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Climate related alterations in Norwegian and Swedish hydropower production and the resulting impact on the Nordic power market in 2050

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Renewable energy

Preface

This master thesis marks the end of six years of studies, and I have acquired my knowledge trough a bachelor's degree in Meteorology and Oceanography from the University of Bergen, and a master's degree in Renewable energy from the Norwegian University of life sciences. This thesis was written at the Department of Ecology and Natural Resource Management, in cooperation with my supervisors Torjus Folsland Bolkesjø and Åsa Grytli Tveten.

My interdisciplinary background was the motivation for choosing a research question that addressed the issue of both climate change and renewable energy. The ambition for this thesis was to investigate how climate change will affect the Norwegian hydropower production towards 2050, and how this will affect the Nordic Power market.

I will like to thank my two supervisors Torjus Folsland Bolkesjø and Åsa Grytli Tveten for all their support and good advice throughout this semester. This thesis would not have been what it is today without the help from a large number of employees in NVE; Wai Kwok Wong, Valentin Johannes Koestler, Harald Endresen and Christina Stene Beisland. They have all answered my questions, and given me access to large amounts of datasets which have been crucial for the results of this thesis. Also, thank you to Bjørn Sønju-Moltzau in Thomson Reuters for the dataset, and Vegard Holmefjord in Statnett for the advice regarding my thesis.

Thank you to Ola Omberg, Kristian Omberg and Tara Botnen Holm for advice regarding my thesis. And last but not least, thank you to my dear Kristoffer Bjornes for all the help and support throughout the last months.

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Abstract

As a result of climate change, global precipitation patterns are predicted to change. For the hydropower nations Norway and Sweden, predictions of increased precipitation levels are expected to result in increased energy inflow. Consequently, both countries will experience increased levels of hydropower capacity, which will have repercussions throughout the Nordic power market.

The main research question for this thesis is as follows: How will climatic changes influence the Norwegian and Swedish hydropower production towards 2050, and how will changes in hydropower production affect the Nordic power market?

Based on the climate scenarios RCP4.5 and RCP8.5, NVE modelled energy inflow series for Norway in 2050. These series were used as basis for constructing inflow series for Sweden in the same period. Simulations were then done with the Balmorel model. The results were analysed with the objective to investigate how varying levels of hydropower production in Norway and Sweden affected the Nordic power market in 2050. Production levels from other technologies, cross-border trading and electricity price levels were the focus of the analysis.

The results show that alterations in hydropower production will have largest effect on the price levels in Finland, Norway, Sweden and Denmark. The most affected technologies are gas power CHP.

The results can be applied by TSOs, authorities and power producers in their planning of the future power market. The results can be implemented in estimations regarding where future investments will give the largest socioeconomic benefits and where it is most needed in the future Nordic and European power market.

Sammendrag

Som følge av klimaendringer er nedbørsmønstre over hele verden forventet å endre seg de neste årene. For Norge og Sverige er nedbørsmengdene de neste årene forventet å øke, og dette vil videre føre til økning av energitilsiget. Siden dette begge er land der en stor andel av elektrisitetsproduksjonen er basert på vannkraft, vil klimaendringene føre til betydelige ringvirkninger i det Nordiske kraftmarkedet i form av endret vannkraftproduksjon. Hvor store endringene blir, avhenger av klimaendringenes omfang.

Problemstillingen for denne oppgaven er hvordan klimaendringer påvirker vannkraftproduksjonen i Norge og Sverige i 2050, og hvordan dette videre påvirker det Nordiske kraftmarkedet.

Basert på klimascenariene RCP4.5 RCP8.5, har NVE modellert energitilsig for Norge i 2050, og disse ble brukt som basis for å generere tilsigsserier for Sverige i samme periode. Gjennom simuleringer i Balmorel ble det studert hvordan de predikerte tilsigsnivåene for Norge og Sverige kommer til å endre vannkraftproduksjonen. Deretter ble det undersøkt hvordan variasjonene i vannkraftproduksjon mellom de forskjellige scenariene kommer til å påvirke elektrisitetsproduksjon for andre teknologier, overføring mellom land og prisnivåer i 2050.

Resultatene viser at det er Finland, Norge, Sverige og Danmark som får størst prisreduksjoner som følge av økt vannkraftproduksjon i Norge og Sverige. Teknologiene som får størst endringer i produksjonsnivå som følge av endringer i vannkraftproduksjonen er gasskraft og CHP, og dette er spesielt tydelig i Tyskland.

Resultatene for denne oppgaven kan brukes av nettselskaper, myndigheter og kraftprodusenter i planlegging av det fremtidige kraftmarkedet. Resultatene kan brukes til vurdering av hvor det gir størst samfunnsmessig nytte og hvor det er mest behov for fremtidige investeringer i det Nordiske og Europeiske kraftmarkedet.

List of figures

List of tables

Translations and definitions

Runoff (*m^3/s)*	Avrenning
Inflow (*m^3/year)*	Tilsig
Inflow series	Tilsigsserier
Energy inflow	Energitilsig
Average/ mean precipitation energy	Midlere nedbørsenergi
Potential hydro-electric energy *The amount of water that can be used for electricity production (OED2015)*	Nyttbart tilsig
Annual mean production	Midlere årsproduksjon
Catchment / Drainage basin *The geographical area that drains into a river or reservoir (Hendriks 2010)*	Tilsig/nedbørsfelt
Dam/storage capacity *"The amount of power that can be produced by emptying a full dam" (OED2015)*	Magasinkapasitet
Multi area power-market simulator (EMPS)	Samkjøringsmodellen

Abbreviations

Abbreviation	Explanation
CHP	Combined Heat and Power
CORDEX	Coordinated Regional Climate Downscaling Experiment
EMPS	EFI’s Multi area Power- market Simulator
ESD	Empirical Statistical Downscaling
EQM	Empirical Quantile Mapping
GAMS	General Algebraic Modeling System
GCM	Global Circulation Model
GHG	Green House Gas
GWP	Greenhouse Warming Potential
HBV	Hydrologiska Byråns Vattenbalanssektions modell
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MES	Ministry of the Environment Sweden
NETP	Nordic Energy Technology Perspectives
NKSS	Norsk Klimaservicesenter
NVE	Norwegian Water Resources and Energy Directorate
	(Norges Vassdrags- og Energidirektorat)
OSF	Official Statistics Finland
RCP	Representative Concentration Pathways
RCM	Regional Climate Model
SRMC	Short Run Marginal Cost
SSB	Statistisk Sentral Byråd
SVK	Svenska Kraftnät
VRE	Variable Renewable Energy
WMO	World Meteorological Organization

Table of contents

1 Introduction

There is a general consensus among the scientific community that climate change is a result of human-induced emissions. According to IPCCs fifth assessment report, climate change and increased atmospheric temperatures have already altered the global precipitation patterns. In the northern hemisphere, there has already been detected an increase in annual precipitation levels, relative to the reference period 1986-2005. Given that the Greenhouse gas (GHG) emissions continue in the same pattern as historically, scientists predict that the changes mentioned above are likely to intensify (IPCC 2013). Many countries are taking steps towards reducing their GHG emissions by transitioning from fossil to renewable energy sources. Solar, wind and hydropower play a central role in this transition.

Hydropower production is largely dependent on weather and climate conditions, and any change in the behaviour of precipitation patterns will be reflected in hydropower production levels. The Nordic power market has a large share of hydropower production, and will consequently be largely affected by climate change. During a normal year, electricity from hydropower production makes up 50 % of the total annual production in the market (Birkedal & Bolkesjo 2016).

Norway is the leading country regarding hydropower production. 96 % of the electricity produced in Norway originates from hydropower (SSB 2016) and the annual average production is 130 TWh (Holmqvist 2013). Sweden also has a large share of hydropower production, with a national share of 50 % and an annual average production of 65,5 TWh (MES 2014). Beisland et al. (2015) and Andréasson et al. (2004) agree that Norway and Sweden are expected to experience an increase in production levels from hydropower the next decades, as a result of climate change.

Due to the system of transmission lines between the countries in the Nordic Power market, the hydropower production in Norway and Sweden also have an influence on consumers and producers in the neighbouring countries. The amount of hydropower electricity that is produced during a year has repercussions through several countries, affecting electricity prices and production levels of other technologies.

A large amount of the energy production in Europe originates from thermal capacity and unregulated renewable energy. Because of this, the flexible hydropower in Norway and Sweden is beneficial for evening out price levels in the Northern-European power market (IEA 2016). The motivation of this thesis is to get an insight into how future hydropower supply for Norway and Sweden will influence the price development for the future years. How the production levels of different technologies, electricity prices and energy consumption will develop in the years towards 2050 is crucial for policy makers in decision making regarding development and upgrading production and transmission capacity.

There are several publications regarding future Norwegian hydropower production, and to which extent it is likely to be affected by climate change. Lehner et al. (2005) investigated how the hydropower potential in Europe might be affected by climate change towards the end of the century. NVE has published several reports on the topic of how the streamflow in Norway is predicted to change in future years. Hisdal et al. (2010), Holmqvist (2014), Wilson et al. (2010) and Rosenberg et al. (2013) also investigated the impact of climate change on streamflow and the resulting changes in hydropower production.

Raje and Mujumdar (2010) investigated how the reservoir performance will be altered in the case of climate change, which is relevant for prediction of the future production losses due to flooding. Mideksa and Kallbekken (2010) collected all available literature, and made an overview of the most central effects climate change will have on power supply, demand and transmission.

Several reports have been published regarding the effect of climate change on both hydropower and market dynamics. However, no study is found to investigate the impact an increase in hydropower output for Norway and Sweden will have on the dynamics of the future Nordic Power market. This specific issue is addressed in this thesis, by applying predicted energy inflow for Norway and Sweden for 2050 as input in the detailed energy market model Balmorel. The Balmorel output will give insight regarding future market dynamics, cross-border trading, production levels and price levels.

1.1 Research questions

The main objective of this thesis is to investigate the following question:

How will climatic changes influence the Norwegian and Swedish hydropower production towards 2050, and how will changes in hydropower production affect the Nordic power market?

To be able to address the main objective, three research questions related to the main objective are defined:

1. Which technologies in the Nordic power market will be most affected by the climate related alterations in Norwegian and Swedish hydropower production towards 2050?
2. How will climate change affect Nordic electricity prices in 2050?
3. How will climate change affect the rate of export and import between the countries in the Nordic power market in 2050?

1.2 Structure

Chapter 2 gives a brief introduction to theory regarding climate change, reference periods and the Nordic power market. Chapter 3 presents previous work that has been published regarding climate change, future hydrological conditions in the Nordic countries and the predicted development in the Nordic power market. By presenting the main publications related to these themes, an introduction to the current state of knowledge is given, together with a clarification of how the objectives of these publications differ from the objective of this thesis. Chapter 4 presents the dataset and the methodology that was used for deriving the data. Chapter 5 describes the methodology used in this thesis, in addition to describing the assumptions that were made prior to the Balmorel simulations. The results are presented and discussed in chapter 6. This chapter also address the analysis limitations, contribution to the literature and implications of this thesis. A conclusion is drawn in chapter 8. Chapter 9 gives recommendations to further work related to this thesis.

2 Theory

The purpose of this section is to present theory regarding subjects that are mentioned throughout this thesis. The subjects involve definitions of future emission scenarios, how to calculate 30-year averages and introductory information regarding the Nordic power market. The theory presented here is used as basis for several preconditions in this thesis, and will give a better understanding of the literature presented in chapter 3 "Earlier work".

2.1 Representative Concentration Pathways

Human induced climate change, in the form of emission of greenhouse gases and aerosols, is a driver with continuously increasing effect that has been present since the industrial revolution (Hanssen-Bauer et al. 2015). The IPCC fifth assessment report states that anthropogenic emissions of CO_2 is the main reason for the changes in climate we see today (IPCC 2013). To which extent the climate will be altered, depends on the emission levels in the coming years. To get an indication of the future climate development, scenarios for possible emission levels of greenhouse gases are developed. These scenarios are then used as input in Global Climate Models (GCMs), which predicts how temperature and other meteorological variables react to the changing concentrations of GHGs.

It is highly uncertain how the levels of anthropogenic emissions of GHG and land use will change towards the end of this century. To give an indication on what to expect, the IPCC fifth assessment report presented four emission scenarios towards year 2100. These scenarios give an indication of the emission levels that can be expected in the future depending on what climate policies are implemented. The scenarios are called Representative Concentration Pathways (RCPs), where each RCP scenario represents an emission-path presented in CO_2 equivalents. All the scenarios and associated concentrations are presented in Table 1. Each scenario is linked to an expected level of rise in atmospheric temperature, which is also illustrated in the table. The GHGs that are taken into consideration for the scenarios are CO_2,

CH_4 and N_2O. The lowest emission scenario is named RCP2.6, where the atmospheric CO_2 concentrations in 2100 reach 421 ppm, and the CO_2-equivalent of CH_4 and N_2O reaches 475 ppm. The higher the RCP number, the higher the atmospheric concentration of GHG. RCP8.5 represents a “business as usual” scenario where the emissions are predicted to continue in the same pattern as historically (IPCC 2013).

Table 1: Representative Concentration Pathways and their corresponding atmospheric concentration of greenhouse gases by the year 2100. The global mean surface temperature change for two periods are listed for all RCP scenarios. The higher the emissions, the higher temperatures are expected (IPCC 2013).

Representative Concentration Pathways	**CO_2 concentration (ppm)**	**CO_2-equivalent of CH_4 and N_2O concentrations (ppm)**	**Global mean surface temperature change (°C)**	
			2046-2065	2081-2100
RCP2.6	421	475	1.0	1.0
RCP4.5	538	630	1.4	1.8
RCP6.0	670	800	1.3	2.2
RCP8.5	936	1313	2.0	3.7

2.2 Reference periods and 30-year averages

When working with atmospheric and hydrological variables, it is common to use 30-year averages instead of values from a single year. A 30-year period is called a reference period, and in the process of detecting climate signals two reference periods are often compared (NKSS 2017). By having a duration of 30 years for each reference period, it is ensured that the normal values will not be affected excessively by extreme weather events (Aune 1993). The official reference periods have been established by the World Meteorological Organization (WMO) as 1901-1930, 1931-1960, 1961-1990. After year 2020 data from the next reference period 1991-2020, will be used (Aune 1993).

The reports and articles referred to in this thesis have used a wide variety of reference periods in their calculations, and Table 2 gives an overview of the reference periods used. The data used in this thesis were calculated on the basis of reference period 1981-2010, and not the official WMO reference period. The dataset originates from a study that investigates how the Norwegian power market of today will experience climate changes towards the end of the century (Beisland et al. 2015). Thus, since the objective was to study the present inflow values in relation to the years towards 2100, it was constructed a new reference period based on the years closer to the present, instead of using the WMO period that dates longer back in time.

Table 2: Overview of the reference periods that are used in the publications referred to in this text

Report	Reference period
(Holmqvist 2013)	1981-2010
(Holmqvist 2014)	1958-2012
(Hanssen-Bauer et al. 2015)	1971-2000
(IPCC 2013)	1986-2005
Dataset used in Balmorel-simulations (accessed from NVE)	1981-2010

2.3 The Nordic power market

This chapter provides a general understanding of the market operation, trade and power generation in the Nordic power market.

2.3.1 Structure of the Power market

The electricity in the Nordic power market is traded through the wholesale electricity market Nord Pool (Skau et al. 2011). In addition to the Nordic countries, the Baltic states also trade electricity through Nord Pool. This was where 84 % of the electricity in Europe was traded 2013, which makes Nord Pool the largest power market in Europe (Mäntysaari 2015).

Nord Pool consists of the three markets Elspot, Elbas and N2EX, which each serves a different purpose. Elspot is the day-ahead market for electricity trade in the Nordic and Baltic countries. Elbas is the market that balances the market in the same areas, in addition to Germany. N2EX is the market for UK (Mäntysaari 2015).

The spot price is set by Nord Pool, which receives offers from both demand and supply side, and balances between the offers determine the system price. When financial agreements are to be made, the system price is used as a reference (Skau et al. 2011). In the case of no transmission constraints in the grid, there will be an equal price for all the areas in the market. This is not the case, however, due to transmission constraints in the grid. This is called a bottleneck situation, where the limited transmission capacity acts as a bottleneck so not enough power can pass between the different areas (Nambu & Ohnishi 2010).

In order to manage the price differences, the Nordic power market is divided into different price areas, which are called elspot areas. Norway is divided into five areas, Sweden four, Denmark two and Finland one (Statnett 2013). The areas are illustrated in Figure 1. Norway has powerlines connected to Sweden, Denmark, Netherlands and Russia, and new lines to Germany and Great Britain are planned. The largest share of cross-border trading is through Sweden (Skau et al. 2011).

