Environmental effects of international electricity trade

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Thesis for Master of Philosophy in Economics

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May 2016

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http://www.duo.uio.no

Print: Reprosentralen, University of Oslo

Abstract

The severe estimated effects of climate change have induced European governments to seek alternatives to fossil fuel as an electricity generating source. The European Union aims at reducing greenhouse gas (GHG) emissions by 40% in 2030, compared to 1990 emission level. In order to do so, the European Commission has adopted ambitious energy- and climate targets. Investments in modern infrastructure to better integrate the European electricity market, are one of the strategies implemented to reach the targets, arguing that interconnecting transmission cables will facilitate a larger share of renewable electricity. The past few years have seen a great expansion of solar- and wind power production in Germany. This has caused for a large power surplus in periods where wind- and solar capacity is high and hence induces large price fluctuations in the German electricity market. As of 2020, the German and the Norwegian electricity market will be coupled, implying that abundant renewable energy in Germany can be stored in Norwegian reservoirs, and exported back to Germany when renewable energy is scarce. Thereby, facilitating electricity trade will lead to a better resource utilization of the existing renewable energy plants. However, trade will also affect the electricity prices, and it is not obvious how these price changes will affect the optimal production level of alternative electricity generating sources in Germany, namely fossil fuels. Therefore, it is of interest to analyze the effect on emission level of opening up for electricity trade.

The thesis provides for an in-depth theoretical analysis of the price dynamics resulting from electricity trade. By introducing certain extensions as well as assumptions to a dynamic model developed by Førsund (2015), the impact of electricity trade on total electricity production is thoroughly analyzed. Furthermore, I develop a model to analyze how investments in intermittent energy sources are affected by the price changes resulting from trade. The theoretical analysis reveals that opening up for electricity trade between two countries with different electricity generating technologies will affect the electricity prices in both countries. Through the changes in electricity prices, electricity trade affects both optimal production level of thermal power as well as investment level in intermittent energy. I find that the relative price change as well as the intermittent capacity coefficient determines the overall effect on total emissions, which in turn is ambiguous. However, increasing the share of electricity generated from intermittent sources without interconnecting transmission cables, will put the security of electricity supply at risk. In conclusion, cross-border transmission cables may serve as an important catalyst to increase the RES-E share and thereby to mitigate climate change.

Preface

Firstly, I would like to thank my supervisor, Bård Harstad, for constructive comments and valuable feedback throughout the theory development. Secondly, I would like to thank the Oslo Centre for Research on Environmentally Friendly Energy (CREE) for awarding me their scholarship as well as providing me with an office space. That I am grateful for.

Finally, I would like to thank everyone who helped me throughout my work, both with structural advice and motivation. Thank you Eline, Line and Mad for taking the trouble to read through my paper. Thanks to Ida, Signe and Marte for discussions, laughs and coffee breaks throughout the study program. And thanks to mamma for preparing and delivering delicious meals and unlimited amounts of Cola Zero at Blindern. You guys are awesome.

Any remaining errors in this thesis are my responsibility alone.

Oslo, May 2016
Marie Brun Landmark

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List of variables and parameters

T - Time horizon

D_t^C - Demand for electricity in country C in period t

$p_t^C(x_t^C)$ - Demand for electricity on price form in period t

$p_t^{C,AU}$ - Autarky electricity price in country C in period t

$p_t^{C,Tr}$ - Trade electricity price in country C in period t

x_t^C - Consumption of electricity in country C in period t

e_t^H - Hydropower produced in period t

$\overline{H}$ - Total production of hydropower in two periods

e_t^{Th} - Thermal power produced in period t

e_t^I - Intermittent energy produced in period t

$\overline{e}^{Th}$ - Max production capacity of thermal energy

$\overline{e}^I$ - Max production capacity of intermittent energy

r_t - Water released into the hydropower turbines in period t

n - Requirement of water to produce one unit of electricity

R_t - Water in the reservoir at the end of period t

w_t - Inflow of water in period t

$c(e_t^{Th})$ - Production cost of thermal power

λ_t - Shadow price of water in period t

a_t^I - Intermittent capacity coefficient in period t

$e_{C,t}^{XI}$ - Export from country C in period t

$\overline{e}^{XI}$ - Max transmission capacity

$\alpha_{N,t}$ - Shadow price on the export constraint for Norway

$\alpha_{G,t}$ - Shadow price on the export constraint for Germany

Δp_t^G - Price change in Germany from autarky to trade in period t

Δe_{tot}^{Th} - Production change of thermal power production from autarky to trade in period t

$\Delta\overline{e}^I$ - Investment change in intermittent energy

1. Introduction

80% of global greenhouse gas (GHG) emissions stem from energy generated by the use of fossil fuels (European Commission, 2014a). The severe estimated effects of climate change have induced European governments to seek alternatives to fossil fuel as an electricity generating source. Since 2009, the European Union (EU) has sought to take on a leading role in global climate change mitigation and has adopted ambitious energy- and climate targets. In order to reach these targets and secure a long-lasting solution to the climate change issue it is vital for the EU to increase the renewable energy share of total energy production. However, electricity generated from intermittent[1] sources varies in volume over time, due to uncontrollable production. As a consequence, an electricity market based on a high share of intermittent power has to be supported by flexible sources to ensure supply in periods with low production (Gaudard & Romerio, 2014). Hydropower plants with reservoirs might serve as this type of green, flexible back-up source. However, hydropower production with water storage possibilities necessitates certain geographical conditions. It means that countries without necessary conditions are dependent on cross-border connections to acquire this flexibility. For that reason, the European Commission has launched strategies with the aim of encouraging substantial investments in infrastructure, with specified interconnection targets (European Commission, 2014b).

In 2020, the Norwegian and German electricity markets are set to be connected by a subsea transmission cable, namely NordLink (Statnett, 2013). Germany has a large production of renewable energy, and accounts for one third of installed wind power plants in Europe (de Menezes & Houllier, 2015). However, large daily price fluctuations in Germany render visible the potential disadvantage of basing the energy production on such a high share of renewable energy sources. Because production is free at the margin, producers enter remarkably low bids when the renewable capacity is high. The bidding price is pushed down to zero, bending the German electricity market out of proportions (The Economist, 2015). In Norway, hydropower with reservoirs serves as the main electricity generating source. It results in rather stable daily electricity prices, contrary to what is the case in Germany (Statnett, 2013). Connecting the German and the Norwegian electricity markets implies that abundant renewable energy in Ger-

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[1] Includes all types of renewable energy sources with the exception of hydropower with reservoirs

many can be stored in Norwegian reservoirs. Postponing production in Norway until renewable energy in Germany is scarce serves as a short-term flexibility in both markets. NordLink will allow Norway to act as the flexible backup source, as Germany can export intermittent energy instead of pushing the prices close to zero.

The purpose of this thesis is to answer the following research question: Will international electricity trade lead to a higher share of electricity generated from renewable sources? More specifically, the study examines whether the price effects of opening up for electricity trade are sufficient to induce lower emissions and a higher production of electricity from intermittent sources, by using Norway and Germany as a case. The research question is addressed by applying a theoretical model. By introducing certain extensions as well as assumptions to an existing model developed by Førsund (2015), the framework enables me to thoroughly analyze the impact of trade on total electricity production, and how these changes in turn depends on the different parameters included in the model.

The theoretical analysis reveals that opening up for electricity trade between two countries with different electricity generating technologies will affect the electricity prices in both countries. As the problem we are facing is a dynamic one, a binding transmission constraint in one period will affect the prices in the period where the transmission constraint is non-binding. An important find is that price change caused by changing an exogenously given parameter is largest in the period with a binding transmission constraint. Through changes in the electricity prices, electricity trade affects both production of thermal power as well as investments in intermittent energy. I find that the relative price change as well as the intermittent capacity coefficient determines the overall effect on total emissions, which in turn is ambiguous.

The remainder of the thesis is organized as follows. Chapter 2 provides a description of the Norwegian and German electricity markets as well as an explanation of NordLink. Chapter 3 describes the current and future energy and climate targets of the European Union. Chapter 4 presents the base model applied in the theoretical analysis and derives autarky prices. Chapter 5 derives the effects on the electricity market when opening up for trade. In chapter 6, I analyze how investments in intermittent energy are affected by cross-border electricity trade. Chapter 7 discusses the validity of the underlying assumptions behind the theoretical framework and presents a broader discussion of the main findings in context of the EU's future electricity supply challenges. Finally, chapter 8 concludes and summarizes the thesis.

2. The electricity market

2.1 Introduction to energy economics

Electricity is an essential and necessary commodity for the modern society, and has been so for the past centuries. The degree of necessity is illustrated by the Value of Lost Load (VLL), a measurement of estimated price consumers are willing to pay to avoid electricity disruptions. The VLL is dependent on time of the day, season, and duration of lost electricity load and therefore VLL varies over the hours and location. At certain times, the VLL is estimated to equal 100 times the existing electricity price (Wangensteen, 2012). Although the electricity price is quite low, the willingness to pay to avoid disruption of supply is very high.

Electricity has many special features which are crucial to take into account when discussing electricity economics. Firstly, electricity is a unique commodity as production and consumption of electricity happens simultaneously. Supply and demand of electricity has to balance at all times. According to economic theory, the market is in balance when supply equals demand, at the so-called market-clearing price. However, as electricity travels at the speed of light the price mechanisms is not able to balance the market in real-time. This is why electricity is priced either before or after real time (Wangensteen, 2012). Secondly, generated electricity cannot be stored in any economically significant amounts, due to lack of sufficient battery capacity with the existing technology.

Electricity can be generated by a range of different processes and sources. These sources can be renewable, such as water, wind and solar, or exhaustible, such as brown coal, hard coal and gas. For the final consumer, electricity from the different sources are initially perfect substitutes, if climate damage is disregarded. However, the various generating technologies differ with respect to externalities caused by production. Burning fossil fuels has a negative environmental impact and contributes to global warming.

The electricity generating technologies analysed in this paper are hydropower, thermal power and intermittent energy. Starting with hydropower, it utilizes gravity by releasing water from dams to run electricity generating turbines. Potential energy is stored in the water reservoirs and transformed into electricity when water is released. Hence, the vertical distance between the dam and the turbines as well as the mass of water determines the amount of electricity generated. The larger vertical distance, the more potential energy is saved in the reservoirs (Førsund, 2015). This property permits hydropower to be used as a battery in terms of potential energy, when the energy market is abundant with auxiliary energy sources. This will be stressed in detail in chapter 4.

The second generating technology discussed in this paper is thermal power, which is generated through combustion of coal, oil, gas or wood. The steam created by heating water runs the turbines, which generates electricity. However, the environmental effects of burning fossil fuels are severe, both on a regional and global level. Firstly, the combustion process emits harmful gasses, such as NO_x and SO_2 that causes air pollution as well as acid rain. Secondly, the burning of fossil fuels generates GHG such as CO_2, which contributes to global warming (Førsund, 2015).

The third type of generating technology I will discuss is intermittent energy. Intermittent energy plants employ renewable sources to generate energy. As opposed to hydropower plants with reservoir, production of intermittent energy is uncontrollable with the exception of wasting energy. The different intermittent energy sources are wind, solar, geothermal, wave, run-of-river hydropower and thermal power based on biofuels. Wind power is created by wind energy running turbines, which generates electricity. Solar power can be created in two ways, either by converting solar power into electricity by using photovoltaic cells or using solar power to heat water, so that the steam will run the turbines which creates electricity (Førsund, 2015). Solar power generation is generally higher in summer than in winter, and is equal to zero after sunset. Wind power on the other hand is less predictable as it either fluctuates over the hours, but can also stay constant over a number of days. Furthermore, wind power generation is generally higher in the winter season than in summer (Gaudard & Romerio, 2014, p. 178). Hence, production of intermittent electricity is highly dependent on weather conditions, and generation is therefore rather varying. However, as weather conditions are fairly stable on long-term basis, quite accurate predictions can be estimated in the long run.

2.2 Electricity production in Norway

Almost all electricity production in Norway is based on hydropower. Norway is thus dependent on trade with its neighboring countries to manage hydrologic fluctuations. Due to natural causes, the inflow may vary with around ± 30% between wet and dry years (Førsund, 2015, p. 21). This accounts for around ± 40 TWh of average yearly production[1] in Norway between 2006 and 2014[2]. Additionally, Statnett (2013) argues that inflow is correlated with temperature, which in turn is negatively correlated with demand of electricity as low temperature increases demand for energy. This implies that years with low inflow tend to be followed by high demand. Hence, Norway is, with reference to the security of supply, exposed in seasons with low inflow, which is a strong argument for cross-border electricity trade.

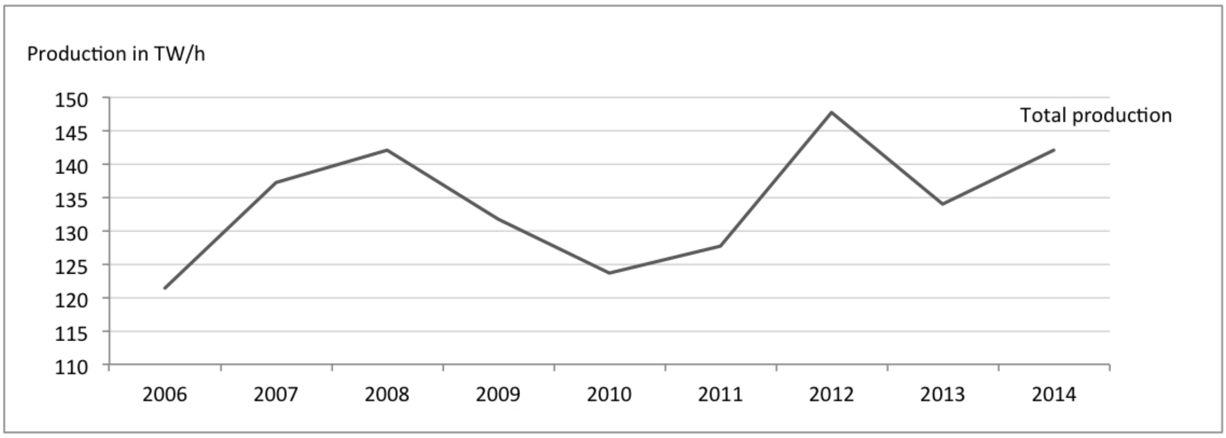

Figure 2.1: Production of electricity in Norway from 2006 - 2014
Source: Statistics Norway (table nr. 08307)

Figure 2.1 illustrates the changes in production of electricity in Norway between 2006 and 2014. Production within this period varied with around 20 TWh, which amounts for approximately 15% of average production[3]. Recent data from 2016 indicates that 96,6% of total production of electricity is hydropower, whereas the remaining consists of wind- and thermal power[4].

In Norway, 70% of all production is adjustable, entailing that the producer can adjust production to demand, at basically zero cost (Førsund, 2015, p. 14). Large reservoirs permit storing of water for production at a later time, when the prices are higher. The extensive market share in addition to large storage capacity gives relatively small price fluctuations throughout the

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[1] Terawatt-hours

[2] Based on own calculations. Average yearly production of electricity in Norway between 2006 and 2014 was 134 152 GWh, approx. 134 TWh. Data retrieved from Statistics Norway.

