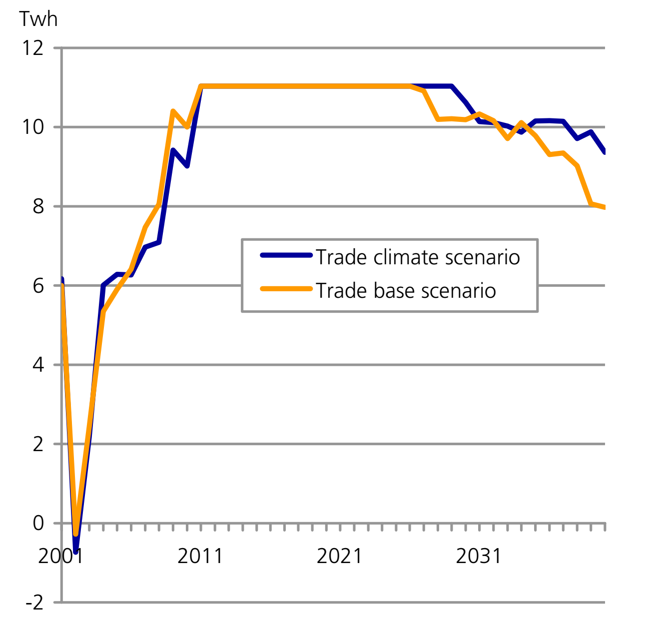
Figure 4.34 The effect of climate changes on annual supply, demand and the price of electricity



The demand for electricity will be 0.2 TWh or 0.5 % higher as a result of the climate changes. The temperature model revealed less than a 1 C° increase in temperature, and as Denmark's demand is not very dependent on temperature[22], it didn't fall by much. The changing inflow and wind doesn't contribute much to the domestic supply, but as the Nordic region has abundant electricity, the price falls and the temperature effect on demand is offset by lower prices. Figure 4.34 b) shows that the electricity price in Denmark in 2040 will be about 1 Nøre/kWh lower in the climate scenario relative to the base scenario.

Denmark has no transmission of electricity between the east and west of the country, so there will be more import from abroad in the period where the coal production is reduced. This import is coming from the other Nordic countries, as Denmark is exporting to the non-Nordic part of Europe. 11 % or 0.1 TWh will reduce the net export in 2040, from 0.85 TWh in the base scenario to 0.75 TWh in the climate scenario. In 2040 Chapter 4.4.1 and 4.4.2 showed that Denmark's export to Sweden from 2001-2005 will result in an effective bound, but this is not very much affected by the climate changes. Denmark is importing from region NO3 in Norway and region SW2 in Sweden. There will be an effective bound on the transmission of electricity in the entire period, but there is not much difference between the base and the climate scenario. Figure 4.35 show that there is not capacity to transmit more than 11 TWh from Denmark to Europe each year.

Figure 4.35. Trade from Denmark to Europe



This bottleneck will increase the cost of transmitting electricity by the shadow price, τ. The effect of climate change is a longer period where the bound on transmission is effective. In the end of the time period, region DEN1 will export less to Europe as the production of electricity in this region levels out whereas the demand continues to increase. This removes the effective bound on transmission from region DEN1 to Europe. However, the transmission line from region DEN2 will be overloaded in most of the years from 2030-2040, resulting in a shadow price on transmission from region DEN2.

[22] See appendix 4 for details.

5. Summary and conclusions

The climate model predicts Nordic inflow into the hydropower reservoirs to be 6-14.5 % larger in 2040. Finland will together with the west coast and north of Norway face the largest increase in inflow. RegClim's data series on wind shows an increase in the average wind speed of approximately 1-2 %. These results are in accordance with earlier research. Applying RegClim's temperature forecast on the temperature dependent model by Johnsen and Spjeldnæs, we simulate an average reduction in temperature dependent demand for electricity of 3-4 % in the Nordic countries.

With Normod-T, we produced one base scenario excluding the simulated changes in inflow, temperature dependent demand and wind, and one scenario where the climate changes were included. Comparing these scenarios indicates that the Nordic region in total is expected to have an increase in supply of electricity of 1.8 % (8.1 TWh) in 2040 due to climate change. This increase seems little at first, but hydropower only amounts to approximately 50 % of total production in the Nordic region and increased hydropower production substitutes marginal production in Sweden and Finland. In addition, as the supply of electricity increases in the climate scenario, the price falls and this reduces new investments in production capacity over the time period (cf. the increasing marginal cost of investment). Total demand for electricity is predicted to increase by 1.4 % (6.3 TWh), despite the reducing effect from increased temperature. This is due to the increased supply of electricity and a reduction in the average price of 2.4 Nøre/kWh. The price effect is then expected to offset the temperature effect. In addition, not all demand is temperature dependent. There will be an increase in net exports from the Nordic area to the rest of Europe of 22 % (1.8 TWh) in 2040, limited by effective bounds on transmission.