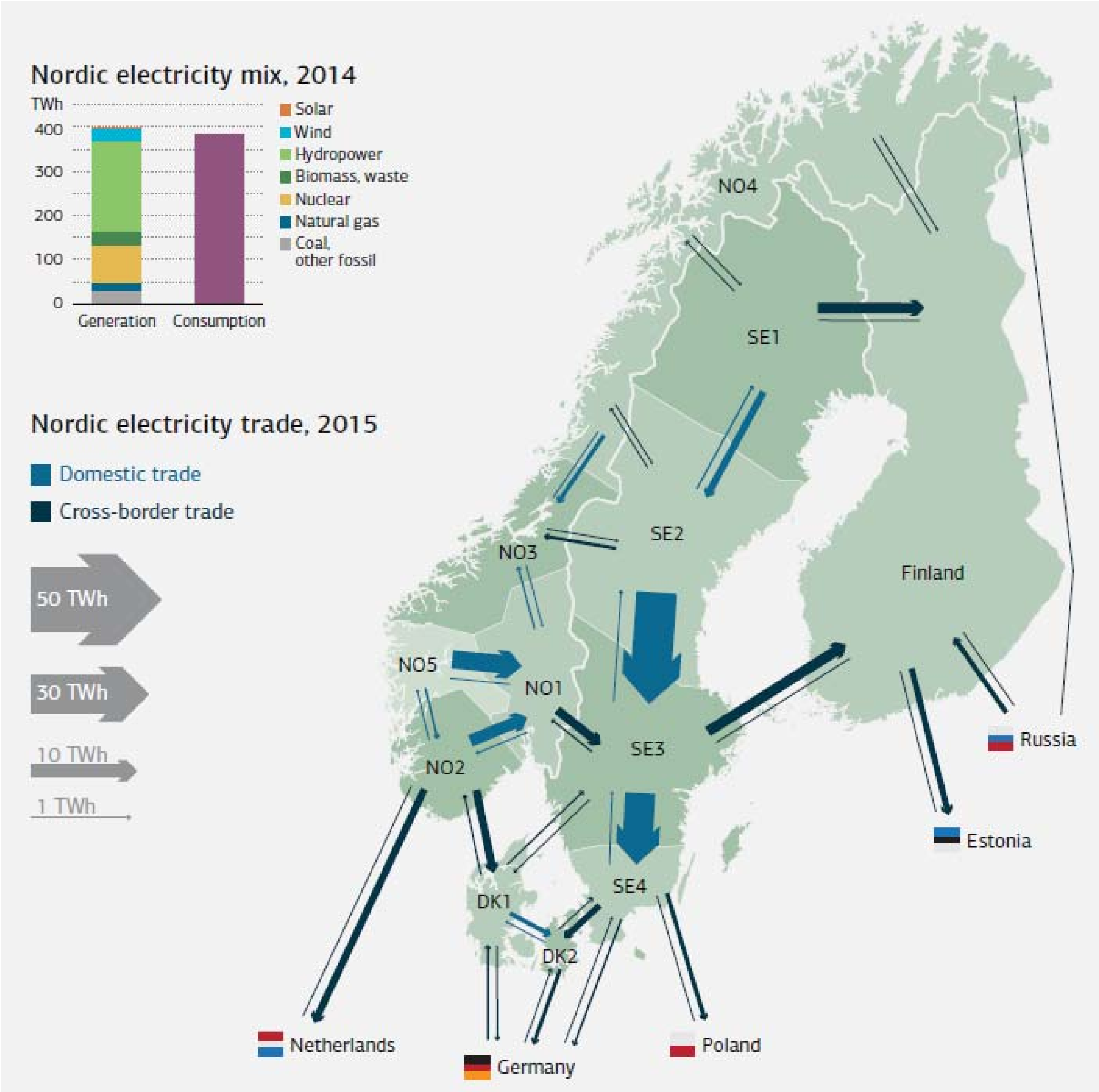

Figure 1: Illustration of the Nordic power flow between countries and regions in 2015. Top left corner illustrates the Nordic electricity mix in 2014 (IEA 2016).

2.3.2 Source of power supply

The source of power supply differs between the countries in the Nord Pool system. Norway has the largest share of hydropower, with almost all the produced electricity coming from hydropower (IEA 2016). In total, hydropower production carries out 50 % of the total power production in the Nordic power market (Jensen et al. 2016).

In Sweden, the largest amount of electricity is produced from hydropower and nuclear power. In 2016, the production from hydropower made up 42 % of the total electricity production, and nuclear 41 %. Wind comes third, with a production of 10 % in 2016. The rest of the electricity is produced from heat, sun and gas power (SVK 2017).

Thermal production makes up the largest share in Finland, and the rest originating from nuclear power and hydropower (IEA 2016). In 2015 the largest share of electricity production originated from nuclear, CHP and hydropower whose production levels made up 33 %, 31 % and 25 %, respectively. Finland also has electricity production from wind, solar and condensing power (OSF 2016).

Denmark has thermal power and wind power as main power sources, which in 2015 made up 46 % and 51 % of the electricity production. The country also has production from solar power (Nielsen 2016).

2.3.3 Price

The price in the Nordic electricity market is largely dependent on the levels of hydropower production (IEA 2016). As Figure 2 illustrates, there is a close connection between precipitation levels and the electricity price in the Nordic region. In a situation with dry weather, the prices in Norway and Sweden will be affected the most. Finland and Denmark will also notice a difference, but to a lower extent (Lise et al. 2008). CO_2-prices also have a large influence on the Nordic electricity prices. The CO_2-price is expected to increase from 2020, which will lead to an increase in Nordic electricity prices (IEA 2016).

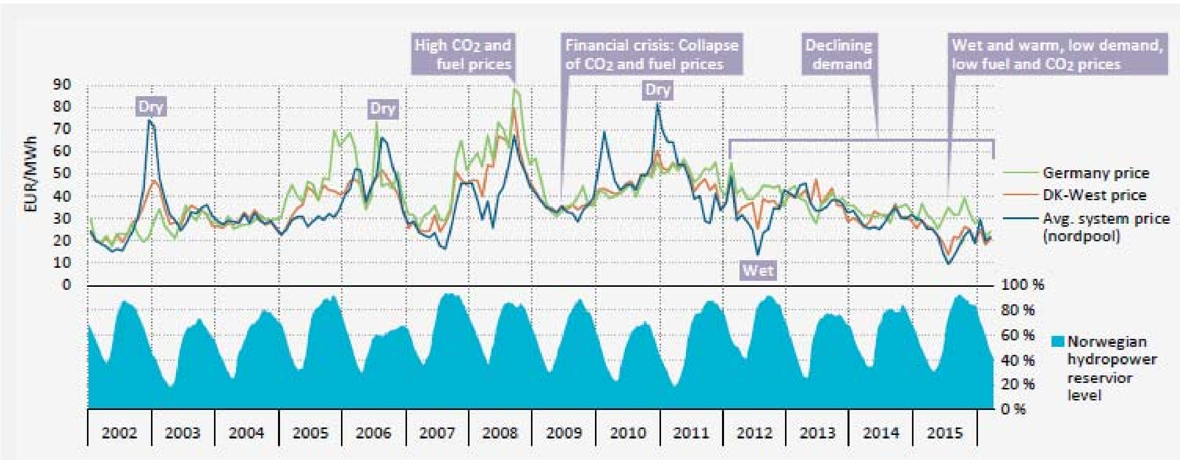

Figure 2: Historical electricity prices in the Nordic power market (EUR/MWh) compared with the reservoir levels of Norwegian hydropower reservoirs. The figure illustrates that there is a connection between dry years and high electricity prices, and wet years and low prices (IEA 2016).

3 Previous studies

This section presents existing studies on the influence of climate change on hydrology and power market dynamics in the Nordic region. There has been done comprehensive work regarding the impact of climate change on both hydropower production and the power market in the Nordic region. Key studies will be presented below, and in that way, an introduction to the state of knowledge is given.

3.1 Hydrology and climate change in Norway

There seems to be a general consensus in the literature that the Nordic countries already have experienced a change in streamflow due to atmospheric temperature increase. This conclusion is similar for both Hisdal et al. (2010) and Wilson et al. (2010). These authors studied historical records, and found that there has been an increase in annual streamflow, in addition to a change in the seasonal pattern. The streamflow in winter months has increased due to warmer temperatures and increased precipitation levels. Mainly due to an earlier spring flood, the streamflow has also increased in springtime. This effect is evident in areas with both snowmelt and rain floods during spring. In summer, the streamflow has been reduced, and the occurrence of more severe droughts has increased. This is due to the earlier snowmelt and increased evaporation resulting from the higher temperatures. The autumn is the only season where the patterns have remained largely unchanged. Hisdal et al. (2010) and Wilson et al. (2010) agree that the effects of climate change have already started to take place, and that the increased streamflow in the Nordic countries is a result of this. The changes that were found for the Nordic countries also applies for Norway, according to Holmqvist (2014).

The observed annual and seasonal changes in streamflow are expected to intensify with time. This is stated by Roald et al. (2006) in the report “Climate change impacts on streamflow in Norway”, where the projected streamflow for 2071-2100 is investigated. An intensification of the abovementioned trends is expected for all seasons causing increased temperature and streamflow levels. As opposed to Hisdal et al. (2010) and Wilson et al. (2010), who did not find these trends for autumn, Roald et al. predicts an increase in streamflow also for the late autumn in future years.

Norway has a mix of precipitation- and snowmelt dominated runoff regimes, and thus, the amount of snow that accumulates in the mountain areas during winter is crucial for the hydropower production throughout the year. Due to a predicted increase in atmospheric temperature, the precipitation during winter months will more often fall as rain instead of snow. This results in accumulation of smaller snowpack volumes, and an earlier and smaller snowmelt flood in the spring. As a result of this, there will be a decrease in snowmelt generated events, and the largest change in flood seasonality will occur for the snowmelt dominated catchments. Towards the end of the century the autumn and winter floods are expected to increase in both strength and frequency (Vormoor et al. 2015).

Holmqvist (2014) also investigated future trends for snow. On a regional scale, there is a clear negative trend in maximal snow magazines near the coast, and a positive trend for the mountain areas. To some extent the changes cancel each other out on a national scale. Thus, there has not yet been detected a large change in culmination values for snow magazines nationally.

Hanssen-Bauer et al. (2015) investigated the effect of the two climate scenarios RCP4.5 and RCP8.5 on the hydrology in Norway. The extent to which the hydrological conditions will change depends on how much the atmospheric temperatures will rise, and thus on the emission levels of greenhouse gases. Based on the reference period 1971-2000, the annual mean temperature for Norway was +1,3 °C. For RCP4.5, the annual mean temperature for Norway is expected to increase with 1,8 °C within the period 2031-2060, and for RCP8.5 an increase of 2,4 °C is predicted for the same period (Figure 3). Hanssen-Bauer et al. (2015) state that both climate scenarios will lead to an increase in precipitation for all seasons, but RCP8.5 will lead to a larger percentage increase than RCP4.5 (Figure 4). The increased temperature also results in more evaporation, which evens out the impact of increased precipitation levels on runoff values. The percentage change in runoff values is illustrated in Figure 5. Also for the runoff levels, RCP8.5 results in a larger increase than for RCP4.5, regardless of the increased evaporation.

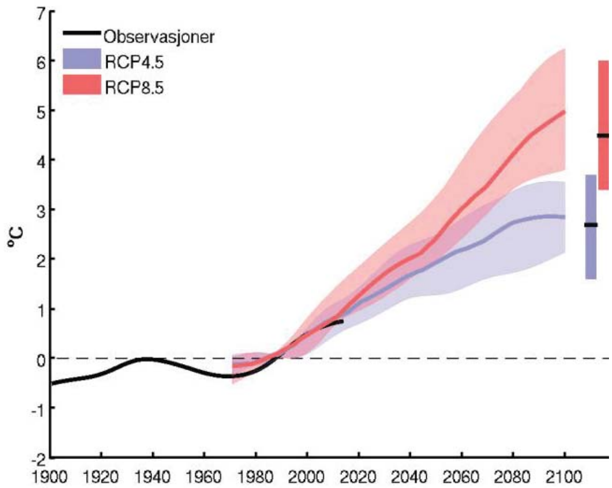

Figure 3: Deviations for annual temperature in °C, for Norway relative to reference period 1971-2000. The black line illustrates observational values, the blue is median simulation values for RCP4.5, and the red RCP8.5. The faded colour indicates the spread between high and low simulation values. All curves are smoothed. (Hanssen-Bauer et al. 2015)

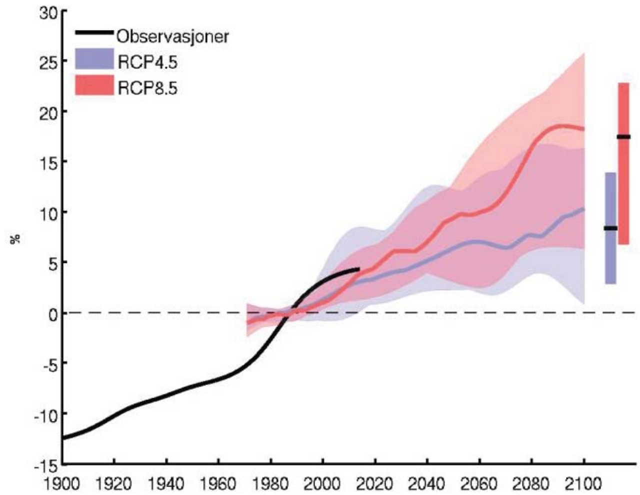

Figure 4: Annual precipitation change (%) for Norway. Red and blue line shows percent of deviation from the reference period 1971-2000. The black line illustrates observational values, the blue is median simulation values for RCP4.5, and the red RCP8.5. The faded colour indicates the spread between high and low simulation values. All curves are smoothed. (Hanssen-Bauer et al. 2015)

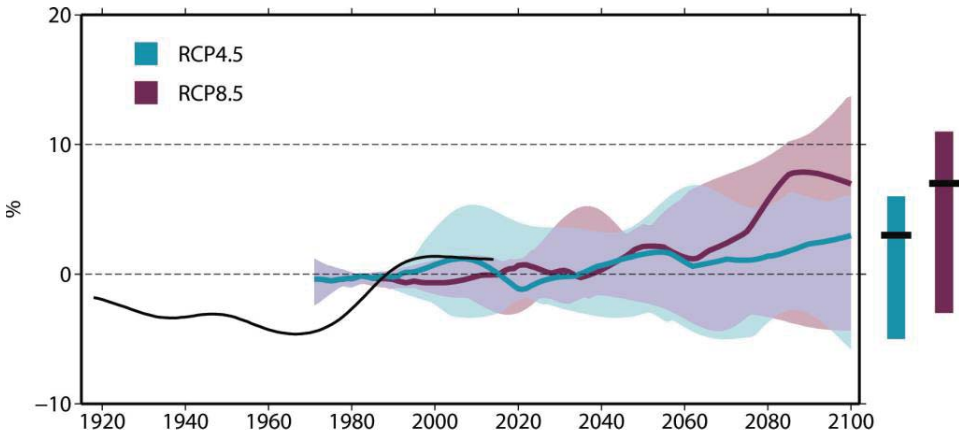

Figure 5: Change in runoff (%) based on reference period 1971-2000. The black line illustrates observed values from 1917 to2014. The blue line illustrates the mean value from model simulations for RCP4.5, and the blue-shaded area is the spread from model simulations. The purple line illustrates the mean value for RCP8.5, and the shaded area illustrates the spread in results from the different simulations. (Hanssen-Bauer et al. 2015)

3.2 Hydrology and climate change in Sweden

The climatological and geographical characteristics for Sweden and Norway are quite similar, and the expected hydrological change in Sweden is in many ways the same as in Norway.

Similarly, with Norway, climatological changes have already started to take place in Sweden. Both annual and winter temperatures have started to increase, in addition to an increase in precipitation levels. The annual mean production level from hydropower is 65.5 TWh/year, based on the period 1960-2010 (MES 2014).

Andréasson et al. (2004) investigated how the hydrological conditions in Sweden are expected to change in future years, and the main findings of the article indicate that the climate related changes in hydrological conditions will have the same characteristics as Norway. The same conclusion was drawn by Hisdal et al. (2010). Both studies state that the runoff is expected to increase during the winter and autumn seasons, and decrease during summer. The spring flood will be reduced relative to historical values, while the autumn floods will increase in both frequency and intensity. As for the annual runoff, the largest increase is predicted to occur in the northern part of the country, while the annual runoff will decrease in the southern part.

3.3 Hydropower production

A number of previous studies have investigated how the hydropower production will be altered under the changing hydrological conditions.

Lehner et al. (2005) published a paper with the objective to investigate how global climate change will affect the hydropower potential of Europe, by accounting for both climate and socioeconomic changes in the calculations. Projections for socioeconomic changes were used to predict the demand for water, which was combined with projections for climate change. By combining these two factors, the expected discharge volume for 2020 and 2070 was found. The results state that there will be an increase in discharge volumes for northern Europe, as opposed to southern and eastern Europe which will experience a decrease.

Lind et al. (2013) studied what changes the Norwegian hydropower producers can expect in the future. It was found that the Norwegian hydropower producers can expect an increase in production levels, but that the changes vary considerably between different regions. The energy inflow is expected to increase in all Norwegian regions, and western and northern Norway are expected to experience the largest percentage increase in energy inflow.

Beisland et al. (2015) investigated the impacts of climate change on hydropower production in Norway towards 2100. The annual energy inflow is expected to increase with 12 TWh within the period 2031-2060, and even more towards the end of the century. In addition to an increase in annual inflow values, there will also be a displacement of inflow between the seasons. The most significant change is displacement of runoff peaks from spring and summer to fall and winter. The inflow will also be affected by increased melting of the glaciers, which will have the strongest effect towards the middle of the century. Even though the production levels will increase as a result of the increased inflow, the flood losses are also expected to increase. This is due to limited storage and production capacity, and therefore the hydropower producers will not be able to utilize all of the increased inflow.

3.4 Climate change impacts on the Nordic power market

The literature presented in this section gives an introduction to previous studies of how alterations in the hydropower production will affect the Nordic power market.