[3] Source Statistics Norway

[4] Data retrieved from Statistics Norway

day. However, prices tend to be relatively high during the winter seasons in Norway (Statnett, 2013).

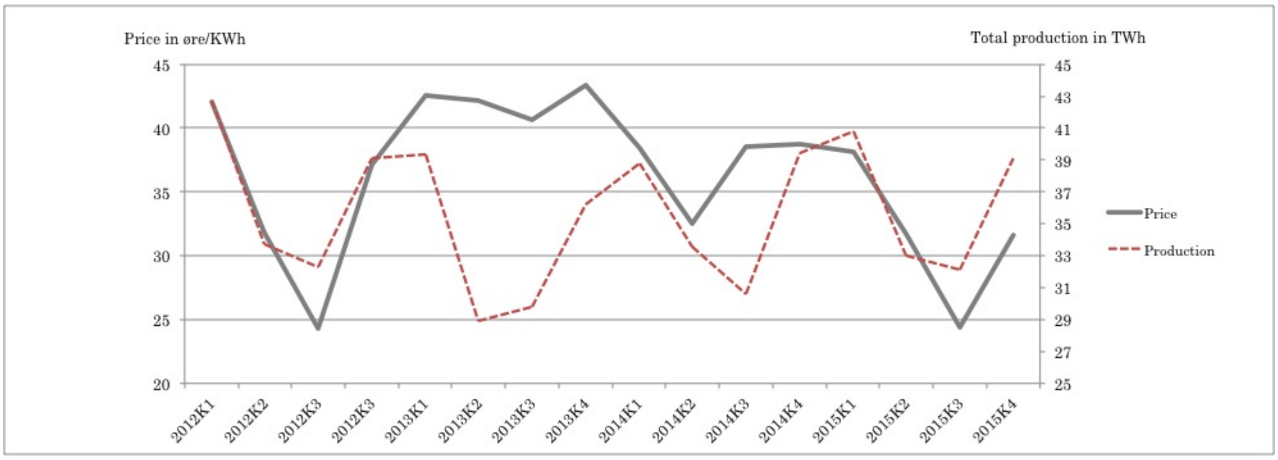

Figure 2.2: Electricity prices in Norway from 2012 - 2015
Source: Statistics Norway (table nr. 08583 and 09364)

Figure 2.2 presents data of electricity prices from the period between 2012 and 2015. Due to higher and more inelastic demand in the winter season, prices are higher for these periods. The prices fluctuated with around 20 øre/KWh. By inserting production data from the same period, the negative correlation between prices and production level is quite apparent in some time periods. Hence, some of the price fluctuations can be explained by changes in production level, i.e. changes in yearly inflow. Furthermore, the prices are higher in winter than in summer, due to a binding reservoir constraint.

2.3 Electricity production in Germany

Germany is one of the leading countries in Europe when it comes to renewable energy, and has made great effort to appear as a pioneer country with reference to the long term European Union climate targets, as will be discussed in the following chapter. German electricity production has experienced great development over the past 20 years, and data clearly highlight a transition towards renewable energy production, as illustrated in figure 2.3. The German government intend to reduce its emissions by 40 % in 2030 compared to 1990 emission level (Statistisches Bundesamt, 2016; de Menezes & Houllier, 2015).

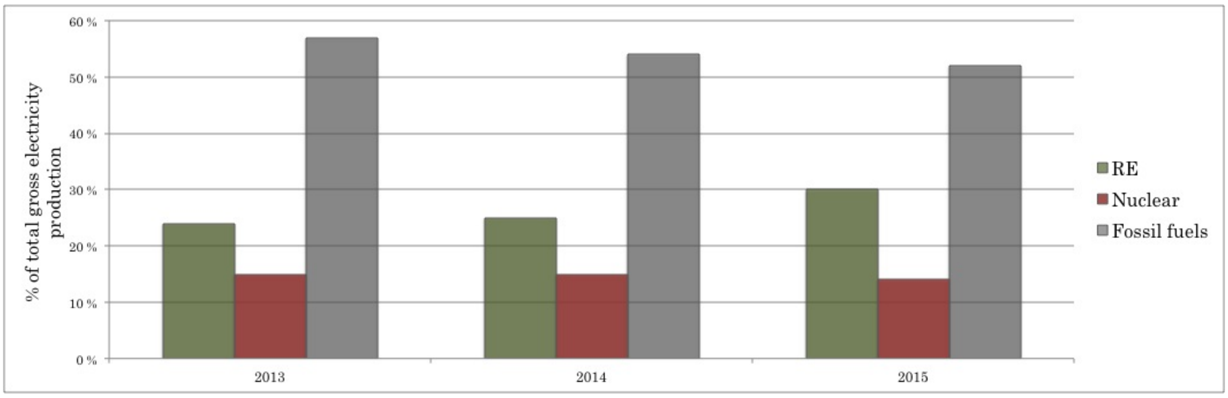

Figure 2.3: Gross electricity production in Germany from 2013 to 2015
Source: Arbeitsgemeinschaft Energiebilanzen (AGEB), Statistisches Bundesamt

Figure2.3[5][6] illustrates that 30% of gross electricity production is generated from renewable sources, mainly solar- and wind power. This accounts for a 25% increase of total renewable energy production since 1990. However, it is worth noting that coal is still the main source of electricity in Germany in 2015, even though the use of coal has decreased by around 15% since 1990. Moreover, the amount of nuclear power produced has been reduced by around 15% since 1990. This reduction of nuclear power production can be seen in light of the EU's goal of reducing nuclear power production by 50% by 2030 (deLlano Paz et al., 2016). Nonetheless, these figures state that Germany has so far been successful in replacing the reduction in nuclear power with a large fraction of renewable energy (Statistisches Bundesamt, 2016).

Compared to Norway, Germany has relatively high price fluctuations over the hours, and an essential explanation of this phenomenon is the large startup cost of existing thermal power plants as well as variations in input prices (Statnett, 2013). In fact, negative prices are relatively often observed in the German electricity market, as it is profitable for thermal power producers to offer negative prices instead of shutting down the power plants during the night hours with low demand. Furthermore, the increase of renewable production, mainly of solar- and wind power has shifted the supply curve and has led to falling prices. Additionally, renewable energy producers benefit from priority dispatching rules, as well as fixed cost of production being subsidized by the government (Gaudard & Romerio, 2014).

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[5] Data from 2015, retrieved from Destatis, Statistisches Bundesamt

[6] Fossil fuels consists of brown coal, hard coal, natural gas and mineral oil products

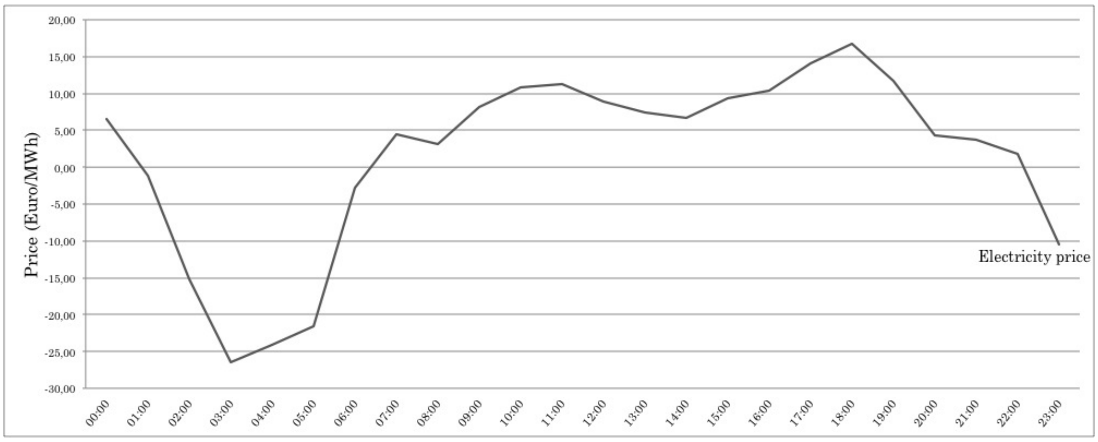

Figure 2.4: Intraday continuous average electricity price in Germany, 8th of February 2016
Source: EXPEX SPOT (Fraunhofer ISE, 2016)

Figure 2.4 shows the daily price variation the 8th of February 2016[7]. The hourly prices varied with around 40 Euro/MWh throughout this day (Fraunhofer ISE, 2016). The electricity price in Norway and Germany follow quite different patterns. The hourly prices in Germany fluctuates greatly due to the mechanisms explained above, whereas the prices in Norway are relatively constant across the hours (Vista Analyse, 2014). However, the prices in Norway are much more fluctuating throughout the year.

2.4 Energy trade and interconnectors

Both Germany and Norway have for many decades been involved with cross-border electricity trade in which they both benefit largely from. Energy trade through Nord Pool Spot[8], facilitates Norway to save water in the reservoirs at full capacity, when optimal, by importing electricity from Denmark and Sweden, among others (Wangensteen, 2012). Germany on the other hand has for the past decades been highly dependent on electricity import from its neighboring countries. Germany's net electricity import has in fact increased from 47% in 1990 to 61% 2014 (Forbes, 2015).

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[7] This date was not arbitrarily chosen, but illustrates a day where the price price fluctuations are very apparent

[8] Nord Pool Spot is the Nordic power exchange market, operating in Norway, Sweden, Finland, Denmark, Estonia and Lithuania (Östman & Hesamzadeh, 2014)

2.4.1 NordLink

10th of February 2015 the investment decision of NordLink was confirmed by Norwegian and German authorities. NordLink is a subsea electricity transmission cable that, for the first time, will connect the German and the Norwegian electricity markets together. The transmission cable will go from Tonstad in Norway to Wilster in Germany. This totals a distance of around 623 km. The capacity of the cable is 1400 MW with a voltage of 525 kV[9]. The project is owned by the Norwegian TSO[10] Statnett, the German TSO TenneT and the German investment bank KfW, each country holding 50 % of the shares. NordLink is intended to be realised in 2019 and ready for commercial use in 2020 (Statnett, 2016; TenneT, 2016).

The past few years have seen a great expansion of solar- and wind power production in Germany. It has caused a large power surplus in periods where wind- and solar capacity is high and hence induces large price fluctuations in the German electricity market. Norway has the highest water reservoir capacity in Europe, which accounted for 84 TWh in 2012 (Førsund, 2015). Connecting the markets thus implies that abundant renewable energy in Europe can be stored in Norwegian reservoirs and exported back to Europe when renewable energy is scarce (Statnett, 2013; Førsund, 2015).

Building cables between Norway and Germany will lead to a better resource utilization of the aggregated electricity generators in both countries. This is the main cause of economic surplus, which is reached through two mechanisms. Firstly, the controllable hydropower plants in Norway may benefit from moving production from one period to another. Postponing production therefore serves as a short-term flexibility for both markets. Secondly, German thermal power production will assist the Norwegian power market to handle hydrological fluctuations (Statnett, 2013). Hence, the transmission cable will improve the energy security and secure a more predictable electricity supply throughout the year and between the years.

As argued in the previous section, Norway is dependent on trade connections to ensure a secure energy supply, especially in years with low inflow. However, this challenge is expected to escalate in the future as the Nordic countries are planning to expand their production of intermittent energy. This implies a larger surplus of the power balance, and optimal export level increases. Without sufficient expansion of export possibilities in terms of transmission

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[9] To ensure minimal transmission loss, electricity is converted from alternating current (AC) to direct current (DC) when transmitted through the cable. The electricity is converted back to AC when connected to the importing countrys transmission grids (TenneT, 2016).

[10] Transmission System Operator

grids, the Nordic countries are in danger of facing very low prices, especially during the wet seasons (Statnett, 2013).

Connecting the markets together will lead to higher production in Norway when prices are high in Germany, and Norway will benefit from exporting electricity to Germany in these periods. On the other hand, Norway will reduce production in periods with low prices in Germany, as it is favorable to import and save water in the reservoir for the next period. Furthermore, the transmission cable will lead to lower production cost in Germany, as fewer thermal power plants are required to start up and shut down to cover varying intermittent power production and demand peaks.

With differing prices between the two countries, facilitating trade will be beneficial for both parties. Trade will lead to a price reduction in the country with the highest autarky price, as production with the highest marginal cost is replaced with import from the country with the lowest autarky price. With the price pattern of relatively low prices at night and high prices in daytime in Germany, this will typically lead Germany to export electricity at night, and import during daytime (Vista Analyse, 2014). This lead to a higher utility for both countries in terms of bottleneck revenues[11] and increased consumer- and producers surplus.

A question of particular interest in this paper is to what extent interconnecting transmission grids will lead to an increased use of electricity generated from renewable sources. The transmission grid will facilitate increased production of renewable energy in both countries and thereby contribute to a sustainable energy system for future generations (Statnett, 2016; TenneT, 2016). Facilitating cross-border electricity trade implies that German intermittent electricity producers will receive a higher price for their output by selling it to Norway. This will likely affect the investment decisions of new renewable energy plants. However, whether or not the price effects when opening up for trade are sufficient to replace thermal power production with intermittent energy will be subject to discussion in this paper.

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[11] Bottleneck revenues occur when power is transferred between areas with different prices and constitutes the net investment value (Vista Analyse, 2014)

3. Energy- and climate policy in EU

IPCC[1] recognizes that climate change is caused by human activities that produce high GHG emissions, such as burning of fossil fuels and deforestation. The European Union is responsible for 10% of global GHG emissions. Furthermore, the energy sector causes the largest GHG emissions with 80% of its output stemming from fossil fuels. Being the worlds second largest economy and the fifth larger consumer of energy, the EU have a great influence in terms of mitigating global climate change (European Commission, 2014b, 2014a). Their energy portfolio is quite diversified. To illustrate, it consists of dams in Austria, large nuclear production in France, gas fields in Netherlands and wind power in Germany among many other energy sources. However, the EU consumes 20% of the world energy and their input factors in thermal power production are to a large extent imported from Russia and OPEC. In order for Europe to become less import dependent and to increase their production share of renewable energy, it is crucial to invest in modern infrastructure in order to better integrate the regional energy market (European Commission, 2016, 2014b).

The EU member countries have to cooperate in order to develop a diversified energy portfolio and to secure future energy supply channels. Ever since the Second World War, energy has been of great importance for the EU project, as it was the starting point for the first European Treaties. It was recognized already at this point that the member countries were obliged to cooperate in order to secure supply of energy. As of today, the objectives are aimed towards creating a European Energy Union (European Commission, 2014b). The electricity sector in Europe is predicted to undergo major changes in the following decades. This is mainly due to the environmental targets the European Commission has set for 2020 and 2030 as well as the road map for 2050, whose aim is a durable reduction in GHG emissions and energy consumption. Norway and Iceland are committed to these targets as well (Gaudard & Romerio, 2014). In order to secure energy supply while simultaneously mitigating climate change, the EU has launched strategies aiming to spur on substantial investments in infrastructure (European Commission, 2014b).

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[1] Intergovernmental Panel on Climate Change

Nonetheless, these targets are not only set to combat global warming, but are also coupled with the fact that the EUs stock of fossil fuels is non-renewable and diminishing. It is thus urgent for the EU to rethink their energy supply security. Furthermore, in the aftermath of the Fukoshima accident in Japan in 2011, several European countries have decided to phase out production of nuclear power, Germany being one of them (deLlano Paz et al., 2016). This will have great implications for the electricity market, as the reduction of nuclear power has to be replaced by alternative sources.

