UNIVERSITY OF OSLO

FACULTY OF SOCIAL SCIENCES

Department of Economics

MASTER'S THESIS

The effect on domestic price of electricity in Norway as a result of further integration to European electricity market

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Finally, I would like to thank Norway for enabling me to complete my master's degree at the Univeristy of Oslo.

Abstract in English

This thesis presents a simple electricity market model designed to calculate the effect of increased transmission capacity between Norway and Germany, and Norway and the UK, on the electricity market in the Nordic countries. It uses historical data on hourly supply and demand curves from Nord Pool day ahead market for the years 2015-2018 to simulate 2 undersea cables, which are under construction. The results show a price increase of roughly 1 €/MWh for the Nord Link cable (Norway-Germany) and around 2 €/MWh for the Nord Sea Link cable (Norway-UK). The cables would lead to redistribution effect on the Nordic market from consumers to producers of hundreds of million euros per year and welfare increase of €8-16 million per year depending on the year and the cable. The price change and redistribution effect are in line with the results in previously published studies. However, the welfare increase found in this thesis is significantly lower than what was previously published.

JEL Classificiation	Q41, Q27, Q54, D69, C88
Keywords	Electricity, price, Nord Link, Nord Sea Link, cable, Norway, Germany, UK, energiewende, Nord Pool, welfare effect, redistribution effect, consumer surplus, producer surplus, hydropower, cross-border transmission capacity
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Sammendrag på norsk

Denne masteroppgaven vil undersøke hvordan elektrisitetsprisen i de nordiske landene, forbrukeroverskudd og produsentoverskudd lar seg påvirke av flere mellomlandsforbindelser med Tyskland (Nord Link) og Storbritania (Nord Sea Link). Historiske data om tilførsel- og etterspørselskurver fra Nord Pool day ahead marked for årene 2015-2018 blir brukt i elektrisitetsmarkedsmodellen. Resultatene viser en prisøkning på rundt 1€/MWh som følge av Nord Link og en prisøkning på omtrent 2 €/MWh som følge av Nord Sea Link. Omfordelingseffekten fra forbrukere til produsenter var estimert til hundrevis av millioner euro årlig med en velferdsøkning på 8-16 millioner per år. Priseffekten og omfordelingseffekten er i tråd med resultatene i tidligere publiserte studier. Modellen utviklet i denne masteroppgaven har derimot estimert betydelig lavere velferdsøkning enn andre studier.

JEL klassifisering	Q41, Q27, Q54, D69, C88
Nøkkelord	Elektrisitet, pris, Nord Link, Nord Sea Link, undersjøiske kabler, Norge, Tyskland, Storbritania, energiewende, Nord Pool, velferdseffekt, forbrukeroverskudd, produsentoverskudd, omfordeling, vannkraft, mellomlandsforbindelse

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Contents

Acronyms

EU European Union

UK United Kingdom

DE Germany

NO Norway

SE Sweden

NRC Nordic Countries

TWh terawatt hour (1 000 000 000 kWh)

GWh gigawatt hour (1 000 000 kWh)

MWh megawatt hour (1000 kWh)

kWh kilowatt hour

NOK Norwegian krone

Chapter 1

Introduction

The motivation for writing this thesis is the current discussion about the shift towards renewable electricity production in Europe. This transformation brings new challenges and opportunities, which require international cooperation to be addressed. This thesis focuses mainly on the direct power grid interconnection between Norway and Germany and between Norway and the United Kingdom. The interconnection towards Germany, Nord Link undersea cable, which is under construction, is expected to be in operation in 2021. (Statnett, 2019a) The cable towards the UK is also under construction, and it is expected to be completed in 2021. (Statnett, 2019b) Such and similar future projects generate passionate debate between various stakeholders in Norway. This chapter is intended to give background information about this discussion, and the following chapters will try to address some of the arisen questions by quantitative analysis of historical market data.

1.1 Norwegian electricity market

In 2017, 95,8% of the electricity produced in Norway came from hydropower sources, 1,9% from wind and 2,3% from thermal power production. Table 1.1 compares the key statistics of the Norwegian, German and UK electricity markets. It is apparent that the Norwegian per capita consumption is much larger than in the other two countries. In fact, Norway, after Iceland, has the second highest per capita electricity consumption in the world. (World Bank, 2014) Such consumption is mainly given by the energy-intensive industry, which uses 30% of the net consumption. The non-ferrous metal production (mainly aluminium production) stands alone for 17% of the net consumption. The high

Table 1.1: Key electricity statistics

	Norway	Germany	UK
Total production in 2017 (TWh)	149	620	321
Share of net consumption:			
Industry	44%	44%	31%
Service sector	21%	29%	32%
Private	34%	25%	36%

Data sources: SSB (2018), Eurostat (2019) and IEA (2019)

level of electrification also gives high per capita consumption. Electricity heats 70-80% of buildings in Norway. Nevertheless, the household income share spent on energy lies below European average due to generally low electricity prices and higher purchasing power in Norway. (Olje- og energidepartementet, 2019).