How alterations in the hydropower production will affect the Nordic power market depends on several factors, such as where and when the hydrological changes take place, exchange capacity and production levels from other technologies. Even though the price level in the Nordic power market is connected to the supply of hydropower, the short-term hydropower supply is also affected by the other components in the market Birkedal and Bolkesjo (2016). Thus, it is evident that the dynamics of the Nordic power market is intricate, and it is not only the hydropower production in Norway that affects the Nordic power market, but also the other way around.

Mideksa and Kallbekken (2010) reviewed relevant literature on the effects of climate change on the electricity market. Literature regarding both the supply and the demand side of the market were investigated. The relevant finding states that a result of the increased temperature, the European demand for heating will decrease, and demand for cooling will increase. Northern Europe will experience increased river flow by 2050, which results in an increase in hydropower production. Both the pattern and frequency of inflow will change, which might lead to a situation where limited dam capacity results in a situation where not all the water can be utilized. As for the main trends, northern Europe is expected to experience decreased demand and increased supply, resulting in an increased power surplus. In southern Europe, the demand increases and supply decreases, resulting in a reduction of power surplus.

Schaeffer et al. (2012) reviewed relevant publications with the objective to present the state of knowledge regarding the energy sector vulnerability to climate change. The paper presents all relevant factors that contribute to the balance of the energy market. The impact of climate on energy supply, transmission, distribution, energy use, infrastructure siting and cross-sector impact was investigated and presented throughout the paper. Schaeffer et al. state that there are several parts of the energy sector that have yet to be addressed in relation to climate change. It is also highlighted that the climate models have to be improved, so that they better can be used in relation to planning ahead in the different parts of the energy sector.

van Vliet et al. (2013) investigated the impact of climate change on water constraints and power prices in Europe. All countries in Northern Europe will experience an increase in mean annual river flow, and thus, an increase in hydropower potential. Both Norway and Sweden are predicted to produce more hydropower electricity at a lower cost, and it is therefore expected that power plants with higher production costs will be put out of operation due to lower electricity prices. Electricity export from Norway is expected to increase by 4 %, and export from Sweden with 15 %. Due reduced electricity prices, the annual producer surplus will be reduced in both countries. Southern Europe will experience the opposite effect. Here, reduced water availability will cause increased wholesale prices. Thus, it is suggested to expand grid connection between Northern and Southern Europe to even out the price levels.

Rosenberg et al. (2013) studied the interaction between the demand and supply side of the Norwegian power market. The objective of the report was to make a long-term projection of energy demand in Norway, and illustrate how this affects renewable energy production. There are two scenarios in the report, one assuming increased demand and one assuming reduced demand. For the scenario with increased demand, there will be investments in both new hydropower capacity and wind power. If there is a decrease in the energy demand investments in new wind power will not take place. Regardless of demand, the electricity produced from hydropower will increase because of increased precipitation levels. This results in less need for power from other energy sources, a reduction in electricity price and the opportunity to increase export levels.

As stated by Beisland et al. (2015), there will be a displacement of the inflow pattern from having the peak in spring and summer to fall and winter, and a smoother curve of inflow during the year. This will lead to reduced deviation between resource availability and demand. There will be a reduced need to store water between the seasons, and the storage capacity will be used for inter-annual storage instead. The annual variations in price will be reduced due to a more even inflow throughout the year, in addition to an increased amount of inflow.

3.5 Contribution to the literature

The impact of climate change on the hydrological conditions in Norway and the other Nordic countries has been the topic for a large number of scientific publications.

The results from the publications mainly had the same conclusions regarding what changes that can be expected for hydrological conditions in the Nordic region in future years. Consequently, the valuation of the input variables for the Balmorel simulations made it clear that they give a good prediction for the future inflow, as they correspond with the existing literature on the subject.

There is a large amount of publications that investigate the climate change impact on the Nordic power market. The research questions asked in the publications investigated similar themes as this thesis, as future electricity price levels, production levels and export levels were studied in relation to climate change. However, the studies had a different approach than this thesis, as no literature that were found investigated the isolated effect of hydropower production in Norway and Sweden on the rest of the Nordic power market. This thesis also investigates a few European countries, and how the interaction is between the Nordic power market and northern Europe is likely to be in 2050.

Even though the existing literature has a different approach than this thesis, the diversity in studies, methods and assumptions give valuable contribution to the field of knowledge and gives a better picture of what can be expected in the future power market. As a result, they are useful in the process of interpreting the results from the Balmorel simulations which were carried out for this thesis.

4 Data

This chapter gives a description of the dataset that was used as a basis for the research done in this thesis. The dataset was received from the energy department of NVE, and used as input variables in Balmorel-simulations. The dataset contained predicted values for Norwegian energy inflow in the years 1961-2100, which was based on the two climate scenarios RCP4.5 and RCP8.5.

4.1 How the dataset was produced

This chapter gives an introduction to how the dataset was derived by NVE, by giving a review of the methods and models that were used in the process.

The first step of the data construction was done by Hanssen-Bauer et al. (2015) in the report "Climate in Norway 2100" ("Klima i Norge 2100"). The results from this report was then used as basis for "A weather-dependent power system – a changing climate" ("Et væravhengig kraftsystem – Et klima i endring") written by Beisland et al. (2015).

4.1.1 Climate in Norway 2100 (Hanssen-Bauer et al. (2015))

Based on climate scenario RCP4.5 and RCP8.5, Hanssen-Bauer et al. (2015) derived scenarios for atmospheric, hydrologic and oceanographic variables for Norway towards 2100.

The first set of data was allocated from the Coordinated Regional Climate Downscaling Experiment (CORDEX), which is an international cooperation project with the purpose of supplying climate studies with data. The datasets were originally obtained through simulations with Global Climate Models (GCMs), that gives output data with a gridded resolution of 100x100 km^2. There is a subproject called Euro-CORDEX, which downscales this data to a resolution of 12x12 km^2 through Regional Climate Models (RCMs). It was ten available outputs that had a resolution of 12x12 km^2 for RCP4.5 and RCP8.5, and these were applied in the report "Climate in

Norway 2100". Appendix "A1. Overview of the ten EURO-CORDEX combinations" gives an overview of the five GCM and four RCM combinations that were used to derive the datasets (Hanssen-Bauer et al. 2015).

In the process of downscaling to smaller grids, two separate methods were applied, Empirical Statistical Downscaling (ESD) and dynamical downscaling. The statistical method is based on empirical statistical models, and uses links between local weather variations and global climate patterns to predict local climate variations based on the GCM results. The temperature-variable were derived through the statistical method. The dynamical method, also called Regional Climate Modelling (RCM), was used to derive atmospheric and hydrological variables. An RCM has smaller grids than a GCM, but is constructed in the same way. The results from the GCM-simulations were used as input variables in the RCM. Since systematic errors often occur in the process of dynamical downscaling, the dataset was de-trended and bias-corrected to make the results comparable with observational data (Hanssen-Bauer et al. 2015).

De-trending the projected data series was done to ensure that the trend within the data series were preserved during bias-correction. The method used was the same as presented in "A trend-preserving bias-correction" by Hempel et al. (2013), where the daily precipitation values were divided by the mean value, and for temperature the mean value was subtracted. After the de-trending, the data series were bias-corrected. In this case, the bias correction also included a downscaling component, so an even finer grid resolution was obtained. Based on the simple nearest neighbour method, the data was re-gridded and downscaled from 12x12 km^2 to 1x1 km^2. Data from seNorge.no was used as observational data for the bias-correction. This website publishes high resolution datasets of temperature and precipitation for Norway dated back to 1960. The maps cover the whole country, have a gridded resolution of 1 km. The method used to bias-correct the simulated data, was Empirical Quantile Mapping (EQM). Quality control was then performed on the bias-corrected data series for temperature and precipitation. This was done to ensure that so-called "hot-spots" did not occur, which is either very high or low values that is unlikely to take place. I addition to all the methods mentioned above, wet-day correction was also carried out, because RCM-simulations often predicts too high levels of precipitation.

After being corrected and downscaled, the data was ready to be processed in a hydrological model (Wong et al. 2016).

Temperature and precipitation were used as input variables in the HBV-model, and the output was hydrological variables. Since one does not have observations of the hydrological behaviour of all catchments in Norway, calibration of the model was necessary to achieve output variables that was as close to observational values as possible. This was done by examining 121 different types of catchments, and looking at how the hydrological behaviour of each catchment was relative to the type of landscape and other hydrological factors. Then the hydrological behaviour was ascribed to the type of catchment that matched the profile. This way, one were able to model the whole country, even though there were only measurements for a few of the catchments. The calibration period was 1991-2000 (Wong et al. 2016).

30-year averages were used to present the variables, and they are smoothened with gauss-filters. The results in the report is presented for the periods 2031-2060 and 2071-2100. Due to uncertainty related to the model calculations, the data for each emission scenario is presented by median, low (10-percentile) and high (90-percentile) values (Hanssen-Bauer et al. 2015).

4.1.2 A weather-dependent power system – a changing climate (Beisland et al. (2015))

Based on the results form (Hanssen-Bauer et al. 2015), (Beisland et al. 2015) published the report "Et væravhengig kraftsystem – Et klima i endring". The report was based on collaboration between the energy department and hydrological department in NVE. The objective of the report was to investigate how the Norwegian power system will respond to climate change towards the end of the century. Data material from Hanssen-Bauer et al. was used as input for a power market model.

Due to lack of climate-corrected data from the other Nordic countries, it was the Norwegian hydropower system that was the focus of the report. Temperature and inflow were the two variables that presented climate change, and there were used four temperature series from Oslo, Bergen, Trondheim and Tromsø. The inflow values were corrected for inflow from glaciers, which will be most present towards the middle of the century. The reference period used was 1981-2010. The results presented in the report were based on the highest emission scenario, RCP8.5. The focus of the report was on three 30-year periods, 1981-2010, 2031-2060 and 2071-2100. To simulate the effects of climate change on the power market, EFI's Multi area Power-market Simulator (EMPS) was used to generate future market prices. Then these results were used as input for the EMPS that was calibrated for the study.

In the simulations, the state of the power market was described as a constant, equal to the state in year 2015. This applied to both the exchange, demand and production capacity. This means that the exchange capacity between the Norwegian areas and Sweden, Denmark and Netherlands were constant. No new transmission capacity was taken into consideration. As for the price levels, the trade with the other countries were represented by price levels from 2015. The demand levels were only set to change relative to the increasing air temperatures, and changes in infrastructure and other influencing factors were not taken into consideration. Production levels were set to be constant at 32 GW in total. The wind production was set to be 3 TWh, and the thermal production was also constant.

By having a constant power system, it was possible to investigate the isolated effect of climate change on the power system, in addition to evaluate if Norway has a power system that is built for future climate conditions. On the other side, however, the dynamics in the market were not well documented through this method. Due to the constant price profiles that represented power exchange with other countries, the price in wet years and dry years became artificially high and low respectively. In reality, the market dynamics and trade of power with the neighbouring countries have a large effect on the price level, and a regulating effect on price variations in dry and wet years.

4.2 How the dataset was allocated

NVE was contacted through email correspondence, and after several referrals, a dataset containing energy inflow was sent to me by Valentin Johannes Koestler. Even though only one climate scenario was focused on in Beisland, NVE had datasets for both RCP4.5 and RCP8.5. The data that was sent to me was based on the 82 inflow series that NVE uses in their HBV-models, which is from natural streams without anthropogenic influence. These series were distributed between power plants and magazines, before the EMPS allocated the water between the power plants, as described above.

The dataset from NVE represented two climate scenarios, RCP4.5 and RCP8.5. The data was presented in energy inflow in GWh, covered the period 1961-2100, divided after the five elspot regions in Norway, had a weekly resolution, and was divided between regulated and unregulated energy inflow.

4.3 The dataset

This chapter presents the data that was received from the energy department in NVE. Values for normal years are average values based on the period 2036-2065, and the wet and dry years are single years within this period. To illustrate how climate change is predicted to alter the inflow values, the inflow for the reference period 1981-2010 is also illustrated in this chapter. The wet, normal and dry years in the reference period was derived with the same method as for the period 2036-2065. The data presented in this chapter gives an indication of how the resource basis for Norwegian and Swedish hydropower is predicted to change towards 2050.

4.3.1 Dry and wet years

Figure 6 illustrates the annual energy inflow in TWh for all years in the period 2036-2065, based on simulations for the RCP4.5 scenario. The years that were chosen to represent the dry and wet year in the Balmorel-simulations, are coloured red and green respectively. The wet year is 2052, and the dry year is in 2062.

Figure 7 illustrates annual energy inflow in the period 2036-2065 based on climate scenario RCP8.5. Year 2036 is the year with the highest level of inflow at 270 TWh. All the other wet years in the 30-year period is approximately 200 TWh, and was therefore believed to be more realistic. Therefore, the year 2059 was chosen as the wet year to be represented in the Balmorel simulations. This is the year with the second highest inflow level after year 2036, and is close to the values of the other wet years in the 30-year period.

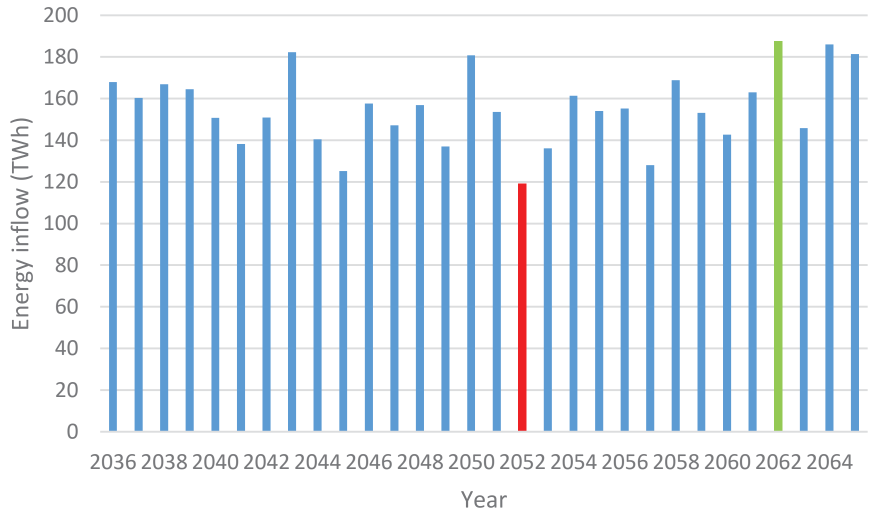

Figure 6: Annual energy inflow in Norway (TWh) for all years in the period 2036-2065, based on climate scenario RCP4.5. The dry year is red and the wet year is green.

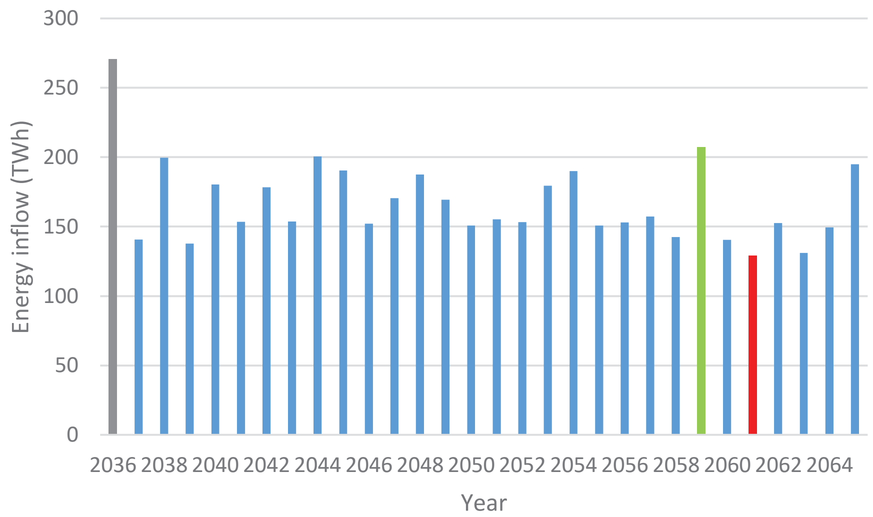

Figure 7: Annual energy inflow in Norway (TWh) for all years in the period 2036-2065, based on climate scenario RCP8.5. The dry year is red and the wet year is green.

4.3.2 Annual energy inflow for Norway

Figure 8 illustrates the annual energy inflow for a normal, dry and wet year. The figure compares historical energy inflow in the period 1981-2010 to the predicted energy inflow in 2036-2065 for both climate scenarios. For all three types of years (normal, dry and wet) RCP8.5 is predicted to lead to a higher level of energy inflow than for RCP4.5. For both climate scenarios in the normal and dry years, the energy inflow is predicted to increase.