3.1 Energy- and climate targets

Based on challenges in terms of energy supply and environmental considerations, the European Commission has laid out a road map with targets for 2020, 2030 and 2050. By doing so, the EU aims at achieving three main objectives. Firstly, the European Union needs to secure future energy supply, which requires improved transmission grids both nationally and across state borders. Secondly, the policies implemented must ensure that the European Union stays competitive with the futures energy prices, as many businesses and industries rely on energy as an important input factor. Lastly, the EUs climate policy goals aim at protecting the environment and mitigating climate change. The ambitious targets has signalized to the world that EU strives towards being a leader in international climate change mitigation efforts (Bürgin, 2015; European Commission, 2014a).

3.1.1 2020-targets

In 2009, the European Commission agreed on the energy and environmental targets for 2020, often referred to as the 20-20-20 package. Firstly, the EU is committed to reduce GHG emissions by 20% within 2020, compared to 1990 level. Furthermore, EU has committed to a 20% RES [2] share by 2020, implying that 20% of final energy consumption are to come from renewable sources. A way of mitigating climate change without compromising the modern society's standard of living is by using electricity in a more efficient manner. The European Commission therefore decided to cut consumption by 20% within 2020, with reference to the 1990 level. This is equivalent to shutting down 400 power stations. Among the measures taken to achieve

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[2] RES share is the share of energy generated from renewable sources

this target is improving indoor heating efficiency and reducing energy waste (Bürgin, 2015; European Commission, 2014b).

With the 20-20-20 package being implemented in 2009, Europe is the first region to legally bind their climate and energy targets. However, due to differing starting points and renewable energy potential, the member countries were allocated different national targets (European Commission, 2014a). The EU targets were therefore converted into national binding targets, based on baseline energy mix, renewable energy production potential and GDP level. Sweden has a RES share target of 49% due to favorable hydropower production conditions, whereas Malta is only committed to a RES share of 10%. Moreover, a small up-scaling in the RES share is required for countries that have initially attained a high RES share, Norway being a good example. Generally, countries in the northern part of EU are committed to a higher RES share than in the southern part due to favorable wind conditions, as wind energy is the most important renewable energy source for the future (Knopf et al., 2015).

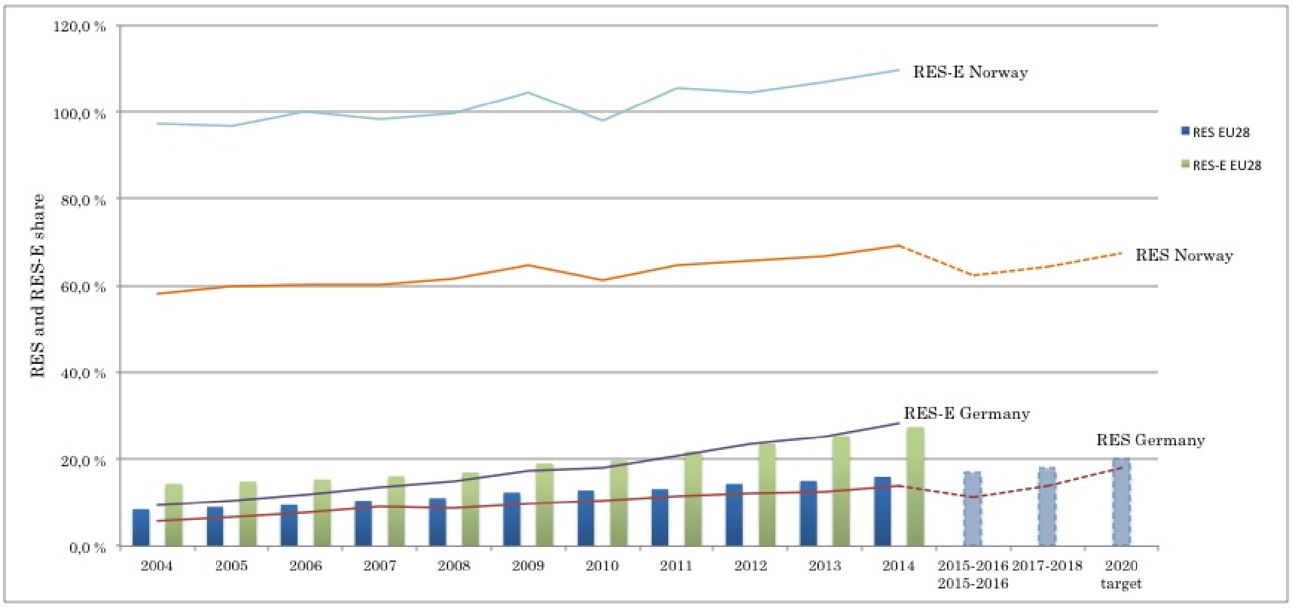

Figure 3.1: RES and RES-E level in EU, Germany and Norway from 2004-2015
Source: EuroStat (Energy statistics - main indicators)

Figure 3.1 illustrates the RES- and RES-E share of Germany, Norway and EU between 2004 and 2015. Furthermore, the RES share targets of EU between 2015 and 2020 are illustrated, as well as the predicted development in the RES share of Norway and Germany. The positive development of the RES-E share is apparent both for Germany and for the EU as a whole.

3.1.2 2030-targets

In January 2014 the EU launched the 2030 targets. The new targets are an extension of the 2020 targets and are designed to increase security of supply, reduce import dependence, ensure competitive and affordable prices as well as reduce GHG emissions (European Commission, 2014a). The target for GHG emissions reduction has increased to 40% compared to 1990 level. Furthermore, the level of RES share was, according to the 2020 targets expected to reach 24.2% with the current policies by 2030. However, the 2030 targets aims to reach a RES share of 27%, thus making the new target slightly more ambitious. Additionally, the 2030 are no longer legally binding for the member states (Bürgin, 2015). Nonetheless, the long-term strategy is of great importance to increase certainty for investors with respect to investment decisions in long-term infrastructure projects, cross-country transmission cables being one of them (European Commission, 2014b). Lastly, the improved energy efficiency target has increased to 27%, as an indicative target.

A RES share of 27% is not arbitrarily determined. A 27% RES share is the cost efficient share to reach a 40% reduction in GHG emission according to the European Commissions own modeling analysis. Furthermore, the 27% renewable energy target corresponds to a 49% RES-E share[3] according to the Impact analysis by the European Commission (Knopf et al., 2015). Hence, the cost-effective benchmark of RES-E share is 49%. The relatively high sectorial target reflects the major influence reconstruction in the electricity sector has with respect to reaching the UN global climate target of preventing the global average temperature to rise more than 2 °C in 2100 relative to 1850 level (United Nations, 2016). As stated in the previous chapter, Germany has increased their RES-E share by 20% the past decade. If this positive development continues Germany is set out to reach the EU's 2030 target of a 27% RES-E share. Even though the 2030 targets have not been translated into national targets it is reasonable to assume that Germany must have a relatively high RES-E share compared to other member countries and must continue to increase their RES-E share if the EU are going to successfully reach their targets.

Compared to the 2020 target, the 2030 targets lack a governance mechanism, as they do not address the national distribution of RES and consequently RES-E shares. Without binding RES-E shares it might become politically difficult to achieve the regional cost efficient benchmark of 49% within 2030. Knopf et al. (2015) supports this argument and highlights that

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[3] RES-E share is the share of electricity generated from renewable sources

non-binding national targets may lead to unfair effort sharing within the region. A possible implication of unfair distribution is that even though the RES-E share target is reached by 2030, it may not be reached at minimum cost. Bürgin (2015) further argues that a reason for the no longer binding national targets are due to high bargaining power of the large energy producers as well as the energy intensive industries. Nonetheless, substantial improvements and investments in infrastructure are required to reach the targets by 2030. Even though the European Commission has not specified legally binding targets for each member countries, Germany plans to have an 80 % RES by 2050 as well as reducing its emissions by 80 per cent compared to 1990 level (Forbes, 2015).

3.1.3 2050-targets

Moreover, EU has ambitious long-term target set to 2050: reduce GHG emissions by 80-95% in 2050 from 1990 level and reduce use of energy by 30%. Increasing energy efficiency is vital to achieve these goals (European Commission, 2014a). In any case, industrialised countries outside of the EU are required to take similar actions for the world to reach the UN two-degree target by 2100 (United Nations, 2016).

3.2 Policies implemented

Based on the objectives and specified targets, policy must be implemented in a manner that promotes production of renewable energy sources and at the same time solve the uncertainty arising from renewable energy production (deLlano Paz et al., 2016).

A current political instrument implemented towards reaching these goals is subsidizing renewable energy production, so called green el-certificates, which is estimated to give a 26 TWH increased production within 2020 (Statnett, 2013). Furthermore, the implementation of the EU Emission Trading System (ETS) has been successful in reducing emissions. By gradually reducing total yearly emission cap, i.e. reducing total quotas distributed, reduction of emissions in EU are estimated to reach 21% in 2020 compared to 2005 level. So far, the implemented policies seem quite successful as a boom in renewable energy has been observed in Europe the latest years. Out of the 100GW solar panels installed globally in 2011, 70% of these were installed in EU (European Commission, 2014a). Furthermore, the investment cost of solar panels has decreased by 70% over the past 7 years (in 2014). Transmission cables will play an important role in offsetting renewable energy in periods with surplus of energy. Lastly, a long term intention is electrification in the petroleum- and indoor heating sector. However, it takes time to develop new technologies, and they will not grow at the speed of increased renewable production. Transmission cables therefore becomes vital to offset energy surplus until demand in these sectors reaches the level of total energy production (Statnett, 2013).

Investments in infrastructure are one of EUs strategies towards reaching their climate targets. More precisely, the European Commission has specified electricity interconnection targets, implying that all member states shall achieve interconnection with neighboring countries of minimum 10% of installed electricity production capacity by 2020. Interconnections across borders increases energy security, as member countries can rely on electricity supply from neighboring countries. By identifying priority interconnections as Project of Common Interest (PCI), the European Commission supports these infrastructure investments with financing from European Fund for Strategic Investments and the Connecting Europe Facility (European Commission, 2015).

Knopf et al. (2015) argues that renewable energy targets and infrastructure planning has to be considered simultaneously. This is due to the fact that the EU RES targets affect the required cross-country transmission grids because some countries will become exporters and some will become importers of energy. Moreover, deLlano Paz et al. (2016) argues that an increased RES share affects the dependency on outside resources as well as it affects the energy security. This indicates that improved cross-border transmission capacity is required. Transmission cables are capable of managing a higher share of intermittent energy in the power system. By carrying out a theoretical analysis in the following chapters I hope to reveal to what extent interconnected European energy markets can lead to more flexible electricity markets and propel a move away from the use of fossil fuels.

4. The model

The model applied in this paper studies the effects of opening up for electricity trade between two countries with different electricity generating technologies. The base model is developed by (Førsund, 2015, pp. 131-159), but some extensions and simplifications are introduced to the model. Firstly, I have included that Germany[1] produces a mix of thermal and intermittent power. Secondly, I have simplified the thermal power production function by only considering one type of thermal power. Furthermore, I have specified the demand functions and marginal cost function of thermal power production with linear functions. Lastly, I have limited the model to only consider day- and night trade. The reason for this is the relatively large price fluctuations within 24 hours in Germany compared to Norway, which facilitates gains of trade for both countries.

The theoretical analysis is divided into three chapters. This chapter explains the properties of the demand function for energy and considers three different energy generating sources, namely hydro-, thermal- and intermittent power. More specifically, Norway (N) produces only hydropower, whereas Germany (G) produces a mix of thermal- and intermittent power. Furthermore, an explanation of how prices and optimal power production are determined in autarky is carried out in this chapter. Chapter 5 analyzes how opening up for trade between two electricity producing countries affect optimal production and prices. The trade prices and output are compared to the autarky solutions. Chapter 6 introduces endogenous investments in intermittent energy. The results from chapter 4 and 5 will be applied to analyse how investment decisions are affected when opening up for electricity trade between two countries. Emphasis will be put on how the capacity of the transmission cable contributes to determining optimal investments in intermittent energy. The aim of the analysis is to investigate to what extent international electricity trade can facilitate the transition to a larger use on renewable energy sources and thereby mitigate climate change.

The model is a partial equilibrium model, implying that interaction with the rest of the economy is not taken into consideration. Furthermore, the model only considers optimal management of

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[1] Førsund (2015) labels this country ”Thermal”

existing power generating facilities and thereby disregards investment costs. This assumption will be eased in chapter 6. Moreover, the model only studies the social optimal situation and no exploitation of market power is considered. Producers are small and take the price as given. Førsund (2013) argues that a two period model captures the main feature of a general solution, which supports the following simplification. The time horizon is constrained to two periods, T, the first period being night and the second being day. The cycle is repetitive, implying that all days throughout a year are identical. Furthermore, the model assumes full certainty with regards to inflow of water, demand, input prices and intermittent capacity for all periods. Lastly, environmental effects are in this analysis considered as effects caused by emission from thermal power production. To what extent the underlying assumptions replicate the real market is subject to discussion in the latter part of the paper. Explanation of variables and parameters are listed on page vi.

4.1 Electricity demand

Electricity demand for country[2] C is modelled in (4.1) as a linear function with standard properties. Demand is negatively dependent on the electricity price.

$$D_t^C = p_t^C(x_t^C) = b_t^C - m_t^C x_t^C \tag{4.1}$$

for $x_t > 0$ and $p_t > 0$, where x_t is energy used in period t and b_t^C and m_t^C are positive, time specific constants. The demand is time specific and will be lower and more elastic by night. From (4.1) we thus have that $b_1 < b_2$ and $m_1 < m_2$. Consumers do not have preferences for green energy implying that renewable- and thermal electricity are perfect substitutes to the consumer (Førsund, 2015, p. 24). A graphical illustration of two different demand curves are presented in figure 4.1, where D_1 and D_2 is the demand curve for electricity at night and daytime, respectively. The electricity demand at daytime has a higher intersection with the vertical axis and is more inelastic than the demand at night. For an arbitrarily chosen price, indicated by p in figure 4.1, the amount of electricity demanded is higher in daytime, $x_2 > x_1$.