The Norwegian electricity market is a part of a larger, common Nordic market. Norway started with its electricity market liberalisation already at the beginning of the '90s. Exchange-based trade was established in 1993, and in 1996 Sweden joined to create common so-called Nord Pool market. Later, Finland, Denmark and the Baltic countries gradually joined. (IEA, 2005) In 2017, 394 TWh was traded on the day-ahead Nord Pool market in the Nordic and Baltic area. (Nord Pool, 2019a) Coupling these markets brings advantages since different production technologies are complements to each other. Figure 1 shows the power production technologies mix in the other Nord Pool countries

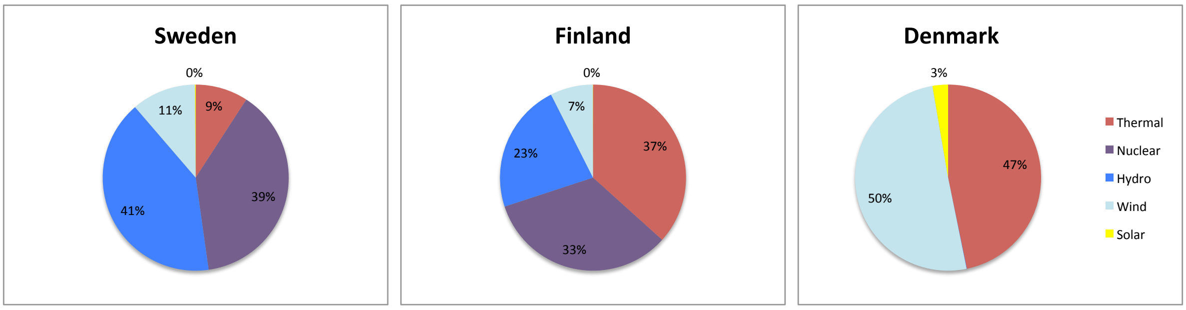

Figure 1: Breakdown of electricity production sources in the year 2017 in the other Nord Pool countries. Data source: IEA (2019)

for the year 2017. These countries can gain from international trade by buffering the production volatility from different power sources. Wind and solar production cannot be regulated, nuclear production can be regulated in long-term time frame, thermal production can be regulated in the medium term, and hydropower can be regulated in short term time frame. Thus, all the Nordic countries gain access to different regulation options by market coupling. The spatial expansion also reduces price volatility given by changes in the input prices. The variation in the prices of fossil fuels may have an impact on the electricity prices mainly in Denmark and Finland, while the precipitation rate influences the price indirectly in Norway and Sweden by increasing the Hotelling rent (scarcity rent) associated with the remaining water in reservoirs. (Førsund, 2015) Sweden also has more non-regulated hydropower plants, so the precipitation rate influences the production directly as well. Mutual power exchange makes this price variation smoother.

1.1.1 Nord Pool market structure

The vast majority of electricity traded in the Nord Pool area is traded on the so-called day-ahead market where all the major producers and consumers bid the amounts they will consume/produce for a given price in a given hour the next day. Nord Pool collects all the bids and finds a clearing price for each hour the next day such that the supply equals the demand. This price is called the system price. The whole area is divided into price zones. The prices for the areas in Norway mostly correspond with the system price. If there is a transmission capacity constraint between price zones, the prices might differ. Apart from the day-ahead market, there is also a so-called intra-day market for balancing the supply and demand in case the actual production/consumption differs from the traded amounts on the day-ahead market. (This can happen, for example, if the weather forecast was not precise enough.) The volume of the intra-day market is much smaller than the volume of the day-ahead market. Apart from spot-market trading, the market actors enter bilateral agreements. These are not as common in Norway as in the other countries. The Nord Pool also offers to trade financial instruments such as futures and price hedging. (IEA, 2005)