In Norway, climate changes will increase the supply of electricity relatively more than demand, and this result in more exports to neighbouring countries and the rest of Europe. Both Sweden and Finland will have reduced supply of electricity until 2030 relative to the base scenario, as endogenous investments in gas power plants are postponed due to cheap hydropower based imports from Norway. After 2030, exports from Sweden to its Nordic neighbours and the rest of Europe increases again due to enlarged production of hydropower and gas power compared to the base scenario. Denmark will reduce its coal production and import more from the south of Norway and Sweden, but at the same time increase exports to Europe. As Sweden, Finland and Denmark will postpone new investments and periodically reduce production, the capacity of the reservoirs and electricity production in Norway will be challenged.

There are two important effects of climate changes on the transmission network. First, effective bounds on transmission occur more often due to more exchange of electricity and second, as the pressure on the transmission grid is larger, the shadow price increases more as a result of climate changes. According to Førsund's theory, the shadow price on transmission will come in addition to the electricity price. There are effective bounds on transmission within each country and between the countries. In Norway, transmission from the western regions to eastern regions is restricted in the winter seasons due to significantly more supply of electricity in the western regions. The northern regions in Sweden are hydropower abundant, and the cables from north to south are increasingly overloaded in the winter seasons due to increased inflow. In the climate scenario, the cables from Norway to Denmark, Sweden and Finland will be overloaded in all seasons from 2010. This is a few years earlier than in the base scenario. There will be an effective bound on transmission from Sweden (SW2) to Denmark (DEN1) in all seasons. The time perspective is not influenced by the climate changes, but the shadow price is higher due to more pressure on the effective bound. The transmission line between Finland and Sweden (SW2) will also face an effective bound in the winter from 2030-2040. This is a few years earlier than in the base scenario. Several other cables will be overloaded in short time periods. The cables between each country and the rest of Europe will also be full in longer time periods due to climate changes. If a transmission-restricted region is hydropower abundant, the pressure on the upper limit of the reservoir will increase and the bound might be effective, and result in a positive shadow price. Effective bounds and increasing shadow prices may indicate profitable investments in capacity, but the analysis of the potential profitability is left for further studies to analyse.

The results of this thesis are mainly based on a climate scenario from RegClim. It is important to stress the uncertainty of climate modelling. The climate scenario is not a predictor of the future, and the results should be handled with some care.

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Appendix 1

Description of climate variables

Climate variable	Shortening	Unit of measurement
2-meter temperature	T	Kelvin
Precipitation	Precip.	Kg/m^2/day
Snow fall	S*	Kg/m^2/day
Rain	R	Kg/m^2/day
Snow water equivalent	S	Mm
Total runoff	P	Kg/m^2/day
10-meter wind Speed	W	M/s
Evaporation	E	Kg/m^2/day
Heating degree days	HDD	-