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[2] C indicates country, either N (Norway) or G (Germany)

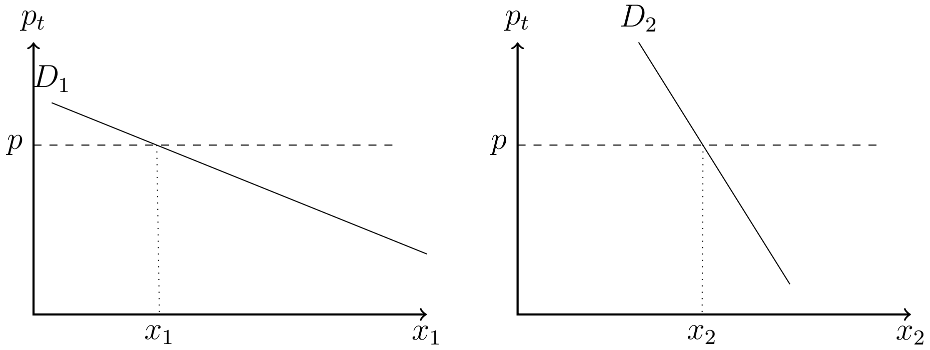

Figure 4.1: Demand for electricity

4.2 Hydropower

Hydropower production in Norway is represented as follows. The variable cost associated with production of hydropower is assumed to be zero. Investment cost are not included as this model only evaluates management of an existing hydropower system. The only cost the producer faces is the opportunity cost of water as one can choose to leave the water in the reservoir for the next period. Thus, optimal production of hydropower is a dynamic problem. Furthermore, the model disregards production constraints within a period as well as evaporation of water. Additionally, overflow of water is never optimal. As the model evaluates two periods, night and day, I assume that the maximum reservoir capacity will not be reached, and a binding reservoir constraint will not be relevant to discuss in a night/day periodic model. Lastly, production of hydropower is assumed to be positive in every period. The following relations describes the dynamics of hydropower production (Førsund, 2013, p. 200).

$$e_t^H = \frac{1}{n} r_t \tag{4.2}$$

$$R_t \leq R_{t-1} + w_t - r_t \tag{4.3}$$

$$R_t, e_t^H \geq 0, \text{ for t= 1,2} \tag{4.4}$$

(4.2) Transformation of water to electricity, where e_t^H is electricity produced in period t, measured in KWh, r_t is the water released into the turbines and n is the unit requirement of water r_t to produce one unit of energy, KWh. This implies that technology is embedded in n, but in this model we disregard any changes in technology and take n as exogenously given.

(4.3) R_t, the amount of water at the end of period t, is less or equal to the water left in the reservoir at the end of the previous period, R_{t-1}, plus inflow in the current period, w_t, minus water outflow used in production, r_t.

(4.4) R_t and e_t^H can never be negative.

By inserting for r_t from (4.2) into (4.3) and dividing with n on both sides we get (4.5), where all variables are now measured in energy units, KWh. For simplicity, n is set equal to 1.

$$R_t \leq R_{t-1} + w_t - e_t^H \tag{4.5}$$

The social planner's optimal solution is found by maximizing the objective function given in (4.6), namely the sum of consumer and producers surplus over all periods T. As the production cost equals zero, the objective function is the gross area below the demand curve (Førsund, 2015, p. 132).

$$\max \sum_{t=1}^{T} \int_{x=0}^{e_t^H} \underbrace{(b_t^N - m_t^N x_t^N)}_{D_t^N = p_t^N(x_t^N)} dx \tag{4.6}$$

subject to (4.3) and (4.4). R_t, w_t and R_0 are exogenously given, $T = 2$ and R_{t+1} is zero, implying that the reservoir will be emptied at the end of the second period.

4.2.1 Solution to the social planning problem

The Lagrange function to the non-linear programming problem in (4.6) is presented in (4.7). In autarky, consumption x_t must equal hydropower production e_t^H.

$$L = \sum_{t=1}^{T} \int_{x=0}^{e_t^H} (b_t^N - m_t^N x_t^N)dx - \sum_{t=1}^{T} \lambda_t (R_t - R_{t-1} - w_t + e_t^H) \tag{4.7}$$

where λ_t is the shadow price of water in period t. We find the necessary Kuhn-Tucker conditions, often referred to as the first order condition, by deriving (4.7) wrt. the endogenous variables e_t^H and R_t (Sydsæter et al., 2008).

$$\frac{\partial L}{\partial e_t^H} = b_t^N - m_t^N e_t^H - \lambda_t \leq 0 \qquad [= 0 \text{ for } e_t^H > 0] \tag{4.8}$$

$$\frac{\partial L}{\partial R_t} = -\lambda_t + \lambda_{t+1} \leq 0 \qquad [= 0 \text{ for } R_t > 0] \tag{4.9}$$

Furthermore, we have the following complementary slackness condition

$$\lambda_t \geq 0 \qquad [= 0 \text{ for } R_t < R_{t-1} + w_t - e_t^H] \tag{4.10}$$

(4.8) In optimum, price is equal to the shadow price on water when hydropower production is positive.

(4.9) The shadow price of water will be equal in both periods, implying that the price is constant.

(4.10) The shadow price on water is greater or equal to zero.

e_t^* and p_t^* is derived by applying the first order conditions above. Furthermore, total production of hydropower in the two periods are exogenously given by $\overline{H}$, where $\overline{H} = e_t^H + e_2^H$. By applying that $x_t = e_t^H$ in (4.8) we have

$$b_2^N - m_2^N[\overline{H} - e_1^H] \leq b_1^N - m_1^N e_1^H \tag{4.11}$$

By assuming that $t = 1$ is the low demand period, and $t = 2$ is the high demand period, $0 < R_1 \leq \overline{R}$ and we therefore have an equality in (4.11) as it is optimal for the producer to save water for the high demand period. As (4.11) holds with equality we thereby have

$$e_1^{H*} = \frac{b_1^N - b_2^N + m_2^N\overline{H}}{m_1^N + m_2^N} \tag{4.12}$$

By inserting for $e_1^{H*} = \overline{H} - e_2^H$ in (4.12) we find optimal production in $t = 2$

$$e_2^{H*} = \overline{H} - \underbrace{\frac{b_1^N - b_2^N + m_2^N\overline{H}}{m_1^N + m_2^N}}_{e_1^{H*}} = \frac{b_2^N - b_1^N + m_1^N\overline{H}}{m_1^N + m_2^N} \tag{4.13}$$

p_1^* is derived by inserting for optimal production in the demand function from (4.1), where $e_t^H = x_t^N$. From (4.9) we have that prices will be equal in both periods, such that

$$p_1^{N*} = b_1^N - m_1^N\left[\frac{b_1^N - b_2^N + m_2^N\overline{H}}{m_1^N + m_2^N}\right] = \lambda_1$$

$$p_1^{N*} = \frac{b_1^N m_2^N + b_2^N m_1^N - m_1^N m_2^N\overline{H}}{m_1^N + m_2^N}$$

$$p_1^{N*} = \frac{b_1^N m_2^N + m_1^N[b_2^N - m_2^N\overline{H}]}{m_1^N + m_2^N} = p_t^{N*} \tag{4.14}$$

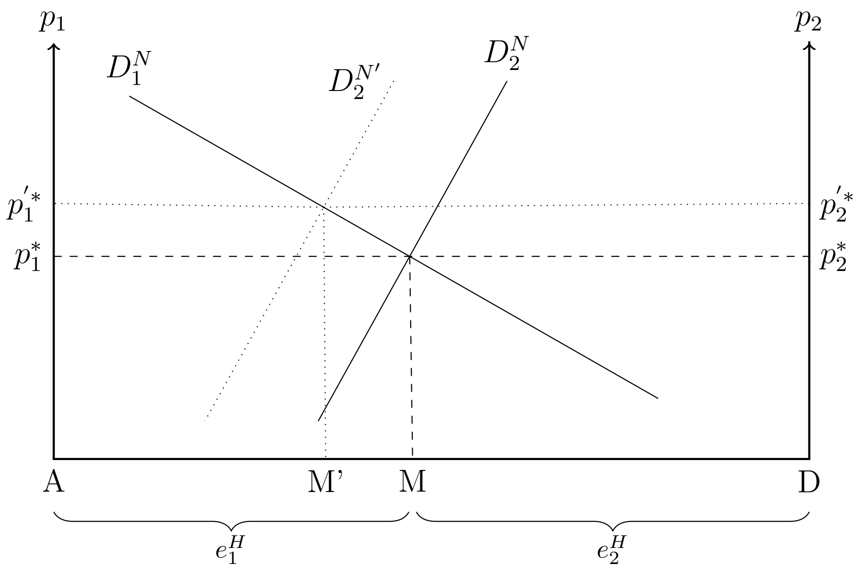

Figure 4.2: Two period model of optimal hydropower production

Figure 4.2[3] illustrate the optimal solution in a two period bathtub model, and the optimal allocation of water between the periods. Period 1 is measured from the left hand bathtub wall and rightwards whereas period 2 is measured from the right hand bathtub wall and leftwards. The horizontal distance between A and D is the total water available in both periods, $\overline{H}$. The intersection between the two demand curves indicate optimal storage of water between the periods on the horizontal axis, labeled with M. At this point, the shadow price of water in each period are equal. Optimal production, e_1^{H*} and e_2^{H*} is defined by respectively A-M and M-D.

To illustrate the effect of a change in demand, an alternative demand function for period 2 is included, $D_2^{N'}$, where $b_2^{N'} > b_2^N$. A higher demand in the second period leads to higher prices in both periods as well as a change in allocation of water between the periods. In this case, it is optimal for the producer to save more water for period 2. This implies a lower production in the first period, $e_1^{H'}$, and a higher production in the second period, $e_2^{H'}$.

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[3] Source of figure 4.2 is a combination of two figures in (Førsund, 2013, p. 2014), where the reservoir constraint is removed.

4.3 Thermal power generation

This section presents the properties of thermal power production, which is based on the following assumptions. Optimal production of thermal power is represented by a static problem, not dynamic as was the case with hydropower. Thus, start up and shut down cost are disregarded. Furthermore, the cost function is not time specific and assumed to be equal for all periods. Lastly, production is assumed to be positive for all periods, t.

$$e_t^{Th} \geq 0 \text{ for } t = 1, 2 \tag{4.15}$$

The aggregated operation cost of all thermal power production plants are represented in the following function

$$c(e_t^{Th}) = \frac{1}{2}k(e_t^{Th})^2 + qe_t^{Th} + C$$

where k, q and C are positive constants. C represents a fixed cost independent on output and q represents a fixed part of the operation cost (Wangensteen, 2012, p. 120). The marginal production cost is a linear function increasing in output and is represented by (4.16)

$$c'(e_t^{Th}) = ke_t^{Th} + q \tag{4.16}$$

where the constant k is the slope of the marginal cost curve, and q is the intersection with the y-axis. The marginal cost function is graphically illustrated in figure 4.3.

4.4 Intermittent energy generation

A simplified model of energy generation from intermittent sources is represented by the following functions

$$e_t^I \leq a_t^I \overline{e}^I \text{ where } a_t^I \in [0, 1] \tag{4.17}$$

where e_t^I is intermittent power generated, a_t^I is the capacity factor of intermittent energy and $\overline{e}^I$ is the maximum capacity of production. a_t^I and $\overline{e}^I$ are exogenously given in the model, implying that production of intermittent power, e_t^I is also given exogenously. Furthermore, I assume that $a_1^I > a_2^I$, meaning that the intermittent capacity is higher in the first period. Production of intermittent power has a zero marginal cost and investment cost is, until further, disregarded. By assuming that $\overline{e}^I$ is never sufficient to satisfy demand alone, we have that $e_t^I = a_t^I \overline{e}^I$.

4.5 Mix of thermal- and intermittent power plants

In Germany, electricity generation is based on both thermal- and intermittent power and the energy balance is therefore given by

$$x_t^G = e_t^{Th} + e_t^I \tag{4.18}$$

Since a_t^I and $\overline{e}^I$ are predetermined, e_t^I is exogenously given. The optimal solution is found by maximizing the objective function given in (4.19), subject to (4.1), (4.16) and (4.18).

$$\max \sum_{t=1}^{T} \left[\int_{x=0}^{e_t^{Th}+e_t^I} (b_t^G - m_t^G x_t^G) dx - c(e_t^{Th}) \right] \tag{4.19}$$

4.5.1 Solution to the social planning problem

The Lagrange function to the problem in (4.19) is the following

$$L = \sum_{t=1}^{T} \left[\int_{x=0}^{e_t^{Th}+e_t^I} (b_t^G - m_t^G x_t^G) dx - c(e_t^{Th}) \right] \tag{4.20}$$

We find the first order condition by deriving (4.20) wrt. e_t^{Th}

$$\frac{\partial L}{\partial e_t^{Th}} = b_t^G - m_t^G(e_t^{Th} + e_t^I) - (ke_t^{Th} + q) \leq 0 \qquad [= 0 \text{ for } e_t^{Th} > 0] \tag{4.21}$$

From (4.21) we find optimal production of thermal power $e_t^{Th^*}$ in period t, assuming that $e_t^{Th} > 0$.

$$\begin{aligned} b_t^G - m_t^G[e_t^{Th} + e_t^I] &= ke_t^{Th} + q \\ e_t^{Th}[m_t^G + k] &= b_t^G - m_t^G e_t^I - q \\ e_t^{Th^*} &= \frac{b_t^G - m_t^G e_t^I - q}{m_t^G + k} \end{aligned} \tag{4.22}$$

By inserting $e_t^{Th^*}$ in the demand function we find the price in period t.

$$\begin{aligned} p_t^G(x_t^{G^*}) = b_t^G - m_t^G &\left[\frac{b_t^G - m_t^G e_t^I - q + e_t^I[m_t^G + k]}{m_t^G + k} \right] \\ p_t^{G^*} &= \frac{b_t^G k + m_t^G \left[q - e_t^I k \right]}{m_t^G + k} \end{aligned} \tag{4.23}$$

As both production of thermal- and intermittent power are static problems, the price equation in (4.23) will be equal for all periods t.

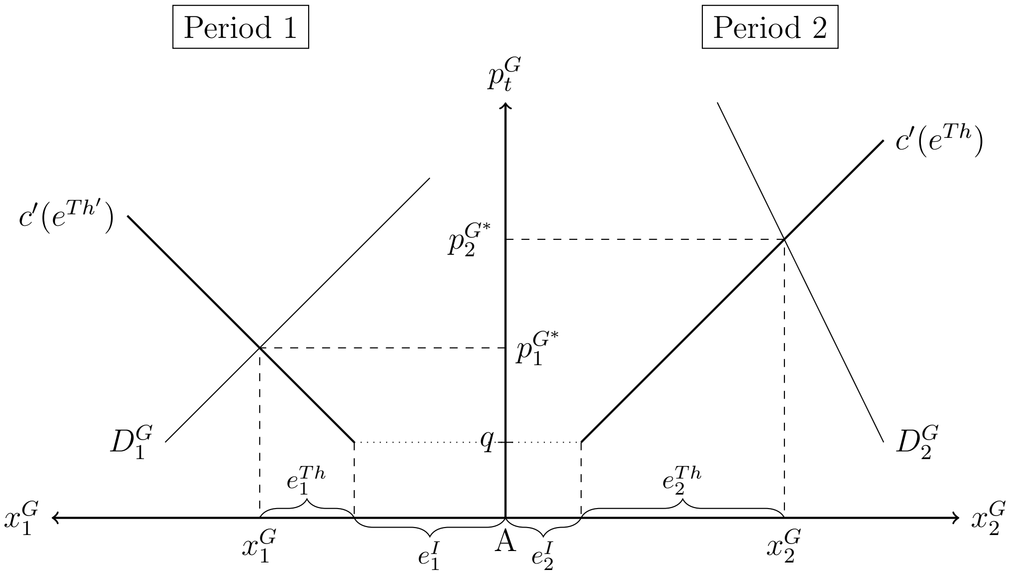

Figure 4.3: Two-period model of optimal production of thermal power and intermittent

Figure 4.3 illustrates how prices and quantities of electricity are determined in a market with thermal- and intermittent power producers, in a two period model. The market is in equilibrium when the marginal cost of production intersects with the demand curve. Period 1 is measured from A and leftwards, whereas period 2 is measured from A and rightwards. As we are facing a static problem, what happens in the first period does not affect the outcome of the second period. The figure illustrates how prices may differ between two periods when production of intermittent energy is higher in the first period, $a_1^I < a_2^I$. The marginal cost of thermal power production curves are equal in both periods, but the demand curves differ between the periods. Prices are higher in period 2 due to a higher demand as well as a lower intermittent capacity.