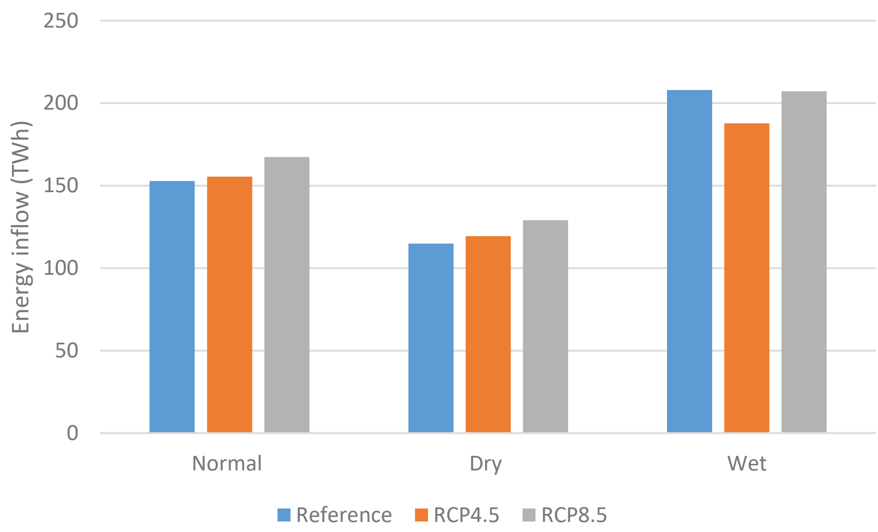

Figure 8: Annual energy inflow for Norway, for a normal, dry and wet year. Blue illustrates the inflow levels from the reference period 2036-2065. The two climate scenarios RCP4.5 and RCP8.5, orange and grey respectively, are based on predicted values for 2036-2035.

4.3.3 Annual energy inflow for elspot areas

The predicted energy inflow in the five Norwegian elspot areas are illustrated in Figure 9. For RCP4.5 the energy inflow is predicted to decrease in NO3 and NO4 relative to the reference period. The other areas are expected to experience an increase in inflow values. For RCP8.5 the annual energy inflow is predicted to increase in all areas, relative to the reference period. Elspot area NO1 is the area with the least interval between reference values and RCP8.5 scenarios, and area NO4 has the largest interval.

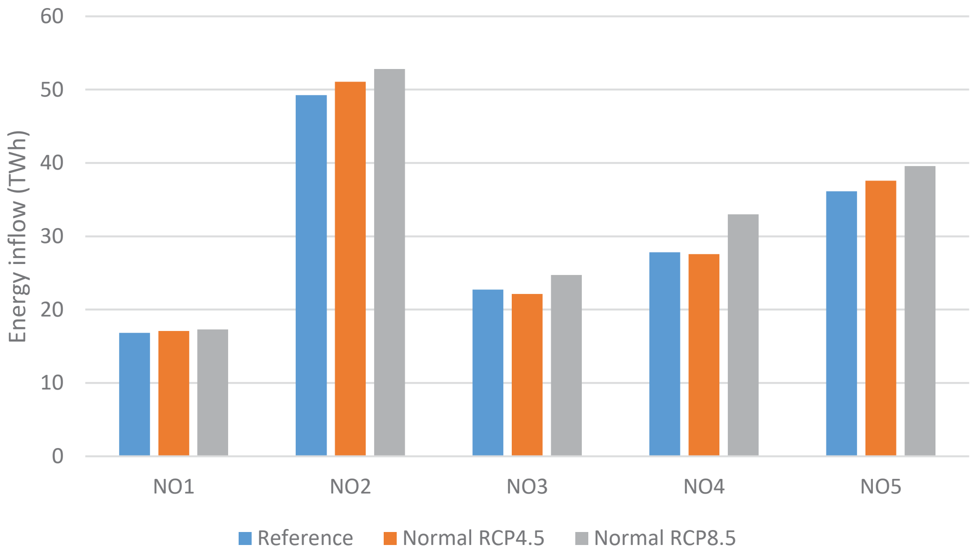

Figure 9: Comparison of predicted energy inflow in each of the Norwegian elspot areas

4.3.4 Seasonal energy inflow for Norway 2036-2065

The predicted seasonal energy inflow is illustrated in Figure 10 and Figure 11, representing climate scenario RCP4.5 and RCP8.5 respectively. It is evident from these figures that the seasonal changes in energy inflow are expected to be larger than the annual changes. Compared to RCP4.5, RCP8.5 is predicted to lead to larger variations between the seasons in addition to larger variations between the dry and wet years.

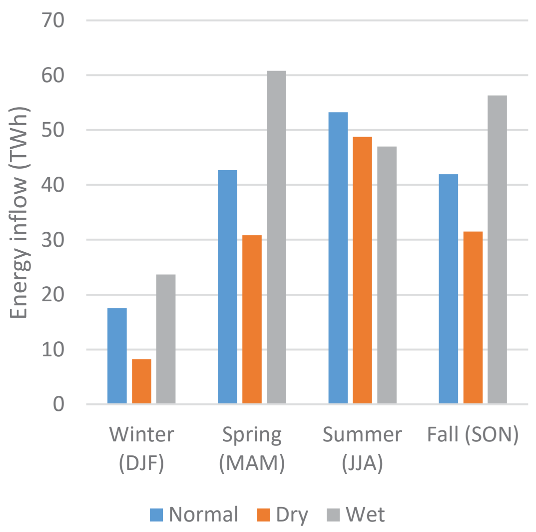

Figure 10: Seasonal energy inflow in Norway based on climate scenario RCP4.5. Blue represents a normal year, orange dry year and grey wet year

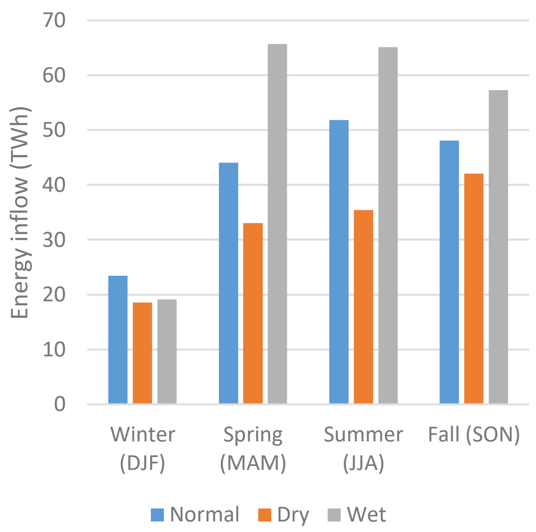

Figure 11: Seasonal energy inflow in Norway based on climate scenario RCP8.5. Blue represents a normal year, orange dry year and grey wet year.

4.3.5 Relative change in energy inflow between seasons

Figure 12 illustrates how much the regulated and unregulated energy inflow is predicted to change in percentage within 2036-2065 relative to the reference period 1981-2010. The figure illustrates the same tendency as presented in Hanssen-Bauer et al. (2015). Even though the annual energy inflow is not expected to change to a large extent, there is expected larger changes in between the seasons. Relative to the reference period 1981-2010, the winter, spring and fall is predicted to experience an increase in energy inflow, and the summer a decrease in energy inflow. For both climate scenarios, the winter is the season that will experience the largest percentage increase in energy inflow. In addition, this is also the season that has the largest percentage of difference between the two climate scenarios. For both climate scenarios, the summer inflow is expected to decrease, with RCP8.5 leading to the largest reduction. The regulated energy inflow is predicted to experience the largest change in all seasons.

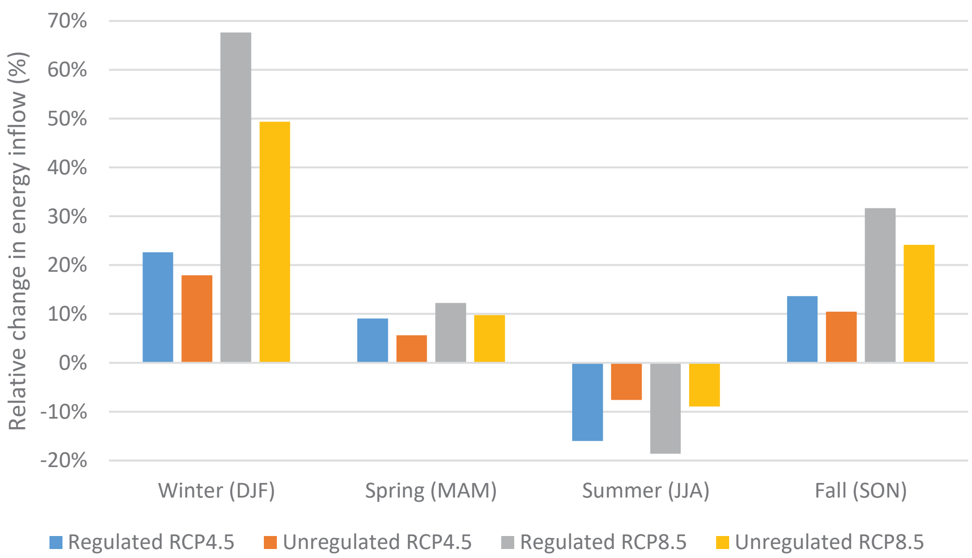

Figure 12: Seasonal change in energy inflow in 2036-2065 relative to 1981-2010. The figure compares the relative change in regulated and unregulated energy inflow for both climate scenarios. The regulated energy inflow is represented by blue and grey. Orange and yellow represents the unregulated energy inflow.

4.3.6 Weekly energy inflow for 2050 in a normal year

Figure 13 illustrates the average weekly energy inflow for a normal year, based on values from the reference period 2036-2065. The figure illustrates inflow for the reference, RCP4.5 and RCP8.5. Relative to the historical inflow values, it is evident that the inflow during the winter increase, that the spring flood comes earlier in addition to having a shorter duration, and the flood-period in fall becomes more evident. All these trends are stronger for RCP8.5 than for RCP4.5.

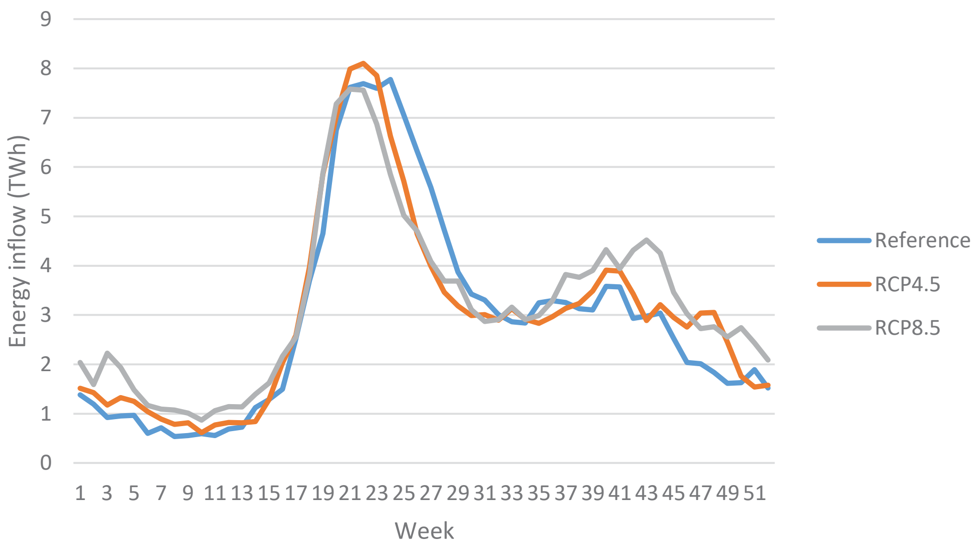

Figure 13: Weekly energy inflow for normal years. Blue illustrates historical inflow values from 1981-2010, orange represents climate scenario RCP4.5 and grey represents climate scenario RCP8.5.

5 Methodology

This section gives an introduction to the methodology used in this thesis, and describes how the dataset from NVE was processed to be used as input in Balmorel simulations. All preconditions that were made are explained here.

5.1 Data processing

The data was accessed from the energy department in NVE, and is the dataset behind the results of the report published by Beisland et al. (2015). The dataset had to be altered to make it suitable as input for Balmorel simulations, and this chapter gives a description of the process.

The equation below explains how the regulated and unregulated inflow were defined. (*Klimaendringer og vannkraft*)

Regulated inflow =
sum production
– unregulated inflow
– energy used for pumping
+ increase in sum magazine content
(or – reduction of magazine content)

Unregulated inflow =
production due to unregulated inflow to the power stations
+ production due to demand of minimum water flow and/or release of water
+ production necessary to avoid flooding
– energy used for pumping

The equation for regulated inflow show that it calculates for "energy used for pumping". This part is also represented in the Balmorel model, where the model calculates when it is necessary to pump water to the reservoirs. Since pumped hydro is considered in both models, it can lead to a situation where the pumped hydro is accounted for more than once, and thus give a misleading value for the total amount of hydropower energy produced. To avoid this situation, the value for regulated hydropower capacity in the dataset was corrected, so that it did not include the energy used for pumping. This was done by adding the value for pumped hydro energy to the value for regulated hydropower.

5.1.1 30-year averages

Due to the way water is allocated in the model, it occurs some negative inflow values in the dataset. It only occurs for regulated inflow, and mainly during the first 15 weeks of a year. During this time of the year, the content of the water magazines is reduced, which means that the amount of water going out is larger than amount of water coming into the reservoir, and thus results in a negative energy inflow parameter.

NVE gave advice to calculate the average value over a 30-year period when examining the energy inflow for a specific year. The reason for this was to remove the negative inflow values in addition to even out annual weather extremes and irregularities that might occur in the dataset. Thus, to investigate the predicted energy inflow in 2050, a 30-year average for 2036-2065 was made. As a result, the values for the year 2050 that is presented in this text, is 30-year averages and not values from that one specific year. When processing the data, the units were converted from GWh to TWh.

5.1.2 Seasons

To be able to present the energy inflow in regards to the four seasons, winter (DJF), spring (MAM), summer (JJA) and fall (SON), the 52 weeks were divided equally between the four seasons, so that each season in the dataset consist of 13 weeks. Since the winter season is in December and January, it goes over two successive calendar years. The week numbers for each season is as follows. The winter season consist of week 49-52 and 1-9, the spring is represented by week 10-22, summer is week 23-35 and fall is week 36-48.

5.1.3 Normal, dry and wet years

Dry and wet years are years with considerably less or more precipitation than in a normal year (Fladen et al. 2010). In the 30-year period 2036-2065 the years with the lowest and highest predicted energy inflow levels was chosen to represent a dry and wet year, respectively. The exception was for the wet year in climate scenario RCP8.5. Here, the year with the highest inflow level was unrealistically high, and did not correspond well with the other values in the 30-year period. As a result, the year with the second highest inflow value were chosen as the wet year, as it corresponded well with other inflow values in this period. In addition, the level of inflow this year was more in line with the inflow increase presented by Hanssen-Bauer et al. (2015) in chapter "3.1 Hydrology and climate change in Norway". The values for the normal year is an average value based on the 30-year period 2036-2065. For RCP4.5 the dry year is in 2052, and wet year 2062. For RCP8.5 the dry year is in 2061, and the wet in 2059.

5.2 Construction of inflow series for Sweden

Due to the lack of future inflow series for Sweden, the future hydropower production was constructed by combining Swedish inflow values from 2012 with predictions for Norway towards 2050. The only reference for inflow values in Sweden was to be found in a dataset from Balmorel containing 2012-values for the four Swedish elspot areas. This dataset was allocated from PhD Åsa Grytli Tveten.

5.2.1 Elspot areas

Sweden is divided into four elspot areas, SE_N1, SE_N2, SE_M and SE_S. Based on the assumption that the energy inflow in Sweden will be affected by climate change in a similar manner as Norway, each of the Swedish regions was linked to the elspot region in Norway with most similarities regarding geography and climate conditions. Each Swedish region was then assumed to experience the same percentage change for energy runoff within 2050 as the Norwegian region it was linked to. To be able to calculate the predicted inflow in Sweden for 2050, a percentage change between 2012 and 2050 was calculated for each of the Norwegian elspot areas. SE_N1 is located north in Sweden. This area has a mountain chain, and the characteristics of this area is similar to the Norwegian elspot area NO4. SE_N2 is located in the middle of Sweden, and has similar characteristics to NO3. SE_M and SE_S is located further south in Sweden, and have a more low-lying geographic profile (MES 2014). Therefore, SE_M and SE_S was set similar to NO1 and NO2 respectively. Based on these assumptions, a dataset was constructed for the predicted inflow in the Swedish elspot areas for 2050. Table 3 gives an overview of the elspot areas that were connected.

Table 3: Overview of which Swedish and Norwegian elspot areas that are connected

Swedish elspot area	Norwegian elspot area
SE_N1 (SE1)	NO4
SE_N2 (SE2)	NO3
SE_M (SE3)	NO1
SE_S (SE4)	NO2

5.2.2 Percentage change for Sweden

To calculate the percentage change between 2012 and 2050, two 30-year periods were constructed to make average values for the two years. To represent 2012, a 30-year average was made based on the years 1998-2027. Values for 2050 were constructed based on 2036-2065.

The 30-year average for 2050 was then compared to the average for 2012, to derive the percentage change in energy inflow between these years. The percentage values for change in energy inflow between the two 30-year periods was found for the five elspot areas in Norway, all 52 weeks and for each of the two climate scenarios.

The percentage values for the different elspot areas was then paired with their matching Swedish elspot areas. After this, the percentage values were multiplied with the Swedish 2012-values for inflow that was presented in an excel sheet with output values from Balmorel.

5.3 Choosing a reference year

To calibrate the Balmorel model, the energy inflow profile for one reference year was used. The reference year was chosen based on a combination of qualitative and quantitative method. First, a selection of normal years in the 30-year period 1981-2010 was done. Then, a visual comparison of the normal years was done, by comparing the weekly energy inflow throughout the year. The year that had a profile which was most similar to the average profile of the 30-year period was chosen as the reference year. The year 1993 was chosen as the year with the most similar profile to the 30-year average. To validate the visual selection, the variance between the normal years and the average value for the 30-year period was calculated. An overview of the variance numbers showed that the year 1984 had the lowest variance, and 1993 had the second lowest variance. Since the year 1993 is closer to today it was considered more suitable for representing the reference year. Based on these criterias, 1993 was chosen as the reference year to calibrate the model.