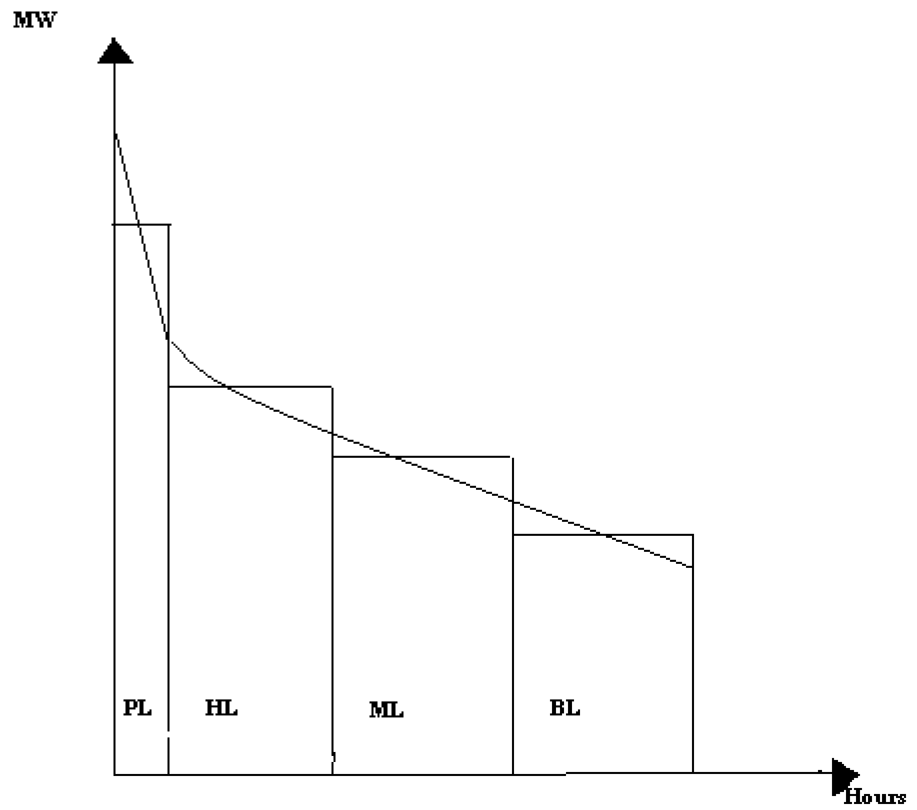
Appendix 2

Load levels in Normod-T

The peak block is assumed to be of shorter length than the high load (HL), medium load (ML) and base load (BL). There are 8760 hours in one year. The table below shows the amount of hours in each block per season.

Season	Base block	Medium block	High block	Peak block
W1	1124	1124	1124	252
SU	910	910	910	198
W2	683	683	683	159

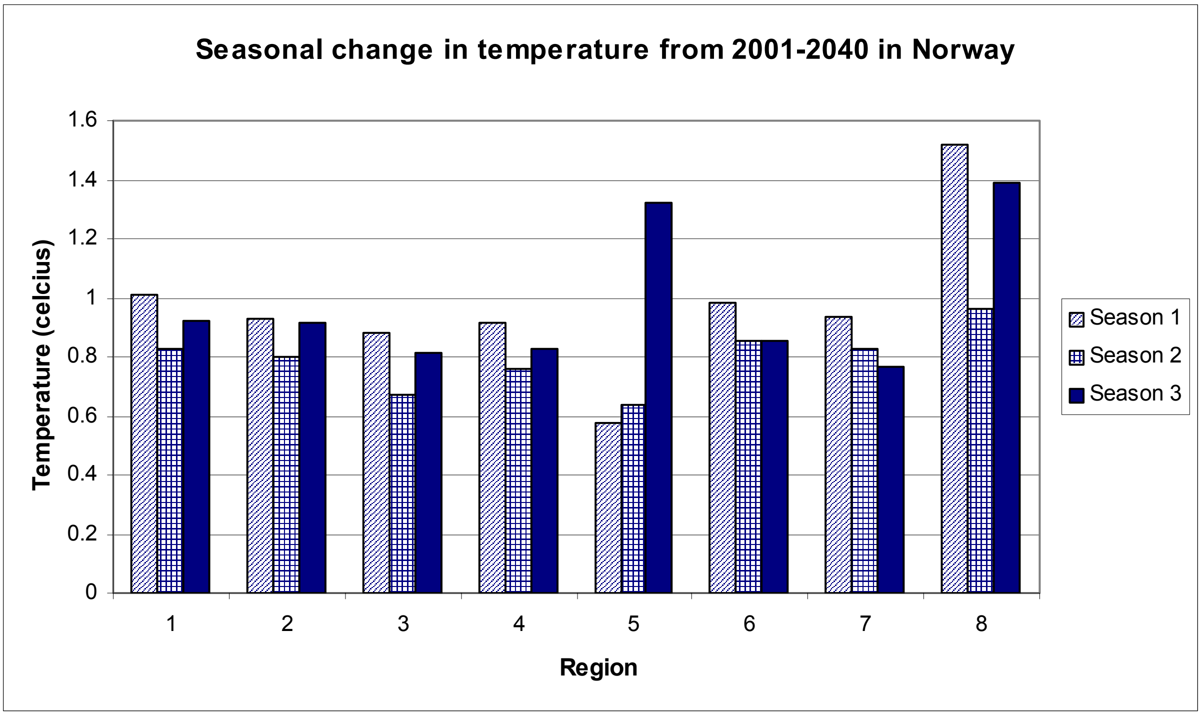
Illustration of a load duration curve and four load blocks