5. Electricity trade

This chapter will analyse the effects of opening up for trade, i.e building a transmission cable, between a country producing hydropower and a country producing a mix of thermal- and intermittent power, Norway and Germany respectively. The aim of the chapter is to explain how prices and output are determined in a market with two power generating countries. The model presented in this chapter is combines the two markets presented in the previous chapter.

Norway and Germany only trade electricity with each other so that one country's import equals the other country's export within a period. However, the model does not require trade balance between the periods, so export from one country is not required to equal import in the second period. Furthermore, the model assumes that Norway and Germany are cooperating and seek a joint social optimal solution. The investment cost of building the transmission cable as well as rent of using the cable is not considered.

5.1 The optimization problem

The cooperative optimization problem in (5.1) is found by maximizing the sum of consumer and producer surplus in both countries, for T=2.

$$\max \quad \sum_{t=1}^{T} \left[\int_{x=0}^{x_t^N} (b_t^N - m_t^N x_t^N) dx + \int_{x=0}^{x_t^G} (b_t^G - m_t^G x_t^G) dx - c(e_t^{Th}) \right] \tag{5.1}$$

Subject to

$$\begin{aligned} x_t^N &= e_t^H + e_{G,t}^{XI} - e_{N,t}^{XI} && (5.2)\\ x_t^G &= e_t^{Th} + e_t^I + e_{N,t}^{XI} - e_{G,t}^{XI} && (5.3)\\ e_{G,t}^{XI} &= e_{Th,t}^{XI} + e_{I,t}^{XI} && (5.4)\\ R_t &\leq R_{t-1} + w_t - e_t^H && (5.5)\\ e_{N,t}^{XI} &\leq \overline{e}^{XI} \text{ and } e_{G,t}^{XI} \leq \overline{e}^{XI} && (5.6)\\ & && (5.7) \end{aligned}$$

where $x_t^H, x_t^G, e_t^H, e_t^{Th}$ are $> 0, e_{N,t}^{XI}, e_{G,t}^{XI}, R_t \geq 0$

and $T, w_t, R_0, \overline{e}^{XI}$ are given and $R_T = 0$ for $t = 1, 2$

(5.2) Electricity consumption in Norway equals total hydropower production minus net export to Germany in period t.

(5.3) Electricity consumption in Germany equals the sum of production of intermittent and thermal electricity minus net export of electricity to Norway in period t.

(5.4) Germany's export in period t is the sum of electricity produced minus demand in Germany.

(5.6) Illustrates that export is constrained by the capacity of the transmission cable. Export cannot exceed the transmission capacity in one period.

5.2 Solution to the social planning problem

The Lagrange function to problem (5.1) is

$$\begin{aligned} L = \sum_{t=1}^{T} \left[\int_{x=0}^{e_t^H + e_{G,t}^{XI} - e_{N,t}^{XI}} (b_t^N - m_t^N x_t^N) dx + \int_{x=0}^{e_t^{Th} + e_t^I + e_{N,t}^{XI} - e_{G,t}^{XI}} (b_t^G - m_t^G x_t^G) dx - c(e_t^{Th}) \right] \\ - \sum_{t=1}^{T} \lambda_t (R_t - R_{t-1} - w_t + e_t^H) - \sum_{t=1}^{T} \alpha_{N,t} (e_{N,t}^{XI} - \overline{e}^{XI}) - \sum_{t=1}^{T} \alpha_{G,t} (e_{G,t}^{XI} - \overline{e}^{XI}) \end{aligned} \tag{5.8}$$

where $\alpha_{N,t}$ is the shadow price on the export constraint for Norway and $\alpha_{G,t}$ is the shadow price on the export constraint for Germany. We find the necessary first order conditions by deriving (5.8) wrt. the endogenous variables

$$\frac{\partial L}{\partial e_t^H} = b_t^N - m_t^N x_t^N - \lambda_t \leq 0 \qquad [= 0 \text{ for } e_t^H > 0] \tag{5.9}$$

$$\frac{\partial L}{\partial e_{N,t}^{XI}} = -(b_t^N - m_t^N x_t^N) + b_t^G - m_t^G x_t^G - \alpha_{N,t} \leq 0 \qquad [= 0 \text{ for } e_{N,t}^{XI} > 0] \tag{5.10}$$

$$\frac{\partial L}{\partial R_t} = -\lambda_t + \lambda_{t+1} \leq 0 \qquad [= 0 \text{ for } R_t > 0] \tag{5.11}$$

$$\frac{\partial L}{\partial e_t^{Th}} = b_t^G - m_t^G x_t^G - (k e_t^{Th} + q) \leq 0 \qquad [= 0 \text{ for } e_t^{Th} > 0] \tag{5.12}$$

$$\frac{\partial L}{\partial e_G^{XI}} = b_t^N - m_t^N x_t^N - (b_t^G - m_t^G x_t^G) - \alpha_{G,t} \leq 0 \qquad [= 0 \text{ for } e_{G,t}^{XI} > 0] \tag{5.13}$$

Furthermore, we have the following complementary slackness conditions, for t=1,2.

$$\lambda_t \geq 0 \qquad [= 0 \text{ for } R_t < R_{t-1} + w_t - e_t^H] \tag{5.14}$$

$$\alpha_{N,t} \geq 0 \qquad [= 0 \text{ for } e_{N,t}^{XI} < \overline{e}^{XI}] \tag{5.15}$$

$$\alpha_{G,t} \geq 0 \qquad [= 0 \text{ for } e_{G,t}^{XI} < \overline{e}^{XI}] \tag{5.16}$$

5.2.1 Interpretation of the solution

(5.9) Optimal price is found were the demand equals water value, $b_t^N - m_t^N x_t^N = \lambda_t$, as production of hydropower is assumed to be positive for both period, $e_t^H > 0$.

(5.10) and (5.13) implies that when export is positive, the prices will be equal for both countries unless the export is at maximum capacity, $e_{N,t}^{XI} = \bar{e}^{XI}$. Prices will only differ when the transmission cable is constrained.

(5.10) When Norway is export constrained, $\alpha_{N,t} > 0$ prices will be lower in Norway, $p_t^N < p_t^G$. Norway is forced to use more electricity at home, which pushes the domestic prices down. Germany, in this case, is rationed by import, which results in higher prices in Germany.

(5.13) When Germany is export constrained, $\alpha_{G,t} > 0$ and prices will be lower in Germany, $p_t^N > p_t^G$.

(5.12) Prices in Germany are determined where demand equals the marginal cost of thermal power production, $b_t^G - m_t^G x_t^G = k e_t^{Th} + q$. With a non-binding trade capacity constraint, $\alpha_{G,t}^{XI} = 0$, we have equal prices in both countries, which in turn are equal to the marginal cost of thermal power.

We have until now assumed that the supply of intermittent energy is exogenously given. Production of intermittent energy is determined by the intermittent capacity, a_t^I and has an upper production limit due to a maximum production capacity. Furthermore, as production of intermittent energy has a zero marginal cost, electricity will always be produced when $a_t^I > 0$. The level of a_t^I contributes to determining the electricity prices in Germany. Since prices are endogenously determined in the model, the intermittent capacity also affect electricity prices in Norway.

5.3 Deriving optimal trade prices and production

As argued in chapter 2, Norway's export will continue to grow in the coming years. Furthermore, the cable capacity of NordLink is rather small compared to total energy balance surplus in Norway, and I will therefore assume that the transmission capacity is binding in the period Norway export to Germany, which will be in daytime, $t = 2$, when prices are relatively high in Germany. Data from 2015 shows that Norway exported 15%[1] of total production, which was 22 038 GWh. This is equal to an average export of around 2500 MW at all times[2], which is much higher than the capacity of NordLink at 1400 MW. On the other hand, as mentioned in chapter 2, Germany is a net importer of electricity, and imports around 60% of total consumption. Thus, I will assume that the transmission capacity does not bind in the period where Germany exports to Norway, $t = 1$.

Based on data presented in chapter 2, the electricity prices in Germany are characterized by low prices at night and high prices during the daytime, whereas Norway has relatively equal prices in both periods. A non-binding transmission capacity will lead to equal prices in Norway and Germany from (5.13) and (5.16). Furthermore, prices in Norway are equal in both periods (5.11). Due to a binding export constraint for Norway in the second period, (5.10) implies a difference in prices between the countries so that $p_2^N < p_2^G$. A sufficient amount of export from Norway in order to equalize the prices is not feasible with the given transmission capacity. The price gap is the shadow price on the export constraint, $\alpha_{N,2}$.

The following set of equations, consisting of 5 equations with 5 endogenous variables, determines optimal prices and production level.

$$b_1^N - m_1^N x_1^N = \lambda \tag{5.17}$$
$$b_2^N - m_2^N x_2^N = \lambda \tag{5.18}$$
$$b_1^G - m_1^G x_1^G = \lambda \tag{5.19}$$
$$k e_1^{Th} + q = \lambda \tag{5.20}$$
$$x_1^N + x_2^N + x_1^G = \overline{H} + e_1^{Th} + e_1^I - \overline{e}^{XI} \tag{5.21}$$

---

[1] Data retrieved from Statistics Norway

[2] Where $\frac{220\ 380\ 20 \text{ MWh}}{24*365} = 2516$ MW

Firstly, I find x_1^N, x_1^G and e_1^{Th} from respectively (5.17), (5.19) and (5.20) and insert these variables in (5.21) to find x_2^N

$$\frac{b_1^N - \lambda}{m_1^N} + \frac{b_1^G - \lambda}{m_1^G} + x_2^N = \overline{H} + \frac{\lambda - q}{k} + e_1^I - \overline{e}^{XI}$$

$$x_2^N = \overline{H} + e_1^I - \overline{e}^{XI} - \frac{q}{k} - \frac{b_1^N}{m_1^N} - \frac{b_1^G}{m_1^G} + \lambda\left[\frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right] \tag{5.22}$$

Secondly, λ is derived by inserting (5.22) into (5.18)

$$b_2^N - m_2^N\left[\overline{H} + e_1^I - \overline{e}^{XI} - \frac{q}{k} - \frac{b_1^N}{m_1^N} - \frac{b_1^G}{m_1^G} + \lambda\left[\frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]\right] = \lambda$$

$$\lambda\left[1 + m_2^N\left[\frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]\right] = m_2^N\left[\frac{b_2^N}{m_2^N} - \overline{H} - e_1^I + \overline{e}^{XI} + \frac{q}{k} + \frac{b_1^N}{m_1^N} + \frac{b_1^G}{m_1^G}\right]$$

$$\lambda = \frac{\frac{b_2^N}{m_2^N} - \overline{H} - e_1^I + \overline{e}^{XI} + \frac{q}{k} + \frac{b_1^N}{m_1^N} + \frac{b_1^G}{m_1^G}}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} = p_1^{G,Tr^*} \tag{5.23}$$

The price change, Δp_1^G is found by subtracting the autarky price in (4.23) from the trade price in (5.23)

$$\Delta p_1^G = \underbrace{\frac{\frac{b_2^N}{m_2^N} - \overline{H} - e_1^I + \overline{e}^{XI} + \frac{q}{k} + \frac{b_1^N}{m_1^N} + \frac{b_1^G}{m_1^G}}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}}}_{p_1^{G,Tr}} - \underbrace{\left[\frac{b_1^G k + m_1^G\left[q - e_1^I k\right]}{m_1^G + k}\right]}_{p_1^{G,AU}} \tag{5.24}$$

When finding optimal prices in $t = 2$ we have from (5.12) that

$$b_2^G - m_2^G x_2^G = k e_2^{Th} + q \tag{5.25}$$

Furthermore, total consumption in Germany in $t = 2$ is the sum of total production in Germany and import from Norway, $\overline{e}^{XI}$.

$$x_2^G = e_2^{Th} + e_2^I + \overline{e}^{XI} \tag{5.26}$$

x_t^G is derived by inserting e_2^{Th} from (5.26) into (5.25)

$$
\begin{aligned}
b_2^G - m_2^G x_2^G &= k(x_2^G - e_2^I - \bar{e}^{XI}) + q \\
x_2^G &= \frac{b_2^G - q + k(e_2^I + \bar{e}^{XI})}{k + m_2^G}
\end{aligned}
\tag{5.27}
$$

By inserting optimal production in the second period into the demand function we find optimal price, p_2^{G,Tr^*}.

$$
\begin{aligned}
p_2^{G,Tr^*} &= b_2^G - m_2^G \left[\frac{b_2^G - q + k(e_2^I + \bar{e}^{XI})}{m_2^G + k} \right] \\
p_2^{G,Tr^*} &= \frac{b_2^G k + m_2^G [q - k(e_2^I + \bar{e}^{XI})]}{m_2^G + k}
\end{aligned}
\tag{5.28}
$$

The price change from autarky to trade Δp_2^G is found by subtracting the autarky price, $p_2^{N,AU}$ in (4.23) from the trade price $p_2^{N,Tr}$ in (5.28)

$$
\begin{aligned}
\Delta p_2^G &= \underbrace{\frac{b_2^G k + m_2^G [q - k(e_2^I + \bar{e}^{XI})]}{m_2^G + k}}_{p_2^{G,Tr^*}} - \underbrace{\frac{b_2^G k + m_2^G \left[q - e_2^I k \right]}{m_2^G + k}}_{p_2^{G,AU^*}} \\
\Delta p_2^G &= -\frac{m_2^G k \bar{e}^{XI}}{m_2^G + k}
\end{aligned}
\tag{5.29}
$$

Figure 5.1[3] illustrates the optimal solution in a two period model, and combines figure 4.2 and 4.3. The autarky demand curves and optimal solutions are indicated with dotted lines, where B and C are respectively the hydro production bathtub walls in autarky. The German electricity market in period 1 is measured from B' (B in autarky) and leftwards, whereas the German market in period 2 is measured from C' (C in autarky) and rightwards. The Norwegian electricity market is measured between B' and C' (B and C in autarky). Initially, I have assumed lower prices in Germany than in Norway in period 1. When opening up for trade, Germany will export electricity to Norway until prices are equal in both countries. Optimal $e_{G,1}^{XI}$ is indicated in the figure, and the left hand bathtub wall B shifts leftwards to B', by $e_{G,1}^{XI}$. As D_1^N is erected from B, this curve will shift horizontally by $e_{G,1}^{XI}$, now erected from B'. The equilibrium price is slightly higher than the autarky price in Norway, but the production of hydropower is reduced remarkably in period 1. Hydropower production increases by the same amount in period 2, as total production of hydropower remains unchanged. As trading results in a higher

---

[3] The figure is a modification from Førsund (2015, p.157).

equilibrium price in Germany, production of thermal power increases. Furthermore, demand at p_1^{Tr} is lower than in autarky. In the second period, prices are initially higher in Germany, and export $e_{N,2}^{XI} = \overline{e}^{XI}$, by assumption. Both D_2^N and D_2^G shift horizontally to the left by $\overline{e}^{XI}$, and the trade equilibrium price in Germany is where D_2^G intersects with the marginal cost curve of thermal power production, $c'(e^{Th})$. A lower price in the second period reduces production of thermal power by Δe_2^{Th} and consumption x_2^G increases by $\overline{e}^{XI} - \Delta e_2^{Th}$. A constrained export capacity in the second period prevents Norway from exporting more to Germany, which gives higher prices in Germany than Norway because Germany are rationed by import. The price change in the second period is indicated in the figure by Δp_2^G. Graphically, a greater maximum transmission capacity will shift the right hand bathtub wall, C', further to the left, as will the demand curves in period 2. Consequently, p_2^G will decrease even further, and Δp_2^G becomes more negative. However, a greater transmission capacity will also affect the first period as Norway will increase its production of hydropower in the second period, and thus further decrease production in the first period. Optimal import in the first period increases, which shift the left hand bathtub wall B' further to the left, and Δp_1^G increases even more.