1.1.2 Attitude towards market expansion in Norway

The common market in Nordic countries is based on the free market principle, and it is often used as an example of well-done liberalisation. (Joskow, 2008) Therefore, further expansion and integration with other markets comes as a natural continuation of this free market idea. Expanding the grid to the rest of Europe will provide even larger buffering possibilities since the power production sources variation will increase. Norwegian transmission system operator Statnett argues in the Interconnector Licence Application for Nord Link and Nord Sea Link cables (Statnett, 2013a) that these undersea cables to Germany and Great Britain bring value creation for the Norwegian society, increase security of supply, enhance climate-friendly power production in connected countries, reduce the need for investment in reserve production capacities and bring long-term price stability. Statnett specifies that the new market access is necessary for the new power stations to sell their electricity for prices that make their production profitable. This document also describes the negative aspects of these projects. Namely, that the overall price level is expected to increase by about 4-5 €/MWh and that the consumer surplus will decrease. The actual shift between the surpluses of producers and consumers is, according to this license application, challenging to estimate. Norwegian economist, Anders Skonhoft, points out in his article (Skonhoft, 2019) that the redistribution effect of these interconnections is an important part of the overall socioeconomic analysis. Some of the stakeholders in Norway are negative towards further integration. For example, a trade union for the industrial employees, Industri Energi, worries about the competitiveness of Norwegian energy-intensive industry after the price of electricity rises. They also mention possible carbon-leakage if the Norwegian aluminium industry moves to places where fossil energy sources are used. (Industri Energi, 2018a). They further claim that each øre (0,01 NOK) of increased price means 400 mil. NOK in direct cost for Norwegian industry. (This claim can be easily verified by simple calculation from the data provided in the Table 1.1.) They indicate that the production of energy-intensive goods brings six times larger value creation than the export of raw energy (which is an unverified claim) and they are strictly against any new cable projects. (Industri Energi, 2018b)

1.2 German electricity market[1]

Germany has an ambitious goal to reach renewable electricity production share of at least 50% in 2030, 65% in 2040 and 80% in 2050 (BMWi, 2016). Phasing out nuclear and coal power plants and building new wind and solar power plants will allow this shift. These so-called intermittent energy sources cannot be regulated, and their production depends on the weather conditions. Figure 2 shows German electricity production source shares

[1]Part of the reasoning and arguments used in the section 1.2 German electricity market were developed in previously submitted seminar paper *How to achieve 90% renewable electricity production in Germany: International transport.* This seminar paper was written by the author of this master's thesis, me, Dalibor Vágner and submitted in autumn 2018 as a part of the master course "707509 - Topics in Energy Markets" taken on my exchange at Humboldt-Universität zu Berlin. Especially the Figures 2, 3 and 4 and the logic behind their explanation were developed in the aforementioned seminar paper.

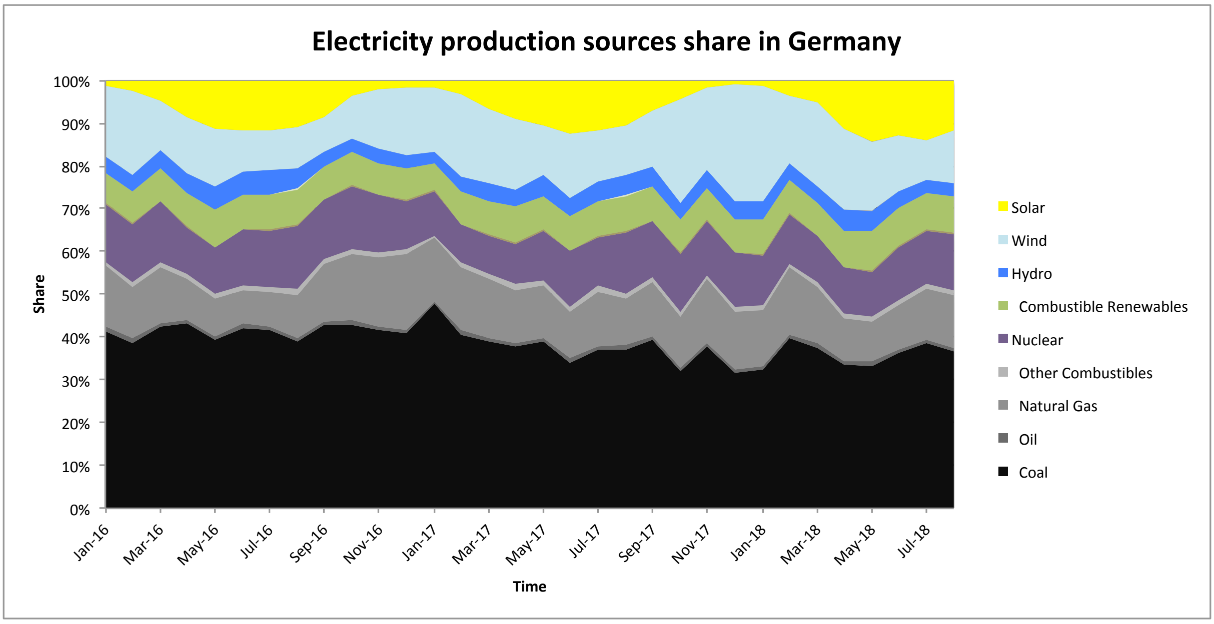

Figure 2: Breakdown of electricity production sources in Germany
Data source: IEA (2019)