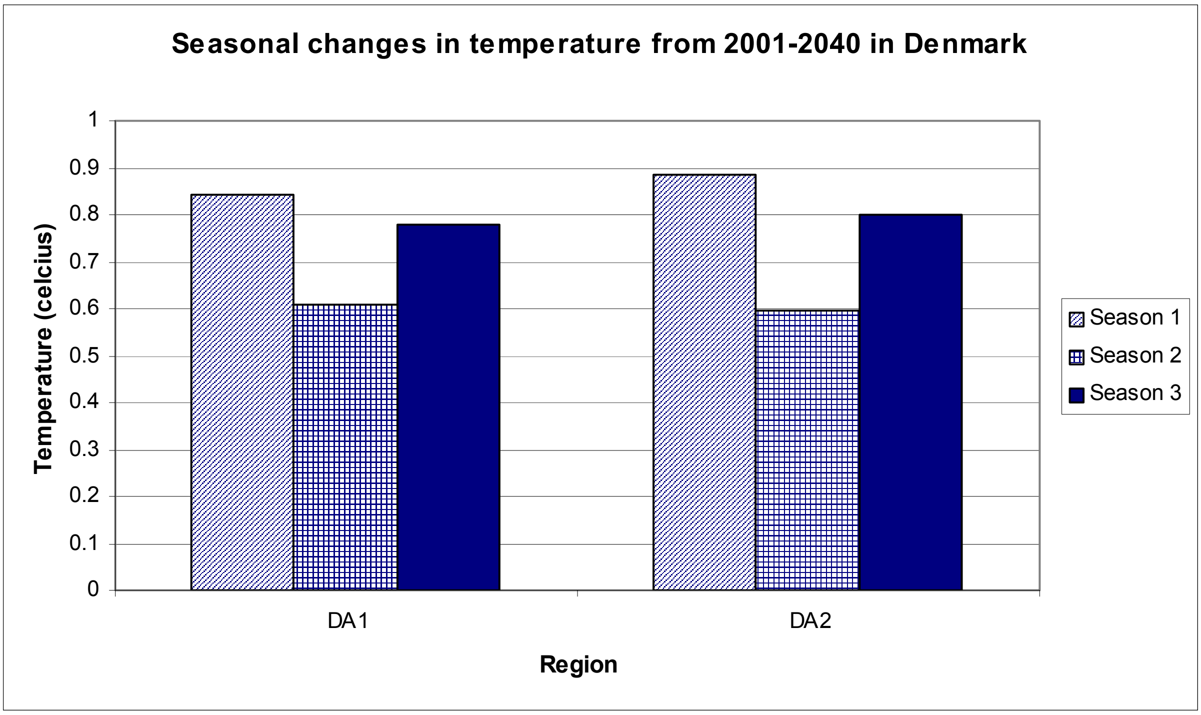
Appendix 3

Regional temperature in the Nordic countries

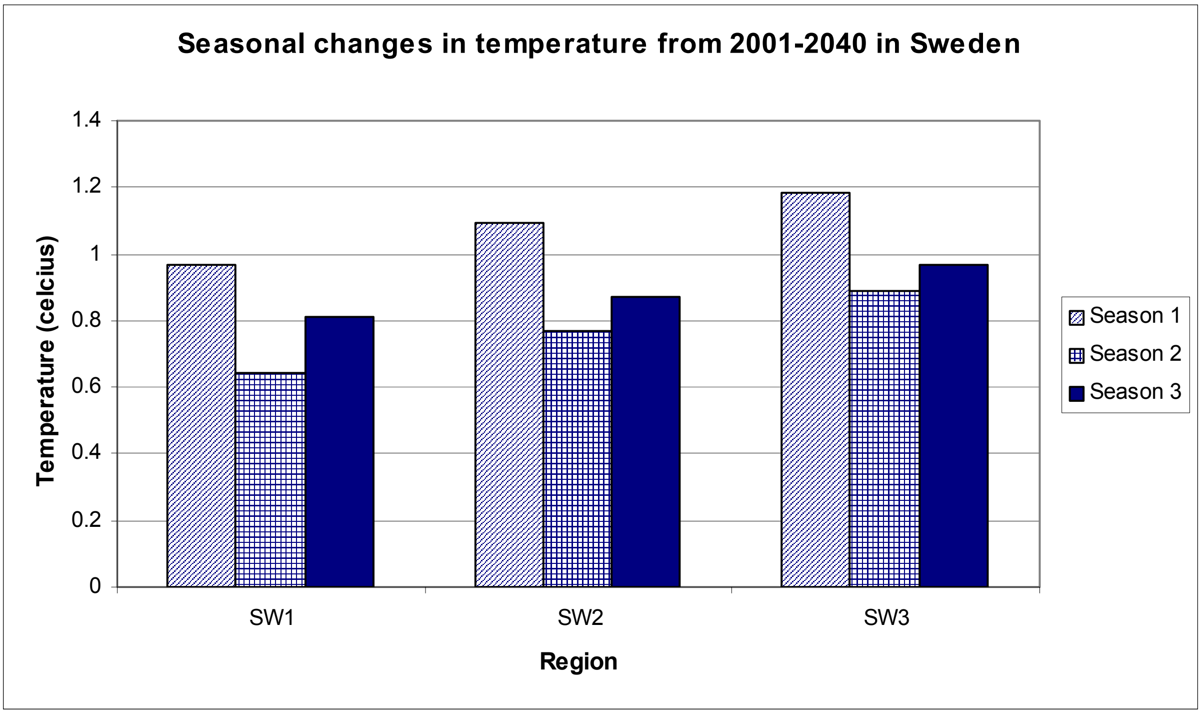
Norway



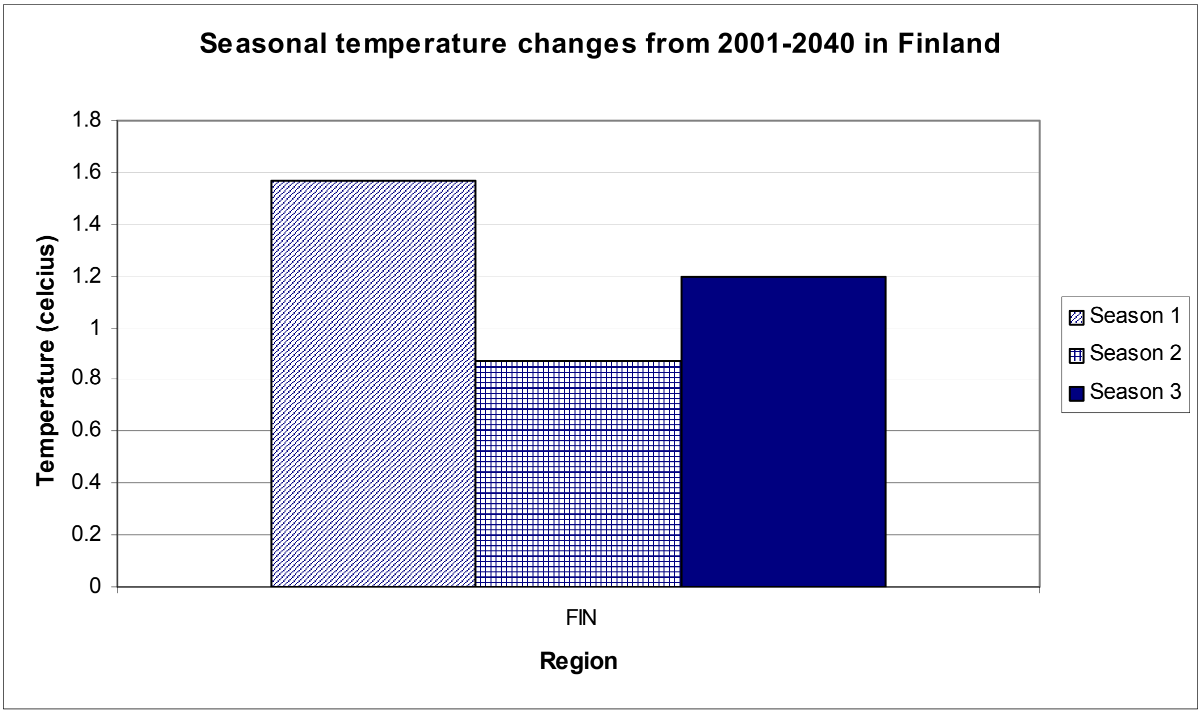
Denmark



Sweden



Finland



Appendix 4

Temperature dependent consumption in Normod-T

This table only concerns the households and service sector.

Region	Season 1	Season 2	Season 3
NOR 1	0,750	0,100	0,750
NOR 2	0,750	0,100	0,750
NOR 3	0,750	0,100	0,750
NOR 4	0,750	0,100	0,750
NOR 5	0,750	0,100	0,750
NOR 6	0,750	0,100	0,750
NOR 7	0,750	0,100	0,750
NOR 8	0,750	0,100	0,750
SWE 1	0,500	0,070	0,500
SWE 2	0,500	0,070	0,500
SWE 3	0,500	0,070	0,500
DEN 1	0,060	0,010	0,060
DEN2	0,060	0,010	0,060
FIN 1	0,375	0,050	0,375

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