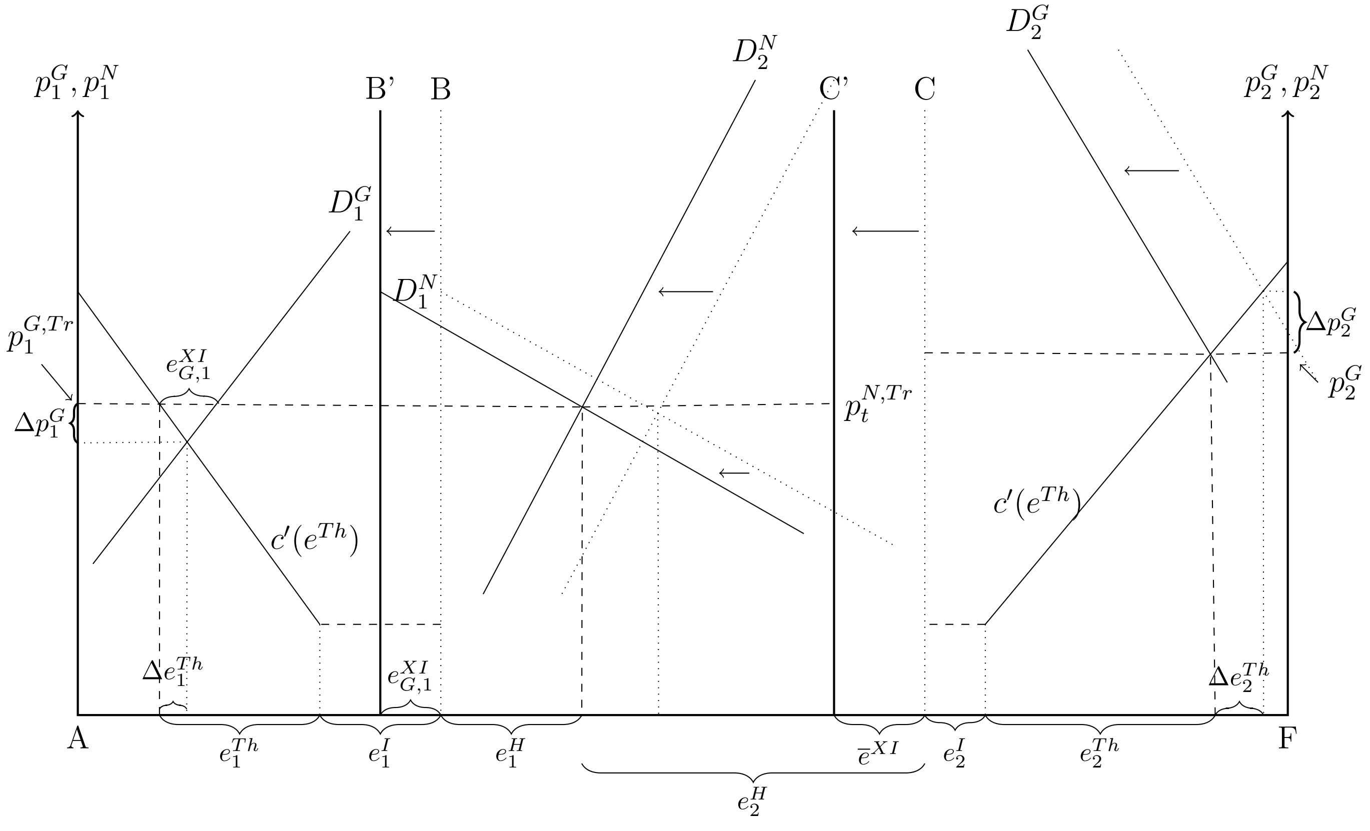

Figure 5.1: Electricity trade between Norway and Germany in a two-period model

5.4 Comparative statics

Equation (5.24) and (5.29), characterizing the periodical price change of electricity resulting from trade, are determined by exogenously given parameters. By analyzing comparative statics, I find the effects of changing an exogenously given parameter on the price change in both periods, Δp_t^G.

The effect on Δp_1^G of an increase in $\overline{H}$

$$\frac{\partial \Delta p_1^G}{\partial \overline{H}} = \frac{\partial p_1^{G,Tr}}{\partial \overline{H}} - \frac{\partial p_1^{G,AU}}{\partial \overline{H}} = -\frac{1}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} < 0 \tag{5.30}$$

From (5.30) I find that an increase in total production of hydropower will lead to a smaller increase in the price change of the first period. A larger hydropower supply in Norway will lead to lower autarky prices in Norway, which in turn will imply a smaller export,$e_{G,1}^{XI}$, required to equalize the prices between the two countries.

The effect on Δp_1^G of an increase in e_1^I

$$\frac{\partial \Delta p_1^G}{\partial e_1^I} = \frac{\partial p_1^{G,Tr}}{\partial e_1^I} - \frac{\partial p_1^{G,AU}}{\partial e_1^I}$$
$$\frac{\partial \Delta p_1^G}{\partial e_1^I} = -\frac{1}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} + \frac{m_1^G k}{m_1^G + k}$$

From (5.24) we see that a higher production of intermittent energy will push both the trade price and the autarky price down. Whether Δp_1^G increases or not depends on which effect that dominates. $\frac{\partial \Delta p_1^G}{\partial e_1^I} > 0$ for

$$\frac{m_1^G k}{m_1^G + k} > \frac{1}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}}$$
$$m_1^G + k > \frac{m_1^G k}{m_2^N} + \frac{m_1^G k}{k} + \frac{m_1^G k}{m_1^N} + \frac{m_1^G k}{m_1^G}$$
$$\frac{m_1^G k}{m_2^N} + \frac{m_1^G k}{k} + \frac{m_1^G k}{m_1^N} + \frac{m_1^G k}{m_1^G} > m_1^G + k$$
$$m_1^G k \left[\frac{1}{m_2^N} + \frac{1}{m_1^N}\right] > 0 \tag{5.31}$$

As all parameters are greater than zero this implies that (5.31) holds. Thus, a marginal increase in e_1^I will lead to a larger increase in the price change in the first period, as the negative price effect in autarky dominates the negative effect on the trade price.

The effect on Δp_1^G of an increase in $\overline{e}^{XI}$

$$\frac{\partial \Delta p_1^G}{\partial \overline{e}^{XI}} = \frac{\partial p_1^{G,Tr}}{\partial \overline{e}^{XI}} + \frac{\partial p_1^{G,AU}}{\partial \overline{e}^{XI}}$$

$$\frac{\partial \Delta p_1^G}{\partial \overline{e}^{XI}} = \frac{1}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} > 0 \tag{5.32}$$

From (5.32) I find that a larger transmission capacity will lead to a larger increase in the price change of the first period. This finding is of particular interest, since the transmission capacity is not constrained in the first period. However, since production allocation of hydropower between the two periods depends on the transmission capacity, a binding capacity in the second period therefore affects production level in the first period. In turn, this will affect the price change in the first period.

The effect on Δp_1^G of an increase in q

$$\frac{\partial \Delta p_1^G}{\partial q} = \frac{\partial p_1^{G,Tr}}{\partial q} - \frac{\partial p_1^{G,AU}}{\partial q}$$

$$\frac{\partial \Delta p_1^G}{\partial q} = \frac{\frac{1}{k}}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} - \frac{m_1^G}{m_1^G + k}$$

From (5.24) we see that a higher production cost of thermal power will push both the trade price and the autarky price upwards. Whether Δp_1^G decreases depends on which effect that dominates. Hence, $\frac{\partial \Delta p_1^G}{\partial q} < 0$ for

$$\frac{1}{k\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]} < \frac{m_1^G}{m_1^G + k}$$

$$m_1^G + k < \frac{m_1^G k}{m_2^N} + \frac{m_1^G k}{k} + \frac{m_1^G k}{m_1^N} + \frac{m_1^G k}{m_1^G}$$

$$0 < m_1^G k\left[\frac{1}{m_2^N} + \frac{1}{m_1^N}\right] \tag{5.33}$$

(5.33) holds as all parameters are greater than zero. Thus, a marginal increase in q will lead to a smaller increase in the price change in the first period, as the positive effect of an increase in q on German autarky prices dominates the positive trade price effect.

The effect on Δp_2^G of an increase in $\bar{e}^{XI}$

$$\frac{\partial \Delta p_2^G}{\partial \bar{e}^{XI}} = -\frac{m_2^G k}{m_2^G + k} < 0 \tag{5.34}$$

From (5.34) I find that a larger transmission capacity will lead to a larger price reduction in the second period. A larger transmission capacity will allow Norway to export more to Germany in the second period, which will push the German trade prices further down.

The effect on total production of thermal power, Δe_{tot}^{Th}

Lastly, I will analyse the total change of production of thermal power, Δe_{tot}^{Th}. If total thermal power production is lower in the trade situation compared to the autarky situation, i.e. $\Delta e_{tot}^{Th} < 0$, electricity trade will lead to reduced emissions. An increased price in the first period implies that production of thermal increases by $\frac{\Delta p_1^G}{k}$. The price reduction in the second periods reduces optimal production of thermal power by $\frac{\Delta p_2^G}{k}$. As k is equal for all periods, we have that

$$\Delta e_{tot}^{Th} = \frac{\Delta p_1^G + \Delta p_2^G}{k} \implies \Delta e_{tot}^{Th} < 0 \text{ for } \Delta p_1^G < -\Delta p_2^G \tag{5.35}$$

Figure 5.1 illustrates graphically the total change in thermal power production. In this particular example, the figure assumes that $\Delta e_{tot}^{Th} < 0$ because $\Delta e_1^{Th} < \Delta e_2^{Th}$. Furthermore, the effect of k is apparent in the graphical solution. The lower k, the more will a small price change affect thermal production level. Analytically, whether $\Delta p_1^G < \Delta p_2^G$ depends on the demand curves in both countries, the marginal cost curve of thermal power production and total production of hydro- and intermittent power. The results from the comparative statics above emphasize the effect of increasing an exogenous variable on the price change in both periods. To sum up, lower total hydro power production, higher production of intermittent energy in the first period, and a lower constant cost of thermal power production will lead to a higher price change in first period. If $\Delta e_{tot}^{Th} < 0$, a higher Δp_1^G will give a smaller total reduction of thermal power production. If $\Delta e_{tot}^{Th} > 0$, a higher Δp_1^G will give a larger increase in total increase of thermal power production.

As previously derived, an increased transmission capacity induce a larger positive price change in the first period and a larger negative price change in the second period. An increased transmission capacity, $\partial\bar{e}^{XI} > 0$, will lead to larger increase in production of thermal in the $t = 1$ and larger decrease in $t = 2$. The dominating effect will determine whether Δe_{tot}^{Th} is greater or smaller than zero. The effect is found by differentiating (5.35) wrt. $\bar{e}^{XI}$

$$\frac{\partial \Delta e_{tot}^{Th}}{\partial \bar{e}^{XI}} = \frac{\partial \frac{\Delta p_1^G}{k}}{\partial \bar{e}^{XI}} + \frac{\partial \frac{\Delta p_2^G}{k}}{\partial \bar{e}^{XI}}$$

$$\frac{\partial \Delta e_{tot}^{Th}}{\partial \bar{e}^{XI}} = \frac{1}{k\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]} - \frac{m_2^G k}{k(m_2^G + k)}$$

Hence, $\frac{\partial \Delta e_{tot}^{Th}}{\partial \bar{e}^{XI}} < 0$ for

$$\frac{1}{k\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]} < \frac{m_2^G}{m_2^G + k}$$

$$m_2^G + k < \frac{m_2^G k}{m_2^N} + \frac{m_2^G k}{k} + \frac{m_2^G k}{m_1^N} + \frac{m_2^G k}{m_1^G}$$

$$0 < k\left[\frac{m_2^G}{m_2^N} + \frac{m_2^G}{m_1^N} + \underbrace{\frac{m_2^G}{m_1^G}}_{>1} - 1\right] \tag{5.36}$$

If $\Delta p_1^G > -\Delta p_2^G$, total production of thermal power increases with trade. However, an expanded cable capacity will imply a smaller increase in total thermal power production. If $\Delta p_1^G < -\Delta p_2^G$, total production of thermal power decreases with trade. An expanded cable will imply a larger reduction of thermal power production. The effect of an increased cable will have a relatively larger effect on the second period price change, which is the period when Germany reduces its thermal power production, regardless of Δp_1^G being greater or lower than $-\Delta p_2^G$. The price change in the second period change fastest with an increased transmission capacity, as a higher capacity implies that Norway exports more in period 2 and Norway now faces higher prices in both periods. In conclusion, an expanded transmission capacity will lead to reduced emissions, relative to before the cable expansion.

6. Endogenous investments in intermittent energy production

It is reasonable to assume that price changes in electricity will change investment decisions in intermittent energy. However, based on the results presented in the previous chapter, it is not obvious whether the positive price change in period 1 relative to the negative price change in period 2 will lead to a reduced production of thermal power. This chapter will develop a model investigating to what extent trade will affect investment decisions in intermittent energy.

6.1 Modelling investment decisions

The previous chapter illustrated the effects of opening up for electricity trade between two countries. I will apply the results to analyse how the price effects will affect investments in intermittent energy, where investment decisions in intermittent energy is modelled explicitly. It is important to note that the previous model found the optimal management of existing facilities. I will apply the results in a model where investment level in intermittent energy is endogenously determined. To simplify, I disregard investments in hydropower and thermal power. This implies that it is only of interest to analyse what happens in Germany. As previously discussed, the model is in a day/night framework, and I assume that the cycle is repetitive. This implies that all nights are equal and all days are equal over the year and seasonal changes are disregarded, and investment decisions are based on the price effect of one cycle. Total optimal investment level depends on the time horizon of the investor. However, it is sufficient for now to evaluate whether optimal investment level is higher or lower after opening up for trade.

I argued in section 4.4 that marginal cost of production of intermittent energy is zero for a given capacity. However, when price changes are anticipated, a producer of intermittent energy will decide on how much to invest in intermittent energy, and optimal investment is determined where marginal investment cost are equal to marginal benefit. The production function of intermittent energy is given by $e^I_t = a^I_t \overline{e}^I$ where $a^I_t \in [0{,}1]$ is the capacity coefficient. In the model, maximum production capacity represents aggregated capacity of all intermittent power plants. Increased investments in intermittent energy will increase the max capacity of production, $\overline{e}^I$.