GERMANY - Non-combustible share (geothermal, solar, wind, ocean)												
Year \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	1,1	1,3	1,4	1,7	1,9	2,2	2,0	2,1	2,0	1,8	1,8	1,8
2001	1,6	1,8	1,7	1,9	1,9	2,2	2,1	2,1	2,1	2,0	1,9	1,9
2002	2,0	2,4	2,4	2,8	3,0	3,4	3,4	3,6	3,4	3,0	3,1	3,0
2003	2,9	3,0	3,0	3,3	3,5	3,7	3,5	3,6	3,6	3,4	3,6	3,5
2004	3,4	3,8	3,8	4,5	4,8	5,2	5,2	5,2	4,9	4,6	4,4	4,2
2005	4,3	4,5	4,4	4,8	5,3	5,4	5,3	5,6	5,5	5,1	4,7	4,5
2006	4,8	5,1	5,7	5,8	8,0	4,2	3,9	5,4	5,4	7,2	8,4	8,7
2007	12,3	6,7	8,5	5,8	7,2	5,4	7,0	5,8	7,6	4,8	8,3	8,9
2008	12,3	8,1	10,4	5,2	6,4	5,5	6,8	7,5	7,0	7,4	8,7	7,1
2009	6,4	6,6	8,4	7,0	10,1	8,8	8,6	7,7	8,6	9,0	11,9	8,2
2010	6,2	8,5	11,3	9,7	8,4	8,4	7,7	9,9	9,0	10,0	8,4	6,8
2011	7,9	11,4	10,0	14,2	14,1	12,5	14,5	12,7	12,1	12,5	8,4	17,8
2012	15,4	10,8	12,9	13,4	16,2	15,4	14,8	13,5	13,5	11,8	10,0	12,9
2013	10,4	8,1	13,3	14,2	15,3	18,5	16,0	15,7	13,6	15,4	10,7	18,5
2014	13,9	17,1	17,0	17,3	19,5	18,7	16,9	18,7	12,8	12,6	10,9	18,9
2015	18,2	13,2	19,1	21,5	23,5	20,8	24,1	19,9	19,0	11,9	22,0	23,1
2016	18,3	22,3	16,8	21,9	25,3	21,5	21,4	20,8	16,9	13,9	16,2	17,7
2017	16,9	22,7	24,4	25,9	22,5	27,7	24,0	22,6	20,6	28,9	21,4	28,4
SUM	**158**	**158**	**175**	**181**	**197**	**190**	**187**	**182**	**167**	**165**	**165**	**196**

Figure 3: Volatility of renewable electricity production in Germany. The darker colour represents relative scarcity of renewable production in a given month of the year.
Data source: IEA (2019)

Sum of non-combustible production share in period 2000-2017												
Country \ Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
GERMANY	158	158	175	181	197	190	187	182	167	165	165	196
FRANCE	34	38	40	41	43	41	41	40	40	42	42	42
ITALY	118	130	151	163	161	145	137	153	137	130	121	123
POLAND	45	45	43	44	36	34	33	33	39	48	51	67
NETHERLANDS	91	85	80	74	84	72	68	70	72	81	87	105
CZECH REP.	11	16	26	32	39	42	43	40	32	21	15	13
SUM (Excl. GER)	***298***	***315***	***340***	***354***	***363***	***333***	***321***	***337***	***320***	***321***	***316***	***350***

Figure 4: Volatility of renewable electricity production in neighbouring countries. The darker colour represents relative scarcity of renewable production in a given month through years 2000-2017. Data source: IEA (2019)

in the period from January 2016 to August 2018. The wind and solar power production are complementary to each other. The solar production peaks in summer while the wind production peaks in winter. However, even if those two sources are combined, there is still large seasonal volatility in power production. It is also clear that random spikes and drops in wind power share are mostly evened by adjusting the level of coal and natural gas electricity production.