The energy inflow for 1993 was scaled down to the production level of an average normal year in the 30-year period 1981-2010, which is 127 TWh. This was then used to increase the production levels in 2050 proportionally in relation to the increase in production capacity that was assumed to be installed within 2050.

5.4 Balmorel

After the values for energy inflow was processed, they were used as input variables in the Balmorel model. This subchapter gives an introduction to the model, in addition to describing the preparations that were done prior to the simulations.

The Balmorel model is a partial equilibrium model that simulates the equilibrium between supply and demand in the energy sector. It focuses on the interaction between heat and power, which makes it possible to also study combined heat and power (CHP) in detail. The model can be run for both long and short time periods. The coding is in GAMS-language, and the model was originally developed by the Danish Technical University (DTU) (*Introduction to Balmorel*).

5.4.1 Preconditions for the Nordic power market

The version of Balmorel that was used in relation to this thesis, simulates the Nordic power market in 2050. The system was set exogenously. This means that the production capacities for 2050 were decided before the model was run, and were set as constants. These preconditions were based on results from the report "Nordic Energy Technology Perspectives 2016" IEA (2016), and Bøhnsdalen et al. (2016). In the Balmorel simulations, climate change was described through the different inflow scenarios, as described in chapter"4 Data".

Based on the report from Bøhnsdalen et al. (2016) there were made preconditions regarding the demand in 2050. The demand levels in the Nordic countries are expected to increase by 60 TWh towards 2040, mainly due to electrification of the transport sector and expanding industry. Norway is predicted to experience a total increase of 15 TWh due to the same reasons. Some factors that reduce the increasing trend is increased energy efficiency, stricter building regulations and rising atmospheric temperatures. The latter one is expected to reduce Norwegian demand by 2 TWh within 2040. The overall demand is expected to increase in both Norway and the Nordic power market (Bøhnsdalen et al. 2016).

For the Balmorel simulations it was assumed that Norway will have a demand of 150 TWh in a normal year, and it was added +/- 3.75 TWh for a dry and wet year respectively. This is based on the assumption that it is usually warmer in wet years, and colder in dry years. For the Nordic countries, the total demand was set to 440 TWh. The preconditions regarding demand in a normal year is listed in Table 4, and the units are given in TWh.

Table 4: Precondition for demand levels in 2050 (TWh)

	DENMARK	FINLAND	GERMANY	GREAT BRITAIN	HOLLAND	NORWAY	SWEDEN
Reference	47.2	90.2	545.8	330.3	108.0	150.0	152.6

There is predicted a comprehensive system transformation of the Nordic power market towards 2050. Some of the reasons for this is the increase of CO_2 price from 2020, and the phasing out of nuclear in Sweden and Finland. The nuclear power supply from Sweden and Finland makes up 25 % of the Nordic power production today, but within 2040 it is predicted a cutback by 30 % of the nuclear production capacity. This number is not certain, as there are split political opinions regarding the subject. Despite the uncertainty, some predictions have been made regarding the predicted supply towards 2050. Sweden plans to phase out all their nuclear reactors within 2046, whereas Finland are currently building new capacity. After the last Finnish reactor is expected to be finished within 2025, the supply decreases, but nuclear power will still be in the market for many years after this, as the life expectancy of a nuclear power plant is 50 to 60 years (Bøhnsdalen et al. 2016).

With the nuclear production capacity in Sweden being phased out by 2046, the need of power supply from other sources will increase. It is predicted an increase of 70 TWh renewable capacity within 2040. Also, it is predicted that rehabilitation and expansion of existing hydropower plants and new small-scale hydro power in Norway will increase the supply. Large investments in new wind capacity play a significant role in all countries (Bøhnsdalen et al. 2016).

The results presented by Bøhnsdalen et al. (2016) correspond with IEA (2016), which also emphasize the importance of the future for nuclear power production in the Nordic power market. Here, it is also predicted that VRE, especially wind and solar, will replace nuclear production capacity towards 2050.

In the Balmorel simulations the preconditions for infrastructure and production capacity were based on the report “*Nordic energy technology perspectives”*. Nuclear production capacity in Sweden is assumed to be zero within 2050, and in Finland a production capacity of 2800 MW is assumed. It is assumed that within 2050 it is invested in 1.7 GW new regulated hydropower capacity.

The interconnectors between the Nordic countries, Europe and UK are assumed to be expanded in the future. The planned investments in transmission capacities are illustrated in Figure 7. The largest increase in transmission capacity from the Nordic countries to Europe is expected to take place between 2030 and 2040.

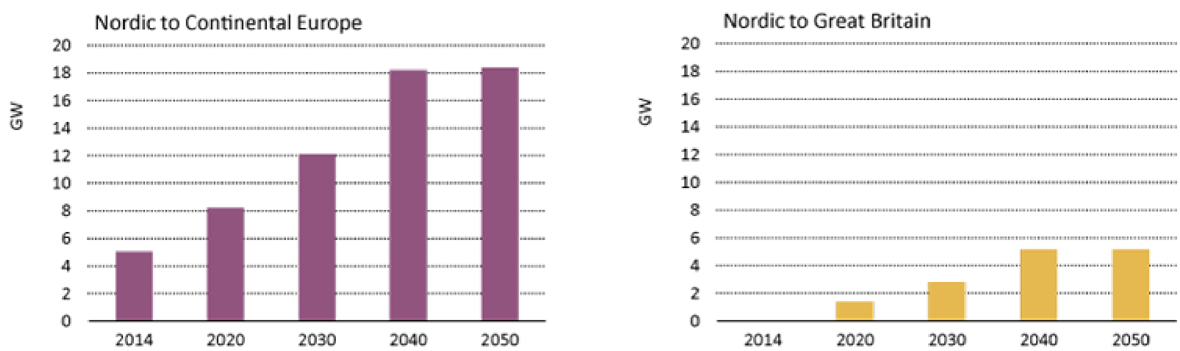

Figure 14: Planned investments in transmission capacity towards 2050. Left side illustrates the planned increase in transmission capacity from the Nordic countries to Europe, and the right side illustrates increased capacity from the Nordic countries to Great Britain (IEA 2016).

The price level of CO_2 is expected to increase from 2020. In the simulations it was assumed a CO_2-price of 150 USD/ton in 2050 (IEA 2016).

5.4.2 Processing the simulation results

The results were presented with both hourly, weekly and annual resolution. The distribution was both for the whole country and elspot areas. The model runs calculated hourly values for every fifth hour, and thus made up a total of 1768 hours per year. When summing up the annual total production, the sum hence had to be scaled to get the correct annual sum.

In some single hours, the price levels were very high due to modeling errors. This was corrected by setting an upper limit of 150 EUR/MWh for the price levels, and by this assuming that these hours were covered by a peak technology with a marginal cost of 150 EUR/MWh.

The results contained simulations for RCP4.5 and RCP8.5 for a normal, wet and dry year. In addition, a reference scenario, based on the inflow values for 1993 was presented.

6 Results and discussion

This chapter presents the results from the Balmorel simulations, and highlights the most important findings. Also, the results are discussed and compared to existing literature.

To clarify the impact of climate change on the Nordic power market, a reference scenario is used. The reference scenario is based on inflow series for the year 1993, since this year had an inflow pattern close to the average inflow for the period 1981-2010. The reference scenario represents a situation with no climate change, but the preconditions regarding the energy market are the same as for the scenarios with climate change. The normal, wet and dry years for RCP4.5 and RCP8.5 are compared to the reference year to illustrate how the climate change impacts the dynamics of the Nordic power market.

6.1 Hydropower in Norway and Sweden

Table 5 shows how the hydropower production in Norway and Sweden is altered relative to the reference scenario in TWh. The main trend is that RCP8.5 leads to a larger increase in hydropower production than RCP4.5. The wet years will experience the largest increase in hydropower production, with the largest increase for RCP8.5. In the dry years, the production is reduced for both countries, but it varies which climate scenario that leads to the largest reduction. All the dry years will experience a reduction in production levels relative to the reference scenario.

Table 5: Electricity generation from hydropower production in 2050 in the reference scenario and changes compared to the reference scenario in the different climate scenarios (TWh).

		Norway			**Sweden**		
		Run-of-river	Reservoir-hydro	Total	Run-of-river	Reservoir-hydro	Total
	Reference	**41.1**	**97.3**	**138.4**	**17.0**	**52.3**	**69.3**
RCP4.5	Normal	1.2	5.2	6.4	-0.2	-2.3	-2.5
	Dry	-9.2	-17.8	-27.0	-4.2	-11.6	-15.8
	Wet	14.8	22.2	37.0	5.4	10.5	15.9
RCP8.5	Normal	4.4	13.3	17.7	1.4	4.7	6.1
	Dry	-11.3	-7.3	-18.6	-5.7	-11.0	-16.7
	Wet	19.8	33.7	53.5	7.4	16.8	24.2

In addition to the increased inflow levels, the increased production capacity of 1.7 GW also leads to increased production levels. The inflow levels are predicted to be more even throughout the year. One example is more rain during the winter, which increase the production levels during the winter months (Roald et al. 2006). This way, the water resources can be utilized more efficiently, and leads to even further increase in production levels. This corresponds to Beisland et al. (2015), which states that the alterations in energy inflow results in a higher utilization of the existing production system. Consequently, the increase in production levels are both due to climate change and increased production capacity.

Among the authors that were presented in chapter ”Previous studies”, it seems to be a general consensus that Norway and the northern part of Europe will experience an increase in hydropower production as a result of climate change. The results of this thesis correlate with the literature to a certain extent, as the normal and wet years shows sign of an increase in production levels for both the normal and wet years. The exception is for Sweden for climate scenario RCP4.5 in a normal year, which shows a reduction in production levels in 2050. One explanation for this can be the way the Norwegian and Swedish elspot areas were connected, as explained in chapter “5.2.1 Elspot areas”. Another explanation can be the strength of the climate signals. According to Hanssen-Bauer et al. (2015), the climate signal will in the next 20 years not be strong enough to overrule weather conditions that take place independently of climate change. If the period around 2050 is modelled to be a dry period, with less precipitation than normal, this can have consequences for the results. Also, RCP4.5 is one of the lower emission scenarios, and thus, leads to less changes in climatic conditions than RCP8.5.

Even though the energy inflow is mostly expected to lead to an increase in production levels, the flood losses are also predicted to increase (Lind et al. 2013). Beisland et al. (2017), state that this is because the existing hydropower plants are dimensioned for historical values for energy inflow, which explains why the increased energy inflow results in both increased production values and increased production losses. The areas that experience the largest percentage increase in energy inflow will also experience the largest increase in flood loss. If there is not performed any sort of upgrade in the hydropower plants, Statnett (2012) implies that the production losses in 2050 might increase to 6 TWh in a wet year.

The increase in flood losses can be avoided by upgrading the storage and production capacity of the existing hydropower plants. This thesis is based on the assumption that there will be an upgrade in hydropower production capacity by 1.7 GW. How much upgrade that actually will take place in the future years depends, however, on aspects like politics and the electric price outlook for the next years.

Lind et al. (2013) state that uncertainties related to expectancies for future el-prices result in uncertainty related to the upgrade of hydropower capacity. Bøhnsdalen et al. (2016), however, imply that it will likely be profitable to upgrade existing hydropower capacity with pumping stations and expanding storage capacity for dams. If this is the case, the hydropower producers will be able to store more water and alter the production pattern to the market situation to a larger extent. This will help the producers to even out price levels in periods with high price volatility. If it turns out that the storage and production capacity is not expanded, however, Raje and Mujumdar (2010) suggests an alteration of reservoir rules as a solution to cope with changed inflow patterns. The way the hydropower producers use the reservoirs might change regardless of an upgrade or change in rules as well, and Beisland et al. (2015) state that the inter-annual storage will increase, and storage between seasons will decrease as a result of the altered inflow patterns.

Price expectations are not the only determinant for investments in dam and production capacity. Also, the security related to dams and production plants are important factors. In NVEs climate adaption strategy, investments in dam and production capacity are mentioned as an instrument for dealing with the expected increase of inflow in Norway. The strain on the dams will increase as a result of the increased inflow levels, and the planning of dams and their security is adapted every 15 years. As a result of this, the capacity might be expanded as a part of security and flood-preventing measures regardless of the expected price levels (Grønsten et al. 2015).

Another aspect that impacts the storage and production pattern throughout the year is environmental constraints. The demand for minimum water flow, and minimum levels of reservoir levels puts constraints on the flexibility of hydropower production, and reduces the production capacity. It is uncertain if the environmental constraints will change towards 2050, and this is an element that will impact the amount of flood loss and production levels in the future. (Havskjold et al. 2002)

Beisland et al. (2015) mention that it is not only the limited production and storage capacity that leads to flood loss. It is also caused by limitations in the transmission grid, which is especially present in Western Norway. If the transmission capacity in the grid is improved, this can also help prevent flood loss.

6.2 Generation

This section presents the annual generation levels for all countries and technologies, based on assumed installed capacities from NETP. Table 6 presents annual production levels in TWh in 2050, and is based on the reference scenario. The table gives a good overview of what technologies that play a central role in the supply side in each country, and the production mix in the power market for 2050. In all countries except Finland, the wind-power make up a large proportion of the electricity production. Electricity production from thermal technologies as gas and other condensing power (which includes bio energy for instance), are significant in Germany, Great Britain and Holland. Germany is the country with the largest production from CHP. Both Finland and Great Britain still has electricity production from nuclear.

Table 6: Generation levels for the reference scenario in 2050 for all technologies and countries (TWh).

	DENMARK	FINLAND	GERMANY	GREAT BRITAIN	HOLLAND	NORWAY	SWEDEN
Run-of-river	0	4.2	19.2	0	0.1	41.1	17.0
Reservoir-hydro	0	9.0	0.4	0	0	97.3	52.3
Wind-power	33.5	7.5	191.0	195.3	48.6	34.0	54.9
Solar-power	0.8	0	63.1	18.7	1.8	0	0.1
Nuclear	0	21.0	0	62.3	0	0	0
Natural-gas	0	0	73.6	17.9	14.8	0	0
Cond-other	0	0.7	71.9	65.2	26.4	0	0
CHP	20.4	21.9	131.4	0	0	3.9	23.4
Total	**54.8**	**64.2**	**550.5**	**359.4**	**91.7**	**176.3**	**147.7**

To illustrate how alterations in hydropower production affects generation levels of the other technologies in the market, the normal years for RCP4.5 and RCP8.5 are used as examples (Figure 15).

For scenario RCP4.5, the hydropower production in Norway increase by a total of 6.4 TWh. The hydropower production in Sweden decrease by a total of 2.5 TWh in the same scenario. Figure 15 illustrates how the production levels in this scenario deviate from the reference scenario. The technologies that are affected the most by the changes in hydropower production are gas and CHP. The electricity generation from CHP is reduced in all countries, while the generation from gas is reduced in Germany and Holland, but increase in Great Britain.

For scenario RCP8.5, the hydropower production has increased to a larger extent than for RCP4.5. The hydropower production in Norway has increased by 17.7 TWh relative to the reference scenario. The variations in production levels relative to the reference scenario are illustrated in Figure 16. For all countries, the gas and CHP production are reduced even more than in scenario RCP4.5. The electricity generation from gas in Germany is reduced by 16.9 TWh, and generation from CHP reduced by 10 TWh. So, as a result of an increase in hydropower production from Norway and Sweden by a total of 23.8 TWh, the total electricity generation from thermal capacity in Germany is reduced by as much as 26 TWh. The reason why gas and CHP are the technologies that are phased out, is that they have higher short term marginal cost than nuclear and VRE (Wangensteen 2012). Thus, when there are high levels of hydropower production and the electricity price is reduced, it becomes unprofitable for the gas-and CHP producers to keep running their production plants.

The production levels from wind-power and run-of river hydro varies slightly between the reference and the RCP8.5 scenario. This is not a result of varying price levels, but rather variations in meteorological conditions between dry and wet years. The electricity production from nuclear only has minor variations between the different climate scenarios. Electricity production from solar is constant for all countries in all scenarios. It is not likely that the solar production remains constant between years, but this is not the technology that was in focus for this thesis.

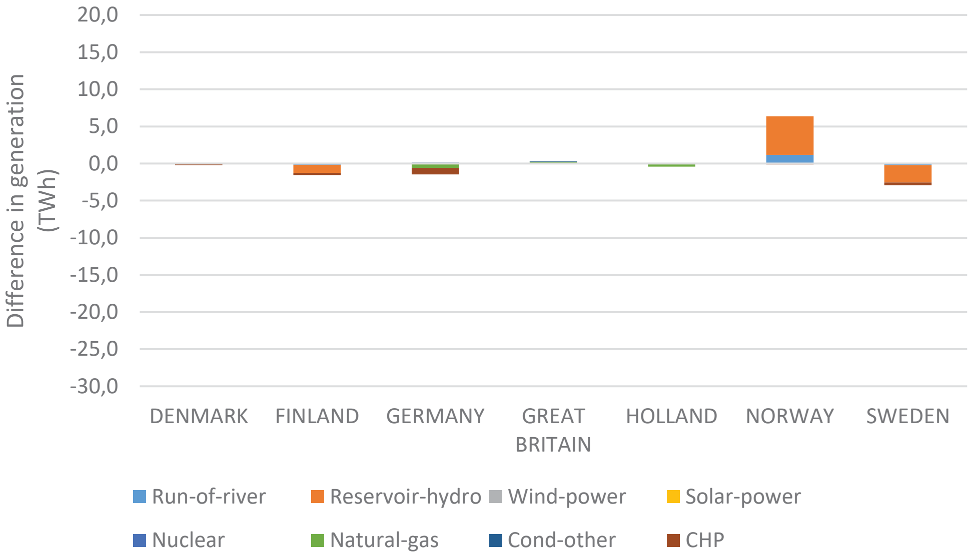

Figure 15: Production levels in 2050 for scenario RCP4.5 normal year relative to the reference scenario.