Furthermore, I will assume that there are no changes in the capacity factor a^I_t, which implies full certainty regarding production level for the investor. Increased investments in intermittent energy will lead to increased intermittent power production. However, the change in production from a marginal increase in investments depends on a^I_t.

The investment cost function $b(\overline{e}^I)$ is assumed to be a convex function, such that $b'(\overline{e}^I) > 0$ and $b''(\overline{e}^I) > 0$. The marginal investment cost is increasing in the number of intermittent power plants, as the the attractive and most efficient spots are taken.

The benefit of investments is given by

$$\sum_{t=1}^{2} p_t \; e^I_t = \sum_{t=1}^{2} p_t \; a^I_t \; \overline{e}^I \tag{6.1}$$

Optimal level of investment is determined where marginal cost of investments equals marginal benefits of investments.

$$b'(\overline{e}^I) = \sum_{t=1}^{2} p_t \; a^I_t \tag{6.2}$$

Hence, investment decision depends on the price change in both periods when opening up for trade, Δp_t, as well as the intermittent capacity factor in both periods, a^I_t.

$$b'(\overline{e}^I) = p_1 a^I_1 + p_2 a^I_2 \tag{6.3}$$

The question of interest is whether the optimal investment level is higher with electricity trade compared to autarky. This implies a positive change in investment level, and therefore $\Delta \overline{e}^I > 0$ will be the case if (6.5) holds.

$$b'(\overline{e}^I)^{AU} < b'(\overline{e}^I)^{Tr} \tag{6.4}$$

By inserting for marginal benefit of investment from (6.1), we have that

$$
\begin{aligned}
\underbrace{p_1^{Tr} a_1^I + p_2^{Tr} a_2^I}_{b'(\overline{e}^I)^{Tr}} - (\underbrace{p_1^{AU} a_1^I + p_2^{AU} a_2^I}_{b'(\overline{e}^I)^{AU}}) &> 0 \\
(p_1^{Tr} - p_1^{AU}) a_1^I + (p_2^{Tr} - p_2^{AU}) a_2^I &> 0 \\
\implies \Delta \overline{e}^I > 0 \qquad \text{for} \qquad \Delta p_1 a_1^I + \Delta p_2 a_2^I &> 0
\end{aligned}
\tag{6.5}
$$

By applying the results from the previous chapter and inserting Δp_1^G and Δp_2^G from (5.24) and (5.29) respectively in (6.5), this gives

$$
\underbrace{a_1^I \left[\frac{\frac{b_2^N}{m_2^N} - \overline{H} - e_1^I + \overline{e}^{XI} + \frac{q}{k} + \frac{b_1^N}{m_1^N} + \frac{b_1^G}{m_1^G}}{\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}} - \frac{\left[b_1^G k + m_1^G (q - e_1^I k) \right]}{m_1^G + k} \right]}_{\Delta p_1^G} - a_2^I \underbrace{\left[\frac{m_2^G k \overline{e}^{XI}}{m_2^G + k} \right]}_{-\Delta p_2^G} > 0 \tag{6.6}
$$

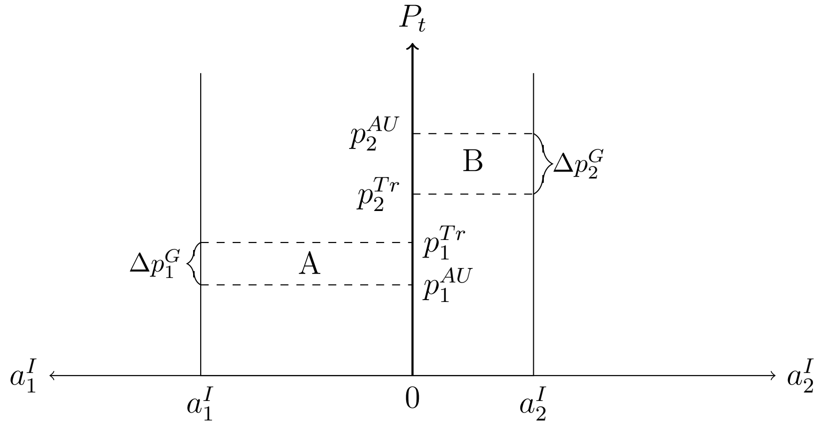

Figure 6.1: Investment change in intermittent energy

Whether (6.6) holds depends on all exogenously given parameters determining Δp_1^G and Δp_2^G as well as a_1^I and a_2^I, but figure 6.1 illustrates the intuition behind (6.6). Firsly, a larger Δp_1^G and a less negative Δp_1^G will give higher investments in intermittent energy. Secondly, the larger a_1^I relative to a_2^I will have the same effect. Graphically, if the area A is larger than B, electricity trade induce higher investments in intermittent energy when opening up for trade.

6.2 Comparative statics

If (6.6) holds, we see from the comparative statics analysis in the previous chapter that an increase in $\overline{H}$ will give a smaller positive price change in the first period and will lead to a lower increase in investments. Furthermore, an increase in q will also lead to a lower positive price change in period 1, which in turn will give a lower increase in investment in intermittent energy. Additionally, a change in investment level depends on initial production of intermittent energy. Again, e_t^I only appears on in Δp_1^G, and from chapter 5 we have that an increased level of e_1^I will lead to a higher positive price change, and therefore a higher increase in investment level.

Lastly, I will derive the effects of an increased transmission capacity on investment level in intermittent energy. As previously derived, $\frac{\partial \Delta p_1^G}{\partial \overline{e}^{XI}} > 0$ and $\frac{\partial \Delta p_2^G}{\partial \overline{e}^{XI}} < 0$. A cable expansion will have a positive effect on the price change in period 1, which have a positive effect on investment level. However, a cable expansion will lead to a larger price reduction in period 2, which has a negative effect on investment level. The dominating effect is found by differentiating (6.6) wrt $\overline{e}^{XI}$

$$\begin{aligned}
\frac{\partial \Delta \overline{e}^I}{\partial \overline{e}^{XI}} &= \frac{\partial \left[a_1^I \Delta p_1^G\right]}{\partial \overline{e}^{XI}} + \frac{\partial \left[a_2^I \Delta p_2^G\right]}{\partial \overline{e}^{XI}} \\
\frac{\partial \Delta \overline{e}^I}{\partial \overline{e}^{XI}} &= \frac{a_1^I}{\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]} - \frac{a_2^I m_2^G k}{m_2^G + k}
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \Delta \overline{e}^I}{\partial \overline{e}^{XI}} > 0 &\implies \frac{a_1^I}{\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]} > \frac{a_2^I m_2^G k}{m_2^G + k} \\
&\implies \frac{m_2^G + k}{\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]\left[m_2^G k\right]} > \frac{a_2^I}{a_1^I} \qquad (6.7) \\
\frac{\partial \Delta \overline{e}^I}{\partial \overline{e}^{XI}} < 0 &\implies \frac{m_2^G + k}{\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]\left[m_2^G k\right]} < \frac{a_2^I}{a_1^I} \qquad (6.8) \\
\frac{\partial \Delta \overline{e}^I}{\partial \overline{e}^{XI}} = 0 &\implies \underbrace{\frac{m_2^G + k}{\left[\frac{1}{m_2^N} + \frac{1}{k} + \frac{1}{m_1^N} + \frac{1}{m_1^G}\right]\left[m_2^G k\right]}}_{\text{X}} = \frac{a_2^I}{a_1^I} \qquad (6.9)
\end{aligned}$$

where $X = -\frac{\frac{\partial \Delta p_1^G}{\partial \overline{e}^{XI}}}{\frac{\partial \Delta p_2^G}{\partial \overline{e}^{XI}}}$. As $a_2^I < a_1^I$ we have that $0 < \frac{a_2^I}{a_1^I} < 1$. All parameters in X are positive implying that $X > 0$. Furthermore, we see from previous calculations[1] that $X < 1$. Thus, we have that when $\Delta\overline{e}^I > 0$, investments increase in transmission capacity when $X > \frac{a_2^I}{a_1^I}$, but decrease in transmission capacity when $X < \frac{a_2^I}{a_1^I}$. The cut-off point is when $X = \frac{a_2^I}{a_1^I}$. A graphical illustration is presented in figure 6.2. X is measured on the horizontal axis, ranging from 0 to 1. The cutoff point is illustrated by the vertical axis. A higher a_2^I will shift this line, and the corresponding cutoff point to the right. For $\Delta\overline{e}^I < 0$, investments decrease less in transmission capacity when $X > \frac{a_2^I}{a_1^I}$, and decrease more in transmission capacity when $X < \frac{a_2^I}{a_1^I}$. In conclusion, the effect an expanded transmission capacity on investment level in intermittent energy is ambiguous, and depends on all parameters determining the demand function, production of hydro-, thermal- and intermittent electricity production.

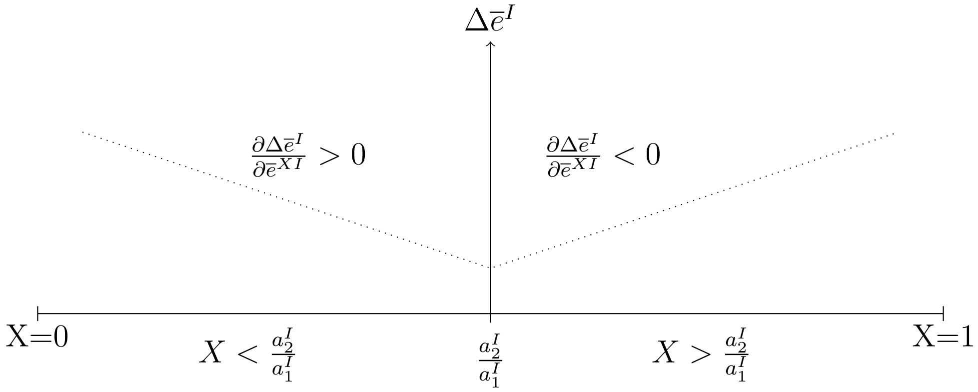

Figure 6.2: Effect of expanded transmission capacity on $\Delta\overline{e}^I$ for $\Delta\overline{e}^I > 0$

Increased investments in intermittent energy will imply increased production of electricity from intermittent sources. As intermittent energy has a zero marginal cost of production, increased supply of intermittent energy will in turn have a negative effect on the electricity prices. The effect is likely to be small when we consider a small increase in intermittent, so it is thus ignored here.

6.3 Effect on RES-E share

The aim of the analysis is not simply to investigate to what extent trade induces investments in intermittent energy, but whether the investments are sufficient to reduce production of thermal power. If so, this will lead to a higher RES-E share as stipulated in the EU commission climate

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[1] See (5.36) from p.35.

targets. With reference to the EU energy- and climate targets discussed in chapter 3, the theoretical framework is applied to analyze the effects on RES-E share when opening up for trade.

As thoroughly analyzed, trade may affect both production of thermal power and investments in intermittent energy. The effect on the RES-E share in Germany when opening up for trade are ambiguous, and depends on all parameters determining Δp_1^G and Δp_2^G [2] as well as k and a_t^I.

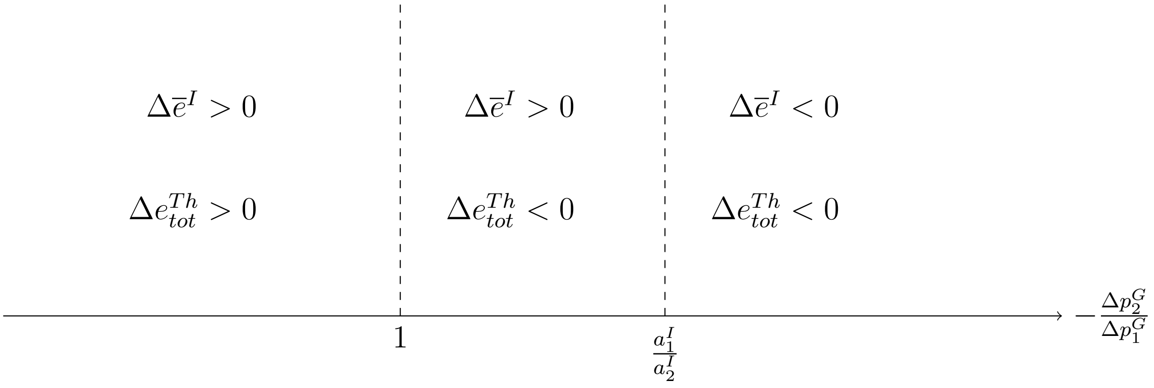

Figure 6.3: Trade effects on RES-E share

For $-\frac{\Delta p_2^G}{\Delta p_1^G} < 1$ both investments in intermittent energy and production of thermal power increases. An increased RES-E share in this particular case therefore requires that the increase in intermittent is larger than the increase in thermal power production, and the following equation must hold

$$\Delta\bar{e}^I(a_1^I + a_2^I) > \frac{\Delta p_1^G + \Delta p_2^G}{k} \tag{6.10}$$

For $1 < -\frac{\Delta p_2^G}{\Delta p_1^G} < \frac{a_1^I}{a_2^I}$ investments in intermittent energy increase and production of thermal power decreased. The RES-E share increases in this case.

For $-\frac{\Delta p_2^G}{\Delta p_1^G} > \frac{a_1^I}{a_2^I}$ both investments in intermittent energy and production of thermal power decrease. An increased RES-E share in this particular case therefore requires that the decrease in thermal power production is larger than the decrease in intermittent power production, and the following equation must hold

$$\Delta\bar{e}^I(a_1^I + a_2^I) > \frac{\Delta p_1^G + \Delta p_2^G}{k} \tag{6.11}$$

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[2] See section 5.4 for how a change in the exogenously given parameters changes Δp_t^G

In conclusion, trade will lead to a higher RES-E share in Germany unless $\Delta\overline{e}^I(a_1^I + a_2^I) < \frac{\Delta p_1^G + \Delta p_2^G}{k}$ when $\Delta\overline{e}^I > 0$ and $\Delta\overline{e}^{Th}_{tot} > 0$ and unless $\Delta\overline{e}^I(a_1^I + a_2^I) < \frac{\Delta p_1^G + \Delta p_2^G}{k}$ when $\Delta\overline{e}^I < 0$ and $\Delta\overline{e}^{Th}_{tot} < 0$. However, the case when $\Delta\overline{e}^I > 0$ and $\Delta\overline{e}^{Th}_{tot} > 0$ is a paradox when the aim of increasing the RES-E share is to mitigate climate change. Although the RES-E share has increased, so has emissions of GHG. This highlight that RES-E share targets must be accompanied by supporting policies to avoid increased emission level. Furthermore, this study highlight that the RES-E, and consequently the RES share does not necessarily increase with international electricity trade.

7. Discussion and critique

This chapter will discuss the validity of the underlying assumptions behind the theoretical framework. Furthermore, a broader discussion of the main finding with reference to EU energy and climate strategies are presented.

7.1 Model critique

The theoretical analysis in chapter 4,5 and 6 presented a stylized view of the effects of international electricity trade. By applying my extended version of the model in Førsund (2015) with specific demand and production cost functions, the analysis identify the price as well as the production level mechanisms when opening up for trade. However, some of the underlying assumptions of the model are subject to critique as they may entail shortcomings, as well as to miss important relations and mechanisms at work in the real world.