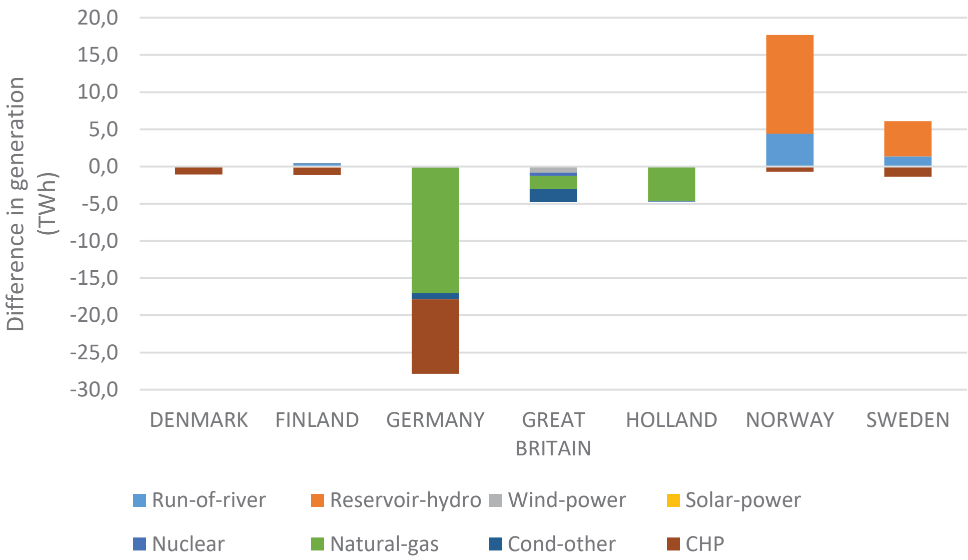

Figure 16: Production levels in 2050 for scenario RCP8.5 normal year relative to the reference scenario

In the preconditions for the Balmorel-simulation, it was assumed that Sweden had phased out all nuclear capacity within 2050, and Finland had a nuclear production capacity of 2800 MW. The future of nuclear has a significant influence on the market considering price and investments, and at what speed Sweden and Finland decides to phase out their nuclear capacities will have a significant effect on the Nordic power market. It is predicted that the phase-out of nuclear production capacity in Sweden and Finland will result in increased investments in VRE capacity. If a different outcome for the nuclear capacity in Sweden and Finland takes place, the investments regarding VRE and other technologies will vary from the preconditions that are made for this thesis. (IEA 2016)

6.3 Price

This section presents the simulated price levels for 2050, and how they deviate from the reference price level. The annual average price levels for the reference scenario is presented in Table 7, and the units are presented in in EUR/MWh. The simulated price levels are considerably higher than they are today, and an explanation for this can be the high CO_2 price that is assumed for 2050. If the price development towards 2050 does not turn out to be as steep as assumed in chapter "5.4.1 Preconditions for the Nordic power market", the price for electricity would be lower as well.

Great Britain stands out compared to the other countries, with an annual average price level that is 25-30 EUR/MWh lower than the remaining countries. This indicates that the preconditions regarding the extensive development of wind capacity towards 2050 is questionable, or that the transmission capacity with other countries are underestimated.

Table 7: Annual average price levels in 2050 for the reference scenario (EUR/MWh)

	DENMARK	FINLAND	GERMANY	GREAT BRITAIN	HOLLAND	NORWAY	SWEDEN
Reference price (EUR/MWh)	85.9	90.0	87.2	61.4	86.3	89.6	90.3

The increase of CO_2-prices is expected to be the main driver for the increase in electricity price levels in the European and Nordic power market. It also results in increased costs for coal, crude oil and natural gas (IEA 2016). Furthermore, if the nuclear power capacity is shut down at a large scale, this leads to an increase in price levels (Bøhnsdalen et al. 2016). If the price levels of CO_2 in 2050 turns out to be lower than 150 USD/ton, the electricity price levels will consequently be lower than the prices presented in Table 7.

In addition to increase the price levels, the alterations in CO_2-prices will also be the driving force behind an expected energy system transformation. Today, the marginal production cost of coal is price setting in the Nordic power market large amounts of the day, and coal makes up a large proportion of the production capacity in the market (IEA 2016). From 2020-however, the coal and lignite power plants are expected to be shut down as a result of the increased CO2-price. This will lead to a situation where gas becomes the price-setting technology if the nuclear, coal and lignite power plants are shut down. (Bøhnsdalen et al. 2016)

How the price levels differ between the climate scenarios are illustrated in Figure 17, where the deviation between the reference price and the price in the different climate scenarios are illustrated. There are minor deviations in the price levels between the normal years and the reference scenario. In the wet year, however, all countries experience a reduction in electricity price. For both climate scenarios, the reduction is largest in Finland, followed by Norway, Sweden and Denmark. In the dry years, all countries experience an increase in price levels. The countries that experience the largest increase are the same countries that experience the largest price reductions in the wet years. The scenario that results in the largest deviations in price levels are the wet year for RCP8.5, where Finland experience a price reduction of almost 35 EUR/MWh. The price levels in RCP8.5 are generally predicted to be lower than in RCP4.5, for both normal, wet and dry years.

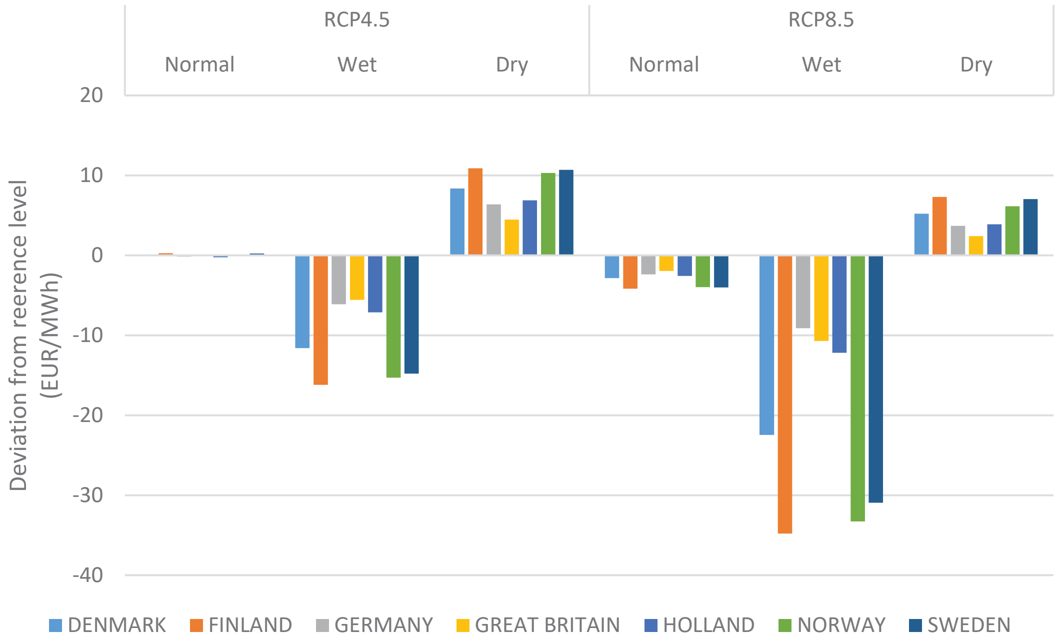

Figure 17: Deviations in price levels for all countries and all climate scenarios in 2050 relative to the price level in the reference scenario (EUR/MWh).

To which extent the price levels vary between the normal, wet and dry years depend on the transmission capacity and production mix in each country. Denmark, Finland, Holland, Norway and Sweden, all have noticeable price variations that correspond well with the different levels of hydropower production in Norway and Sweden. The more hydropower that is produced during a year, the lower the electricity prices are. The same trend is evident in Germany and Great Britain, however, these two countries have less price variations between the normal, wet and dry years. This can be explained by transmission capacity and production mix in the two countries. Both Great Britain and Germany are considered to be thermal countries, which means that large amounts of electricity production originate from thermal production capacity. In addition, they have large amounts of wind and solar, where the production levels are unaffected by variations in price. In addition, the transmission capacity between these countries and Norway is limited, which leads to constraints on how much the hydropower production in Norway and Sweden can affect the price.

Lise et al. (2008) state that Norway and Sweden will be affected the most by dry weather conditions, and Finland and Denmark to a certain extent. This statement corresponds to the results of this thesis to a certain extent. For both climate scenarios, Norway, Sweden and Finland are the three countries that have the largest price variations between a dry and wet year. But in contrast to the findings in Lise et al., Finland has the largest price variation between the wet and dry year scenario, which is most evident for RCP8.5. An explanation for this can be the phasing out of Nuclear capacity in Sweden and Finland towards 2050. As the Nuclear has an important role when it comes to regulating the seasonal balance between supply and demand, this regulating effect disappears when the nuclear production is phased out. It is expected that VRE will replace most of the nuclear (IEA 2016). As a result, Finland and Sweden are likely to become more prone to fluctuating price levels, unless large amounts of storage and transmission capacity are installed.

6.4 Price duration curves

Figure 18 presents price duration curves for three countries; Norway, Sweden and Germany. Sweden and Norway have high shares of hydropower production, whereas Germany is a country with large shares of thermal capacity. This chapter compares the price duration curves between the countries, and studies what impact varying hydropower production has on the hourly price levels.

For both Norway and Sweden, the distinction between price levels between normal, wet and dry years are clear. For these two countries, the price level for the wet year in scenario RCP8.5 stands out as significantly lower than the wet year in RCP4.5. In contrast, for Germany, the price levels between the different types of years does not differ as much as for Norway and Sweden, which be a result of restrictions on the transmission capacity between the countries.

In the case of high shares of VRE, the prices levels become very low in situations with a lot of wind (IEA 2016). Even though high levels of wind capacity are assumed, the results show very few hours where the price level is close to zero. This can be explained with the regulated hydropower capacity, that can be ramped up and down depending on production levels from VRE. This indicates that the Balmorel model assumes a highly flexible hydropower system, that might have a larger ability to regulate price levels than in reality. Another explanation can be based on predictions of more even inflow levels throughout the year, which gives the hydropower producers more flexibility regarding storage and production. This corresponds with the statement from Beisland et al. (2015), that the magazines will be used less for seasonal storage, and more interannual storage will take place as a result of the more even inflow patterns.

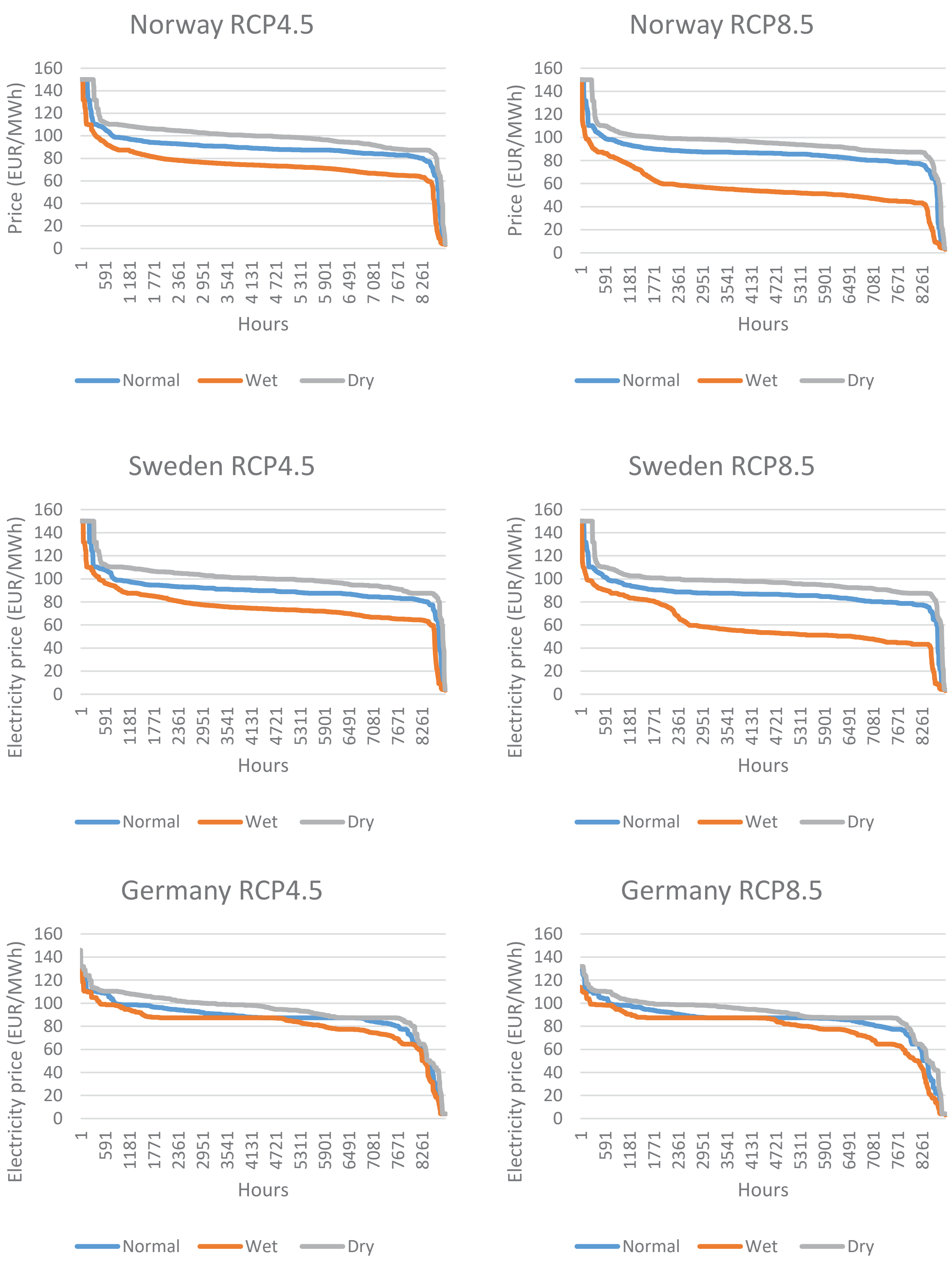

Figure 18: Price duration curves (EUR/MWh) for Norway (top), Sweden (middle) and Germany (bottom), for climate scenario RCP4.5 (left) and RCP8.5 (right). Norway and Sweden has larger price variations between the normal, wet and dry years than Germany.

Figure 19 compares the price duration curves for Denmark, Finland, Norway and Sweden in a normal year for climate scenario RCP4.5. This is the four countries that will experience the largest fluctations in price levels between the climate scenarios. The price variations between the four countries are not large. The reason for this is the well-developed transmission capacity between the countries, as the figure show almost no sign of bottlenecs in the transmission system. Denmark has some hours with lower electricity prices, and this can be explained by the large amount of wind power.

For the scenario with the highest level of hydropower production, RCP8.5 wet year, the bottlenecks in the system become more evident. In Figure 20 the price levles between the countries differ to a larger extent than in the RCP4.5 scenario in a normal year. Denmark and Finland have more hours with high electric prices than Norway and Sweden.

IEA (2016) illustrates price duration curves between the same countries in 2030. In this year, there are more hours with price differences between the Nordic countries than Figure 19 and Figure 20 illustrates. As explained in chapter "5.4.1 Preconditions for the Nordic power market", the largest investments in transmission capacity are expected to take place between 2030 and 2040. The increased interconnector capacity between the Nordic countries, Europe and UK will lead to more trade between countries and will have a smoothing effect on the electricity price (IEA 2016). Since the price duration curves for 2050 illustrates less price differences than for 2030, this demonstrates that if the future investments in transmission capacity turns out to be as assumed in this thesis, the price differences between the countries will be reduced.

The assumptions regarding the investments in transmission capacities are not certain, and if the investments turn out to be less than predicted, the price variations between the Nordic countries will increase relative to what the results indicate. On the other hand, if the investments in transmission capacity turns out to be more comprehensive than expected, the price variations will be further reduced, and the wet year in scenario RCP8.5 might not lead to price variations between the Nordic countries after all.

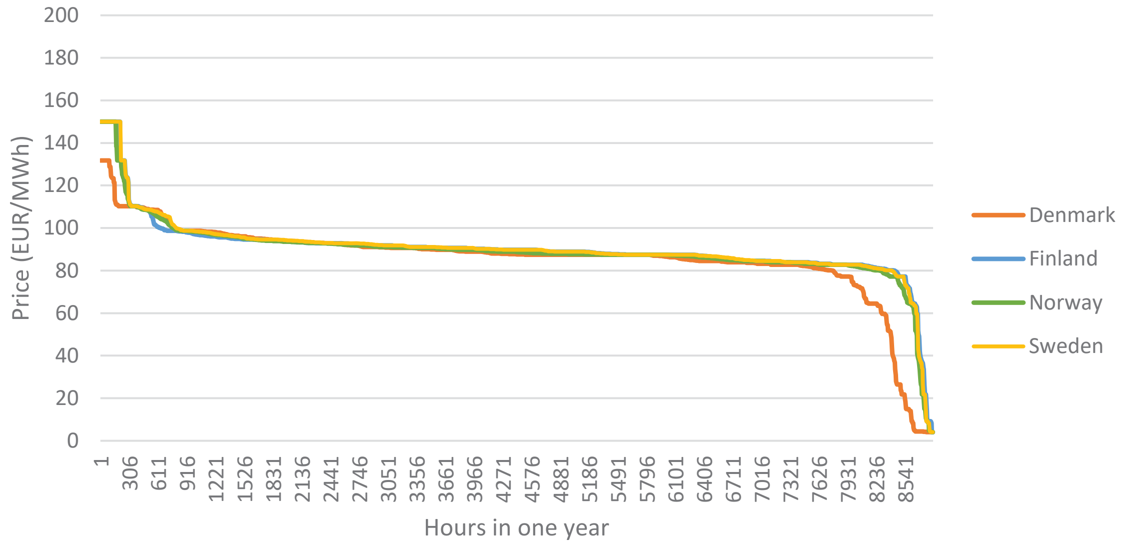

Figure 19: Price duration curves (EUR/MWh) for Denmark (orange), Finland (blue), Norway (green) and Sweden (yellow) in 2050, for a normal year in climate scenario RCP4.5.

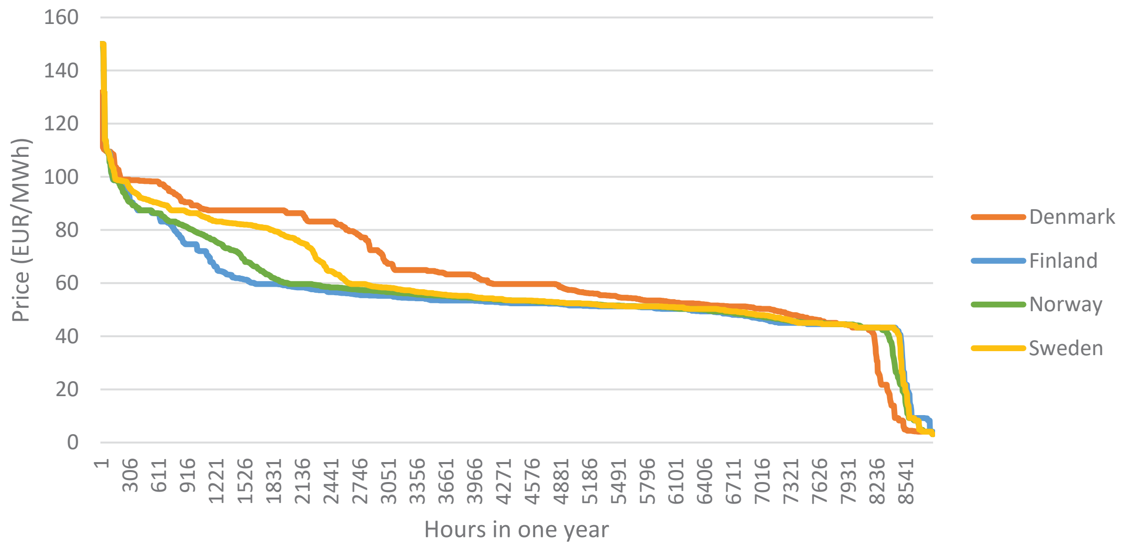

Figure 20: Price duration curves (EUR/MWh) for Denmark (orange), Finland (blue), Norway (green) and Sweden (yellow) in 2050, for a wet year in climate scenario RCP8.5.

6.5 Import and export

Figure 21 shows modelled annual import and export in TWh for all countries in 2050, for the reference scenario. Finland has almost no export compared to the proportion of import, and with Great Britain it is the other way around. If this is a realistic outcome, depends on the investments in transmission capacity towards 2050 and if production capacities turn out to be different than in the assumptions. If the production capacity in Great Britain becomes less than assumed, the export levels will decrease and import levels increase.

Norway is the country that has the largest amount of both export and import, where the export makes up the largest amount. This implies that the level of hydropower production in Norway will have significant repercussions to other countries, and operates as a green battery for other Nordic and European countries. Alterations in production levels will not only be noticed in Norway, but also in the countries that import large amounts of electricity from Norway.

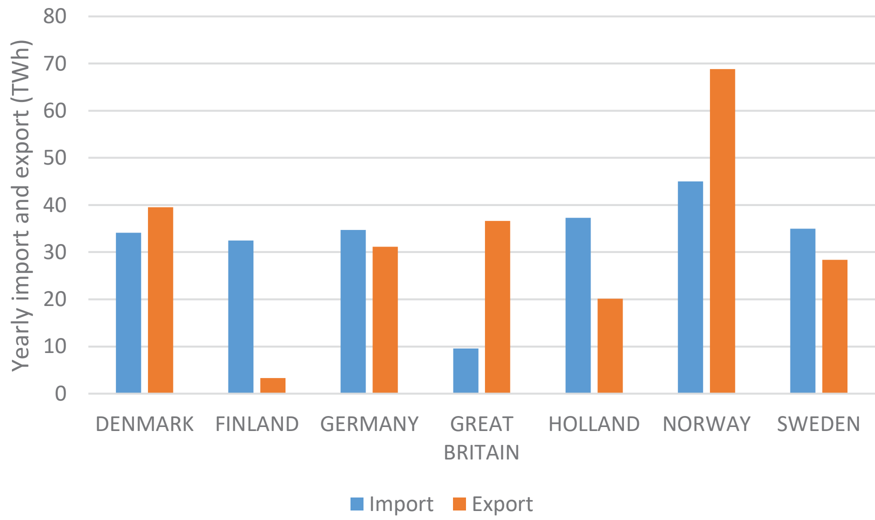

Figure 21: Total levels of import and export (TWh) for each country in 2050 for the reference scenario.

Which countries that interact the most with one another is illustrated in Figure 22. The figure illustrates the reference scenario in 2050. From the right side of the figure, which illustrates the import in percentage, it is evident that Norway imports the largest amount of electricity from Great Britain. Also, Great Britain imports the largest amount of electricity from Norway. Finland imports from both Norway and Sweden, but exports only to Sweden. As illustrated in Figure 1, Finland has interconnector capacity to Estonia and Russia as well, but this is not taken into consideration in the Balmorel simulations. Denmark's main exchange partners are Germany, Norway and Great Britain. This is relevant for the discussion regarding price levels in Germany. Even though it is not directly clear that Norway exports large amounts of power to Germany, some of the electricity might go through Denmark (or Holland) before reaching Germany.

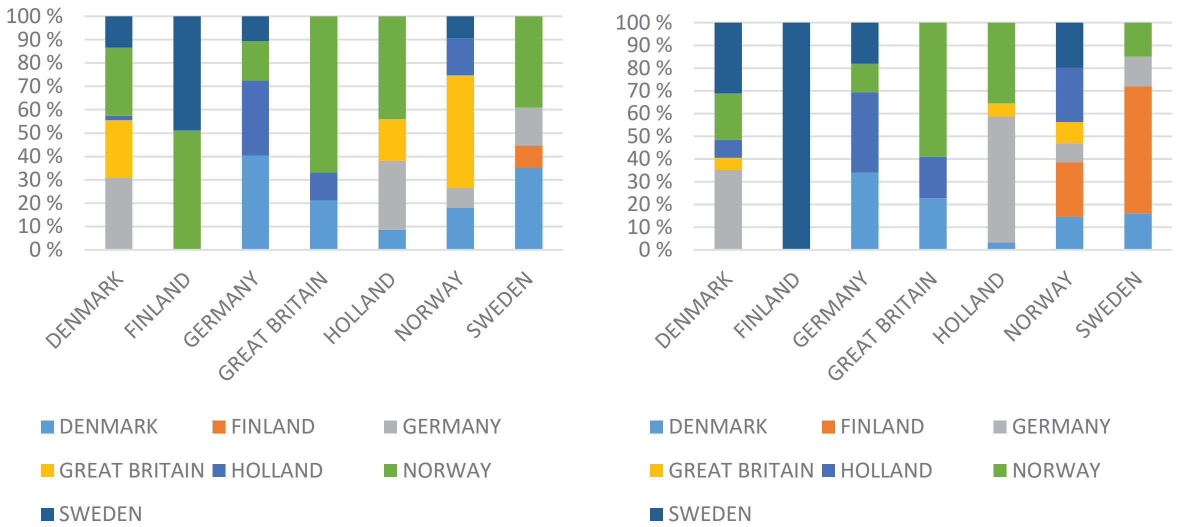

Figure 22: Percentage of cross-border trading between each country for a normal year in 2050. Import (left), and export (right).

To illustrate how variations in hydropower production affects the transmission between the different countries, Figure 23 and Figure 24 illustrates import and export levels for RCP4.5 and RCP8.5 relative to the reference scenario.

In the dry years for both scenarios, Germany will reduce the import, and increase the export. In these years Norway and Sweden will increase import and decrease export. In the wet years, the situation is the other way around. Norway and sweden increase export and reduce their import. Germany increase import levels and reduce the export. Great Britain does not seem to change export and import levels between the reference and climate scenarios, except for RCP8.5 wet. Here, both export and import increase, but with almost similar amounts.

Integration of VRE will establish the need for more flexibility related to supply and demand. In addition it increases the need for storage and transmission capacity between regions and countries (IEA 2016). If there is not invested in storage and transmission capacity, this can lead to increased volatility for the price levels. In periods with high levels of production from VRE the prices will become very low, and when there is low production levels from VRE the price levels will experience a peak.

One aspect that is not taken into consideration in the Balmorel simulations is the import from Southern Europe. In reality, the price levels here will have an impact on the price levels of Northern Europe and the Nordic countries as well. van Vliet et al. (2013), suggest increased grid connection between southern and northern Europe to even out the price differences, as the prices in northern Europe are expected to be lower than in southern Europe in future years. Even though this is an aspect that affects the Nordic power market, this is not directly relevant for this thesis, as the focus is on the Nordic power market and how alterations in hydropower production affects the countries there.

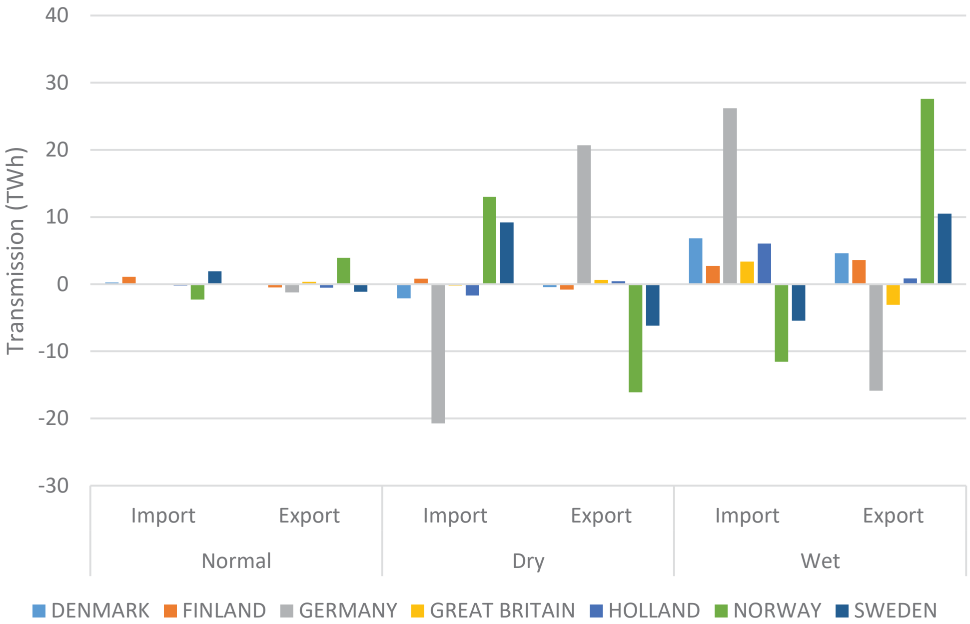

Figure 23: Deviations in import and export levels (TWh) in 2050 relative to reference scenario, for RCP4.5 in a normal, dry and wet year.

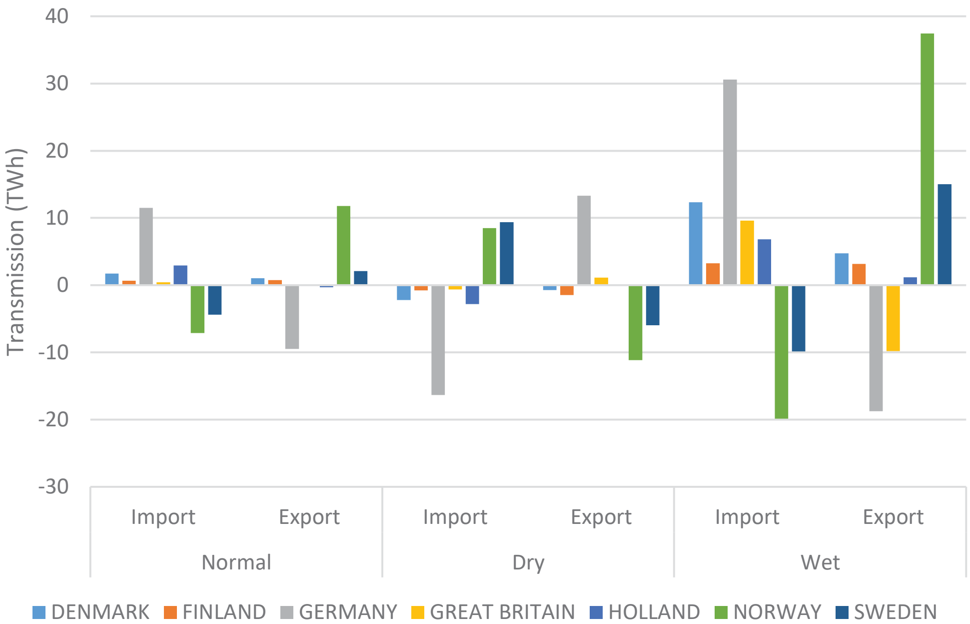

Figure 24: Deviations in import and export levels (TWh) in 2050 relative to reference scenario, for RCP8.5 in a normal, dry and wet year.

6.6 Impact of hydropower production on production levels in Germany

It is Germany, which also has the highest production level of gas and CHP, that experience the largest production decrease due to increasing levels of Hydropower production in Norway and Sweden. Compared to Great Britain and Holland, Germany has significantly larger share of electricity production from both gas and CHP. Even though the production levels in Great Britain and Holland also varies between the scenarios, it is the gas and CHP production in Germany that is affected the most by fluctuating levels of hydropower production. Figure 25 illustrates how the total gas production in the three countries vary between the different climate scenarios. The more hydropower that is produced in Norway and Sweden, the less electricity is produced from gas in three countries. This also applies to the CHP production.

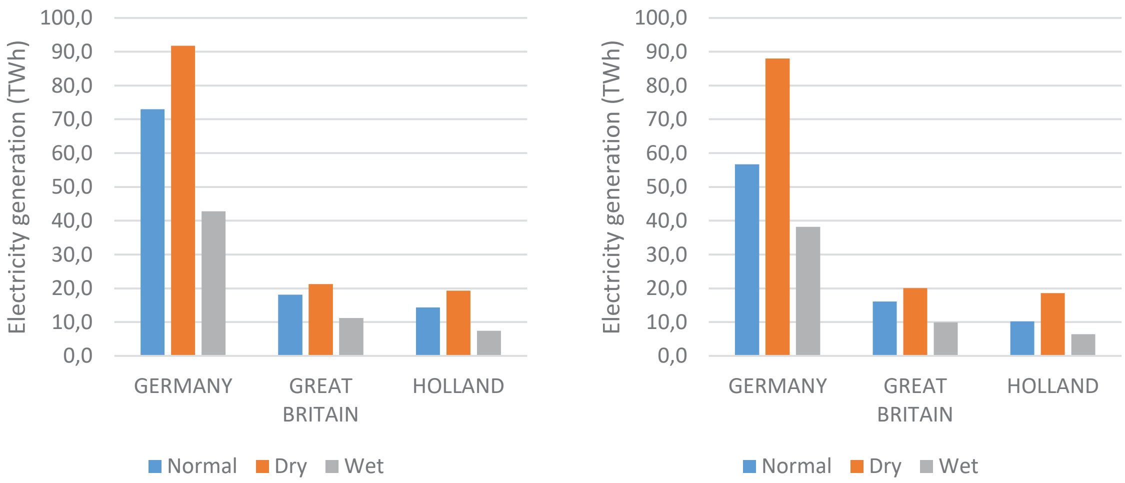

Figure 25: Electricity generation from gas in Germany, Great Britain and Holland (TWh). The left side illustrates the annual production levels for RCP4.5, and the right side illustrates the production levels for RCP8.5.

Even though solar and wind makes up over half of the electricity generation in Germany, the electricity production from gas and CHP also makes up a large amount. The solar and wind does not vary much between the climate scenarios, while the gas and CHP production varies by over 100 TWh between the scenarios with the highest and lowest levels of hydropower production.

The variations in thermal electricity production can be explained by looking at the import and export levels. Germany imports electricity from Denmark, Holland, Norway and Sweden. By looking at a normal year for both climate scenarios, it becomes evident that as the hydropower production in Norway and Sweden increase, the total import to Germany also increase with several TWh. Germany also decrease the export levels in wet years, which also contribute to balancing out the reduced production levels.