7.1.1 Short run model

By assuming that all days and nights over the year are equal, the model fails to consider seasonal changes. This implies that the model disregards a potential binding reservoir constraint, and predicts equal prices in Norway over the year. However, data presented in chapter 2 shows that prices in Norway are fluctuating over the year, explained by a binding reservoir constraint in the winter season. For future research, a possible extension to the model would be to include 4 periods, namely summer night and days, and winter nights and days. The trade effects when considering a binding reservoir for some periods would lead to smaller absolute price changes in Germany, $\mid \Delta p_t^G \mid$. In conclusion, assuming repetitive cycles of night and day may lead to larger price effects than if seasonal changes are incorporated in the model. Including seasonal changes may serve a more realistic study of electricity trade dynamics.

7.1.2 Properties of the different technologies

Three types of generating technologies are considered in the model. Firstly, production of thermal power is assumed to be a static problem as start up and shut down cost are disregarded in the model. This assumption is subject to critique as electricity prices in Germany are in fact affected by large start up cost of thermal power plants. Prices are pushed towards zero at night because it is more expensive to shut down power plans rather than keep them running at prices close to zero. A possible extension to the model would be to consider thermal power production as a dynamic problem, as this would better replicate the real situation. Furthermore, the model assumes constant input prices in thermal power production. The effects of changes in input price were analyzed in chapter 5, and concluded with increased input prices leading to smaller price effects of trade. However, lower thermal input prices are also likely to be correlated with demand of electricity, especially agriculture and industry electricity demand. For these sectors, electricity may be one of several alternative input factors in production, and a reduction of thermal input prices may shift the demand for electricity. This feature is not incorporated in the model, and may therefore fail to reflect the total effect of lower input prices.

Secondly, the model assumes a convex investment cost in intermittent energy and thereby implicitly assumes that the R&D effects are smaller than the increased marginal cost of a marginal increase in total production capacity. This may be realistic for wind power, as total production is very location dependent. However, solar power is less location dependent, and the assumption might be unrealistic. The R&D effects in solar power are prominent, and the marginal investment cost of solar power have fallen with 70 % over the past 7 years (Statnett, 2013), which might lead to a concave investment cost curve.. Additionally, the size of the investment depends on the time horizon of the investor. But investing in intermittent power plants requires large high upfront investments, and the intertemporal aspect must be taken into account, and the time horizon must therefor be quite long (Knopf et al., 2015). Implicitly, the model assumes that Δp_1^G and Δp_2^G is constant throughout the time horizon, which may be subject to critique when the time horizon is very long.

7.1.3 Full certainty

The model assumes full certainty regarding future demand. However, new technology open up for active load management, which will likely affect the demand curves for electricity. Information- and communication technology such as automatic meter reading (AMR), often referred as smart grid, enables the consumer to directly intervene in their electricity consumption and adjust demand according to peak periods and prices (Wangensteen, 2012). The consumer will have financial incentives to reduce their load during peak hours, and this will lead to more similar night- and day demand curves in the model. As AMR will be implemented in Norway by the end of 2016, it would be interesting for further research to evaluate how AMR will affect electricity prices. Additionally, the model disregards the effect of changes in GDP on electricity demand whereas empirical evidence state that GDP growth seem to be a main driver of electricity demand (Wangensteen, 2012).

7.1.4 A power market without market power

The optimizations problem maximizes the social planner's objective function, and consequently assumes that there are no signs of market power. Assuming perfect competition is quite a strong assumption. However, Hjalmarsson (2000) examined the spot market for electricity in the Nordic Power exchange and found no signs of exploitation of market power in the short- and long run. He further argues that there might exist some degree of market power in the peak hours, but if so, they are very small. Whether market power are apparent in the German power market, and to what extent this would affect the analysis should be investigated in future research.

7.1.5 Two countries and one interconnector

Lastly, the model only investigates the effects of trade between two countries with one interconnecting cable. When analyse the effect of an additional cable, the effects of a second cable will be smaller than the effects of a first cable (Statnett, 2013). The trade price effect will thus be affected by other existing connections. The marginal utility of new transmission cables decrease as the number of existing cables increase (Vista Analyse, 2014). This must be taken into consideration if the model is applied for more than one interconnecting transmission cable.

7.2 Further discussion

The main objective of the analysis was to consider whether or not infrastructural investments, in terms of transmission cables, will have positive environmental impact in terms of lower emissions. The analysis concluded that the effects on both total emissions and investments in intermittent energy are ambiguous and depend on a range of different parameters. However, the alternative of increasing RES-E share without coupling national electricity markets, should be considered.

As discussed in the introduction, an issue with significance to today's situation is that increased RES-E share requires improved infrastructure to secure supply. At least this is EU's assertion. As negative prices occur in the German electricity market, this may indicate that the electricity market is saturated for renewable energy in the periods where renewable energy is abundant. Expanding production of intermittent energy without coupling markets together, could induce even lower prices in these periods, and will in turn have a negative investment effect in new intermittent power plants. By applying this argument in more general terms, an increase of RES-E share is not possible, at least not economically beneficial for the intermittent power producers without substantial investments in infrastructure. Furthermore, increasing the RES-E share in Germany will put a higher risk on security of supply, which the model fails to take into account. Interconnecting transmission cables are a necessary condition in the transmission towards a green energy market in Europe, without compromising security of electricity supply. This argument is supported by Knopf et al. (2015). They perform an impact assessment of the electricity sector and investigates to what extent the EU are able to reach their RES-E targets. They find that, with a scenario of a significant expansion of net transfer capacities, it is more realistic to reach the RES target in 2030 when combined with a substantial infrastructure package.

Intermittent energy technologies are rapidly developed and improved, and the production cost of solar power has decreased remarkably the past decade. Policies implemented to increase the RES-E share, combined with a prominent fall in production cost of intermittent energy has resulted in a rapidly increasing RES-E share in some countries. However, a substantial adjustment of the energy mix requires a change in management technologies, as balance between supply and demand is a crucial necessity in the electricity market (Gaudard & Romerio, 2014). Interconnecting transmission cables plays an important role in offsetting electricity surplus, when the RES-E share changes rapidly.

Germany is shutting down remaining nuclear power plants by 2022, and the power deficit is estimated to 11 GW. Additionally, a substantial number of thermal power plants approach their lifetime, which puts a future threat on German electricity supply (Dillig, Jung, & Karl, 2016). What they replace it with will determine how emission level is affected by shutting down nuclear power production (Forbes, 2015). Connecting the German electricity market with other may be crucial to ensure that nuclear power is replaced by renewable energy.

The price effects of trade made the basis for this analysing the effect on total emission level and investments in intermittent energy. However, this is not the only way for trade to have a positive environmental impact. Interconnecting transmission cables will also lead to better resource utilization of existing intermittent energy plants, and prevents energy waste from renewable sources. Receiving a negative electricity prices for intermittent energy, which in turn the government subsidize, can hardly be a part of a optimal market solution.

8. Conclusion

In this thesis I analyzed how international electricity trade affects total production of thermal power and intermittent energy. The main objective was to investigate the effect on total emission level by examining the price changes resulting from trade. I based the analysis on a model developed by Førsund (2015) and introduced certain extensions as well as additional assumptions to the model. Specifying the period- and country specific demand functions and the thermal power production cost function, brought important insight to the model. The price effects where now specific functions, only dependent on exogenously given parameters, which enabled me to analyze the drivers behind the price effects, as well as the change in the RES-E share resulting from electricity trade. By expanding the model to include investments decisions in intermittent energy, the model incorporates how electricity price changes, resulting from trade, also changes optimal production of intermittent energy.

In chapter 4, I derived the country specific autarky prices, which are only depending on exogenously given parameters. In chapter 5, I analyzed the price effects of opening up for trade, and found that the price effect in Germany was positive at night and negative in daytime, period 1 and 2 respectively. By analyzing comparative statics I found that a lower total production of hydropower, a larger production of intermittent power, a larger transmission capacity and a lower constant production cost of thermal power induce a larger positive price change in the first period. A larger transmission capacity induces a larger price reduction in the second period. Most importantly, I found that trade will only lead to a reduction of total thermal power production if the absolute price change in the second period is larger than in the first period. However, by deriving the effects on an expanded cable capacity on changes in total thermal power production, the results were conclusive. An expanded cable capacity leads to reduced emission relative to before the expansion. The results were conditional on a binding reservoir constraint in the second period. In chapter 6, I developed a model analyzing the impact on investment level in intermittent energy, based on the price changes derived in chapter 5. In similarity with the effect of total production of thermal power, the relative price change in both periods plays a determining role on changes in investment level. Additionally, the intermittent capacity coefficient in both periods determines optimal investment. A relatively high intermittent capacity in the export period of Germany, induces a higher investment level in intermittent energy. In contrast to production of thermal power, I found that the effect of an expanded transmission capacity on the investment change is ambiguous. With the intermittent capacity coefficient in a second period below a specified threshold, an expanded transmission capacity will give a larger increase (or a smaller decrease) in optimal investment level. Again the results were conditional on a binding transmission constraint in the second period. Finally, by comparing the changes in thermal power production with the investment change in intermittent energy, I derived the conditions that must be satisfied for the RES-E share to increase as a result of trade. In conclusion, the effect on RES-E share is ambiguous, and according to the theoretical framework, electricity trade does not necessarily imply a higher RES-E share. For trade to induce a higher RES-E share, a certain condition must hold; this condition is determined by the demand curves, total production of hydropower, the cost function of thermal power production and as well as the transmission cable capacity. To ensure that this condition holds, policy must be implemented accordingly.

The underlying assumptions behind the model are rather strong, and must be taken into consideration. Most importantly, the model fails to consider the increasing risk in security of supply a higher RES-E share entails, if the electricity market is not backed up by flexible electricity sources. Hence, increasing the RES-E share without investing in cross-border transmission cables, will put the electricity supply at risk. For the EU to succeed in increasing the RES-E share and reaching their energy and climate targets, interconnecting national electricity markets are a necessary requirement. Furthermore, the price effects of trade are not the only drivers for reducing emissions stemming from the use of fossil fuels. Transmission cables will also lead to a better resource utilization of existing renewable energy plants. In conclusion, cross-border transmission cables may serve as an important catalyst to increase the RES-E share and thereby to mitigate climate change.

References

Bürgin, A. (2015). National binding renewable energy targets for 2020, but not for 2030 anymore: why the European Commission developed from a supporter to a brakeman. *Journal of European Public Policy*, *22*(5), 690–707.

deLlano Paz, F., Fernandez, P. M., & Soares, I. (2016). Addressing 2030 EU policy framework for energy and climate: Cost, risk and energy security issues. *Energy, http://dx.doi.org/10.1016/j.energy.2016.01.068*.

de Menezes, L. M., & Houllier, M. A. (2015). Germany's nuclear power plant closures and the integration of electricity markets in Europe. *Energy Policy*, *85*, 357–368.

Dillig, M., Jung, M., & Karl, J. (2016). The impact of renewables on electricity prices in germany – An estimation based on historic spot prices in the years 2011–2013. *Renewable and Sustainable Energy Reviews*, *57*, 7–15.

European Commission. (2014a). *Climate action. Building a world we like, with a climate we like.* Retrieved 2016-01-04, from http://bookshop.europa.eu/en/climate-action-pbNA0614034/;pgid=Iq1Ekni0.1lSR0OOK4MycO9B00003AJUaXTs;sid=Ghtbp5CFStZbrceZ-jjFAPKgV3hF1ZdWHMg=?CatalogCategoryID=sciep2OwkgkAAAE.xjhtLxJz

European Commission. (2014b). *Energy. Sustainable, secure and affordable energy for Europeans.* Retrieved 2016-01-04, from http://bookshop.europa.eu/en/energy-pbNA0614043/?CatalogCategoryID=sciep2OwkgkAAAE.xjhtLxJz

European Commission. (2015). *Connecting power markets to deliver security of supply, market integration and the large-scale uptake of renewables.* Retrieved 2016-01-04, from http://europa.eu/rapid/press-release_MEMO-15-4486_en.htm

European Commission. (2016). *Infrastructure.* Retrieved 2016-01-04, from https://ec.europa.eu/energy/en/topics/infrastructure

Forbes. (2015). *Germany's Energy Transition Breaks The Energiewende Paradox.* Retrieved

2016-08-04, from `http://www.forbes.com/sites/jamesconca/2015/07/02/germanys-energy-transition-breaks-the-energiewende-paradox/#208d43712968`

Førsund, F. (2013). Hydropower Economics: An Overview. *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, pp.200–208.

Førsund, F. (2015). *Hydropower Economics* (2nd ed.). Springer.

Fraunhofer ISE. (2016). *Electricity production and spot prices in week 06 2016.* Retrieved 2016-11-04, from `https://energy-charts.de/price.htm`

Gaudard, L., & Romerio, F. (2014). The future of hydropower in Europe: Interconnecting climate, markets and policies. *Environmental Science & Policy*, *37*, 172–181.

Hjalmarsson, E. (2000). Nord Pool: A power market without market power. *rapport nr.: Working Papers in Economics*(28).

Knopf, B., Nahmmacher, P., & Schmid, E. (2015). The European renewable energy target for 2030–an impact assessment of the electricity sector. *Energy Policy*, *85*, 50–60.

Östman, K., & Hesamzadeh, M. R. (2014). Transmission pricing in interconnected systems – A case study of the Nordic countries. In *Energy conference (energycon), 2014 ieee international* (pp. 1480–1486).

Statistisches Bundesamt. (2016). *In focus - 42 per cent of electricity came from brown and hard coal in 2015.* Retrieved 2016-02-04, from `https://www.destatis.de/EN/FactsFigures/InFocus/Energy/BrownHardCoal.html`

Statnett. (2013). *Kabler til Tyskland og Storbrittania - analyse av samf.øk. nytte ved spothandel.* Retrieved 2016-15-01, from `http://www.statnett.no/Nettutvikling/NORDLINK/Dokumenter/`

Statnett. (2016). *Nettutvikling Nordlink.* Retrieved 2016-17-03, from `http://statnett.no/Nettutvikling/NORDLINK/`

Sydsæter, K., Hammond, P., Seierstad, A., & Strøm, A. (2008). *Further mathematics for economic analysis* (2nd ed.). Pearson education.

TenneT. (2016). *Nordlink - The first direct connection between power markets in Germany and Norway.* Retrieved 2016-17-03, from `http://www.tennet.eu/nl/grid-projects/international-projects/nordlink.html`

The Economist. (2015). When the wind blows. *The Economist. Special report climate change*, *Nov 28th*, 7–8.

United Nations. (2016). *Promote Sustainable Development.* Retrieved 2016-28-04, from `http://www.un.org/en/sections/what-we-do/promote-sustainable-development/`

`index.html`

Vista Analyse. (2014). *Avkastningskrav ved investering i kabler til England og Tyskland.* Retrieved 2016-15-01, from `http://vista-analyse.no/site/assets/files/6743/rapport_2014_o3.pdf`

Wangensteen, I. (2012). *Power System economics: the Nordic electricity market* (2nd ed.). Trondheim: Tapir Academic Press.