Thus, regardless of the large variations in production levels of gas and CHP, the price and demand levels does not change much due to the changes in output from gas and CHP. The price duration curves for Germany (Figure 18) shows that the country does not experience large variations in price levels between the normal, wet and dry years. The annual average price levels vary to a certain extent, and the price levels are higher in dry years. For both climate scenarios, the annual average price difference in Germany between a dry and wet year is about 12,5 EUR/MWh.

Figure 26 illustrates the connection between increased hydropower production in Norway and Sweden, increased import levels to Germany, and the reduction of electricity production from gas and CHP capacity.

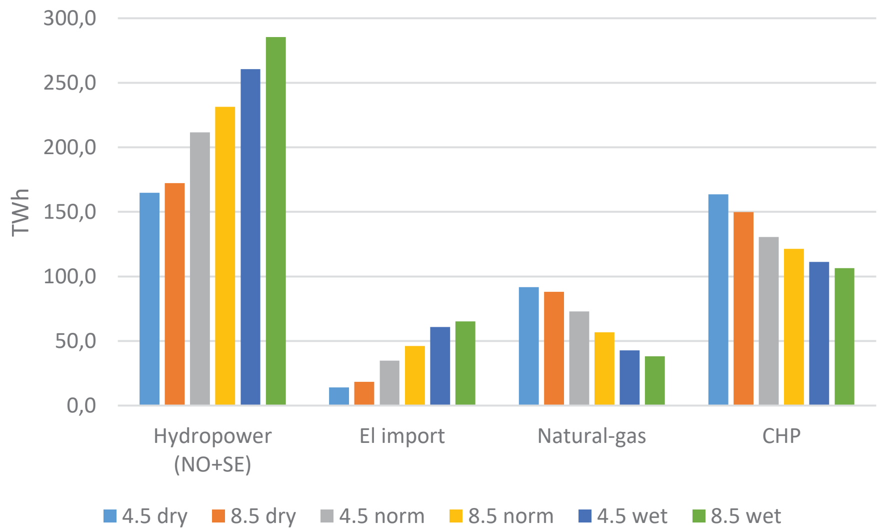

Figure 26: Impact of hydropower production on production levels from thermal capacity in Germany. As levels of hydropower production increase in Norway and Sweden, the thermal production in Germany decrease.

6.7 Limitations related to the dataset

This section address the limitations of the dataset that was received from NVE. There are uncertainties related to the dataset, and this chapter discuss the source and extent of the uncertainties. The models and methods that were used in the process of deriving the dataset are not able to recreate a perfect picture of the real world. This a result of the simplifications and preconditions that were made in the process of deriving the data. When interpreting the results from the Balmorel-simulations, it is important to keep in mind that the simulations are based on variables that are one of many possible outcomes for the future.

The results presented by Hanssen-Bauer et al. (2015) was based on the two climate scenarios RCP4.5 and RCP8.5. Even though these scenarios are widely accepted and used regularly in scientific studies, there are large uncertainties related to what the outcome will be. Thus, these scenarios are only used as guidelines to possible outcomes, which are largely dependent on political decisions made in the next few years.

In addition to not knowing the exact future emission levels, the GCMs that are used for simulating the atmospheric response to the rising GHG levels, does not predict the atmospheric conditions perfectly. Climate sensitivity and feedback-mechanisms are two of the main contributions to uncertainty in climate projections. Due to the complexity of the atmospheric reactions, not everything is fully understood, and can be proved difficult to recreate in model simulations (Wallace & Hobbs 2006).

One of the challenges that are met when modelling atmospheric processes, are the covariation between temperature and precipitation levels. When atmospheric temperature increase, the amount of humidity that can be stored in the air masses also increase, which results in changes of precipitation patterns. When modelling this effect, the rate of increase between temperature and water content does not correlate with observed values. For a Norwegian climate, one degree of temperature increase will theoretically result in an increase of water content by 6-8 %, and the historical values for the last 100 years indicates a correlation of 8-11 % per degree. In the results from Hanssen-Bauer et al. however, the modelled water content increased by 3,4 % per degree of temperature increase.

Due to model simplifications and insufficient knowledge regarding the physical processes in the earth system, the model results do not correspond perfectly with observed values as described above. To correct the simulation results, Hanssen-Bauer et al. used a method called bias-correction. Bias-correction is done by comparing observed and simulated values in a control period. If there are any simulated values that systematically deviates from the observed ones, they are adjusted. Based on the assumption that the variables will behave similarly in the future, the projections for future years are adjusted the same way as the simulated values in the control period. This method ensures more accurate predictions that deviates from the observed values as little as possible. The control period for this report was until 2005, and the simulation period was 2006-2100. Since the bias-adjustment was done separately for temperature and precipitation, (Wong et al. 2016) states that the *"physical consistency between the variables"* (p.22) is reduced.

In the process of downscaling to smaller grids, the uncertainty of the data were increased (Wong et al. 2016). The two different downscaling methods that were used, contributed to some of the uncertainty in the dataset. It is stated by Hanssen-Bauer et al. (2015) that "*Compared to the dynamical downscaling method, the statistical method results in prediction of warmer winter temperatures and colder summer temperatures" (p. 101).*

In the process of deriving the dataset, there were used a large number of different models; GCMs, RCMs, HBV, EMPS. In addition, a large number of assumptions and simplifications were prior to each model simulation. This has resulted in a large uncertainty related to the results. The uncertainties were evident right from the start of the work with this thesis, as they were thoroughly documented and discussed in the reports. No measures were done to overcome the uncertainties related to the dataset. Nevertheless, it is important to address the origin of the uncertainties and be aware of their scope, as it impacts the robustness of the results for this thesis.

6.8 Strengths and weaknesses of the study

This section addresses some limitations and strengths of this study and how they are likely to affect the results.

The assumptions regarding the input variables for the Balmorel simulations were made based on the NETP report published by IEA (2016). These preconditions were based on a thorough foundation, but should only be considered as one of many possible outcomes. The future demand levels, production capacities and investments in transmission capacities might turn out to be different from the scenarios that were used as input the Balmorel simulations. The dynamics of the power market is intricate, and there are many factors that contribute to what the picture will be in 2050. Politics and economic profitability play an important role regarding what the production capacity for each technology will be in the future, and a few single political decisions can lead to a changed picture for the Norwegian power market.

In the literature, there are split opinions regarding the price levels and hence the investment expectations for the future. There is expected an increase in price levels, but to what extent and at which rate the increase will take place, is crucial for investments in production and transmission capacity. This will have an impact on how much capacity that is established, in addition to what technologies that are expected to be profitable. Thus, the preconditions regarding the price levels and production capacities in this thesis are uncertain, and minor variations in the predicted price levels will change the precondition to what technologies that will be present in the power market in 2050.

Definitions related to the regulated and unregulated capacity might be different between the dataset allocated from NVE and the preconditions done prior to the calibrations of production capacity in the Balmorel-model. This can lead to a higher number of full load hours per power plant than what is realistic.

The normal years were calculated as the average over a 30-year period, whereas the dry and wet years were single years within this period. As the dry and wet years were only represented by simulated inflow values for one year each, this might not be representative for the other wet and dry years in this period. Nevertheless, the method is considered to give realistic estimated for 2050.

The construction of inflow series for Sweden was done based on the assumption that the area in Sweden that had geographical similarities compared to Norway, also had similar hydrological conditions. This assumption corresponds with the assumption done by Hanssen-Bauer et al. (2015) during calibration of the HBV-model. As described by Wong et al. (2016), it was assumed that *"…model elements with identical landscape characteristics have similar hydrological behaviour." (p. 18).* The same assumption was done in regards to the Swedish inflow series, even though it in this case was simplified compared to the studies done by Hanssen-Bauer et al. This assumption is valuable to some extent, as the two countries are located in the same climatic zone, in addition to being located at almost the same latitude and longitude. On the other hand, however, this is a simplified assumption as there may be regional differences regarding the hydrology. The hydrological conditions for each catchment are very intricate, each catchment have individual characteristics and the share between regulated and unregulated catchments are most likely different in the areas that were linked together. Thus, this assumption contributes to some uncertainty related to the results. On the other hand, the two countries are located in the same climatic zone, in addition to being located at almost the same latitude and longitude. In light of the study scope, which has a broad system perspective, this simplification is therefore considered sufficient for the purpose of the study.

The production capacity is the same for all the scenarios. Realistically, the investments in production and transmission capacity will become different depending on which climate scenario that turns out to be true. RCP8.5 will lead to lower electricity prices, and thus different profitability for the producers than RCP4.5. Also, the need for upgrade of dam and production capacity will be more comprehensive for RCP8.5 than for RCP4.5. If the capacities had been adapted relatively to the emission scenarios, the simulation of the energy system would give a more realistic picture of the future.

The climate scenarios RCP4.5 and RCP8.5 are well documented and approved scenarios in the global scientific community (IPCC 2013). Even though there are large uncertainties related to future emission levels, these scenarios are widely used in scientific studies and are accepted as valid scenarios.

There is a general perception that use of GCMs gives good predictions of future temperature levels. The results are further strengthened by the use of several models in the process of deriving the climatic variables. Despite the uncertainties related to both the future emission levels and climate sensitivity, the GCM simulations were considered to give good forecasts based on the emission scenarios. Also, by applying two separate methods, ESD and RCM, in the process of downscaling the grid size from the GCM simulations, the robustness of the results were improved. (Hanssen-Bauer et al. 2015)

In conclusion, there are some uncertainties related to both the dataset and the results from the Balmorel simulations. This is due to the number of assumptions and simplifications related to each model simulation. Nevertheless, the results of this thesis are considered to give a good description of the main trends in the Nordic power market towards 2050.

6.9 Contribution to the literature

This thesis is based on the results from Beisland et al. (2015), and has several similarities to the report. This section describes how this thesis contributes to the literature, compared to the report from Beisland et al. Both studies investigate the impact of climate change on the Norwegian power market, and how the energy inflow is predicted to change during the century. Also, power market models are used to simulate the different aspects of the power market, where both supply, demand and price are taken into consideration in the studies. There are however, several differences between the two studies, which will be explained in this section. The differences will be presented to explain how the results differ in this study compared to the study performed by Beisland et al. (2015).

Beisland et al. (2015) based their report on simulations with production capacities equalling 2015-levels, and the Norwegian hydropower was the only technology that was studied in detail. In the Balmorel-simulations for this thesis, the production capacity of each technology was set to expected levels in 2050. Thus, a more realistic situation for the future power market was simulated. The assumed development in future demand levels did not only depend on the temperature change, but were also dependent on investments in industry, new buildings, population increase and changes in transport sector. In addition, inflow series for Sweden were constructed based on Norwegian values, and both regulated and unregulated energy inflow series were studied in detail. The trade with other countries were taken into consideration, and new transmission capacity were implemented, based on expected investments towards 2050.

Compared to Beisland et al. (2015), who investigate one climate scenario in their report, this thesis studies two climate scenarios. Since there are uncertainties related to climate sensitivity and future emission levels, having several scenarios gives a more complete picture of the possible outcomes. This allows comparison between the two climate scenarios, and a study of the varying outcomes related to different emission levels can be investigated.

As a result of all the above-mentioned assumptions, this thesis was able to study the dynamics within the Nordic power market. The interaction between electric and thermal capacity is investigated, what impact hydropower production has on other technologies and how transmission between regions and countries varies in relation to varying production levels of hydropower.

While the objective of Beisland et al. (2015) was to investigate the impact of climate change on the Norwegian power system, this thesis investigated the impact of alterations in Norwegian and Swedish hydropower production in the Nordic power market. As the reports served different purposes, the preconditions differ, and the results should be interpreted with this in mind.

6.10 Implications

The varying levels of hydropower production in Norway and Sweden have significant repercussions to the neighbouring countries. This is especially evident in Germany, where gas and CHP are the technologies that are affected the most. By having good indications on how hydropower production will change the next year, Germany can adapt production and transmission capacity to further benefit from the reduced price levels that arise in years with high levels of hydropower production.

It has been discussed how both nuclear capacity and CO_2-prices influence the price and investment decisions in the Nordic power market. The alterations in Hydropower does also have influence on these decisions. As the nuclear capacity in Sweden and Finland is phased out, and high shares of VRE are introduced, the regulated hydropower capacity becomes an even more important component in the Nordic power market. The regulated power will be valued even more, as the share of unregulated capacity increase. This opens up for the possibility to invest in pumped hydro. In addition, the increased electricity prices make this an even more feasible option to consider for the hydropower producers that has regulated hydropower capacity.

To even out the price levels between the countries in the Nordic and European power market, the importance of increased transmission and storage capacity becomes evident. In a future with an extensive system transformation which includes increased hydropower production, reduced generation from nuclear capacity and phasing out of coal, investments in storage and transmission capacity is crucial to sustain a secure and stable supply of electricity. The increased energy inflow and price levels gives a good opportunity for the hydropower producers to invest in production capacity, increased dam storage and pumping power. As the grid operators, politicians and power producers hold responsibility, the benefits for investing strategically in transmission, storage and production capacity applies to both producers, consumers and operators.

7 Conclusion

The objective of this thesis was to investigate how alterations in hydropower production in Norway and Sweden affects the Nordic power market in 2050. The two climate scenarios that were used as basis for the analysis showed the same trends. The climate scenario with highest emission levels resulted in the largest alterations for hydropower production and consequently led to the most comprehensive repercussions throughout the Nordic power market.

The answer to the three research questions are as follows:

1. *Which technologies in the Nordic power market will be most affected by the climate related alterations in Norwegian and Swedish hydropower production towards 2050?*
   As the share of hydropower production increase, the production of gas and CHP decrease. This effect is especially evident in Germany. For a normal year for RCP8.5, the hydropower production increase by 23.8 TWh in Norway and Sweden, and the gas and CHP production decrease by 26 TWh in Germany.

2. *How will climate change affect Nordic electricity prices in 2050?*
   Increased levels of hydropower production will result in reduction of price levels for electricity. In dry years, the price levels increase. This is valid for all countries that were studied in this thesis. It is Finland, Norway, Sweden and Denmark that will experience the largest fluctuations in price levels as the hydropower production varies. Great Britain will not notice large fluctuations in price levels, as a result of restriction on the transmission lines and a large share of VRE.

3. *Will climate change affect the rate of export and import between the countries in the Nordic power market in 2050?*
   In years with reduction in hydropower production the export from Norway and Sweden will decrease. In years where the hydropower production increase, the export rate will increase. The import to Finland, Germany, Denmark, Holland and Great Britain increase as the hydropower production increase.

Climate change important to take into consideration in long-term market analyzes, as it has significant consequences for the power sector. The hydropower production is predicted to increase with several TWh, which has consequences for the price levels and thus the profitability for other technologies in the market. Regardless of the alterations in hydropower production, the power market will experience a significant change in the next years due to political decisions regarding nuclear capacity and CO_2-price. Coal and nuclear power will be shut down, and replaced by VRE. By taking hydropower production and its predicted alterations in production levels into considerations in when planning the future power market, the future power system will become a robust and secure system with stable price levels.

8 Further work

It is important to keep in mind that the power system is set as constant in the Balmorel simulations, and that this thesis is dedicated to studying how the variations in hydropower production in Norway and Sweden affects the different aspects of the power market. By doing more research on some of the components, there would be given more insight to the dynamics of the future power market. By looking at several levels of demand, production levels of other technologies, and transmission capacities, the study could give a more realistic picture of the dynamics within the power market.

To get more realistic values for hydropower production in Sweden, it would be recommended that inflow series for Sweden would be applied in further studies. The first option is to apply historical inflow series for Sweden, and adjust them for the predicted climate changes presented in Hanssen-Bauer et al. (2015). Alternatively, modelled series for the future inflow levels in Sweden could be generated in the same way as the dataset applied in this thesis.

There is also hydropower production in Finland, Germany and Holland. It was not generated inflow series for these countries, and this could be a point to take into consideration in further work.

Finally, since it is associated uncertainties to the climate predictions, it would be beneficial to perform the study in regards to several of the climate scenarios presented by IPCC, RCP2.6 and RCP6.0.

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10 Appendix

A1. Overview of the ten EURO-CORDEX combinations

Global climate model	Ensemble member	Regional climate model	Time period	Institution
CNRM-CERFACS-CM5	r1i1p1	CCLM4-8-17	1971-2100	Climate Limited-area Modelling Community
CNRM-CERFACS-CM5	r1i1p1	RCA4	1971-2100	Swedish Meteorological and Hydrological Institute
ICHEC-EC-EARTH	r12i1p1	CCLM4-8-17	1971-2100	Climate Limited-area Modelling Community
ICHEC-EC-EARTH	r3i1p1	HIRHAM5	1971-2100	Danish Meteorological Institute
ICHEC-EC-EARTH	r1i1p1	RACMO22E	1971-2100	Royal Netherlands Meteorological Institute
ICHEC-EC-EARTH	r12i1p1	RCA4	1971-2100	Swedish Meteorological and Hydrological Institute
MOHC-HadGEM2-ES	r12i1p1	RCA4	1971-2100	Swedish Meteorological and Hydrological Institute
IPSL-CM5A-MR	r1i1p1	RCA4	1971-2100	Swedish Meteorological and Hydrological Institute
MPI-ESM-LR	r1i1p1	CCLM4-8-17	1971-2100	Climate Limited-area Modelling Community
MPI-ESM-LR	r1i1p1	RCA4	1971-2100	Swedish Meteorological and Hydrological Institute

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