To study this volatility more in detail, the data from EIA Monthly electricity statistics were analysed. Figure 3 shows the non-combustible electricity production shares in each month from the year 2000 to 2017. The number includes the share of geothermal, wind, solar and ocean energy share. It excludes hydropower. The more detailed breakdown is available from the year 2016, and it shows that the geothermal and other renewables share is negligible in Germany. Therefore, these numbers represent mostly the wind and solar production share. The colouring of each row represents the relative abundance or scarcity of renewable production in a given month of a year. The more intensive colouring is, the lower the renewable production share in that month relative to other months in that year. The last row sums those shares and shows the wind and solar production pattern throughout those 17 years. We can see that May and December are the months that have the highest share, while January and February are the months with lowest wind and solar share.

Figure 4 shows the last row of a similar table as presented in Figure 3 created for the five neighbouring countries with the largest power production. These countries combined represent 188% of the total German electricity production. The overall patterns slightly vary due to the different ratio between wind and solar technology used. Poland and the Netherlands, which have a relatively larger share of wind power production, experience scarcity in summer while the Czech Republic and Italy, which rely more on solar production, have the highest scarcity in winter. The last row of Figure 4 shows the scarcity profile for those five countries combined. This profile shows a similar pattern to the German profile. Since the wind and solar sources are complimentary to each other, it is reasonable to assume that the other countries will develop its wind and solar production ratios similar to the German ratio. In that sense, the overall scarcity/abundance of production in the entire region will show the same pattern. This analysis proved that the whole central-European region will face large challenges in terms of seasonal volatility when the wind and solar production shares increase in the future as it is expected.

Some researchers tried to calculate how much power Germany would need in the most critical winter months if the wind and solar production shares rose as promised. The results across studies are surprisingly different and often vary in order of magnitude, mainly because different assumptions are used. Probably the most conservative approach is presented in a paper by Sinn (2017), who developed a model for identifying a storage capacity needed for different scenarios of wind and solar production share. His results show that for 50% wind and solar share, a 22,1 TWh capacity would be needed. This number was achieved under very restrictive assumptions. For example, other power sources provide only a constant (not flexible) flow of energy and that no energy could be wasted by turning off the renewable power plants in cases of excess supply. Zerrahn, Schill and Kemfert (2018) replicated this study with relaxed assumptions, and they concluded that for the same 50% wind and solar share, only 35 GWh (0,035 TWh) would be needed. For 80% renewable share (which is the goal in 2050), the storage capacity 462 GWh would be necessary. The total German storage capacity in terms of pump-in storage is approximately 40 GWh (SRU, 2010, p.60). The eStorage project (DNV.GL, 2016) identified an additional 7 GWh of realisable pump-in hydropower potential on the German territory. Therefore, even if this potential was realised, the storage capacity would not be sufficient for Germany to deal with fluctuations in electricity supply when the renewable production reaches its planned levels. As it is apparent from Figure 4, wind and solar production in the neighbouring countries is correlated with the German renewable production. This means that in the periods of low production, Germany will not be able to import the electricity from neighbouring countries because those will also experience a power deficit at the same time. Thus, Sinn (2017) suggests using water reservoirs in other countries as a buffer for volatile demand. A detailed dynamic model describing a power system characterised by reservoir hydropower, thermal production and intermittent renewable production is presented in Førsund (2015). According to this idea, Germany would export power in times of high domestic production to countries with large reservoirs such as Austria, Switzerland and Norway. These countries could save water in the reservoirs and export this power when the German supply is insufficient. Sinn (2017) emphasises Norway in particular due to its large reservoir capacity. The aggregated capacity of Norwegian reservoirs is equivalent to 85 TWh, which represents roughly half of the aggregated reservoir capacity in Europe. (Bøeng and Holstad, 2013). The important restriction is the insufficient transmission capacity between Norway and Germany which is currently, according to Sinn (2017), only 1,5 GW. The Nord Link undersea cable, with a capacity of 1,4 GW, will represent a substantial increase of cross-border transmission capacity between those countries, and it will help Germany to transform the power sector towards renewable production. (Statnett, 2019a)

Therefore, this project is welcomed in Germany by system operators for the increase in energy security and price stability; by producers for allowing them to increase renewable share; as well as by the end consumers for lower electricity prices.

1.3 UK electricity market

England and Wales were among the first countries which liberalised its electricity market, and the UK is alongside the Nordic countries also given as an example of successful liberalisation (Joskow, 2008). Based on the data from IEA (2019) for the year 2017, the UK produced 58% of its electricity in thermal power plants, 20% in nuclear, 3% in hydro, 15% in wind and 4% in solar power plants. As we see, there is a large share of fossil fuels that need to be phased out and a relatively small share of hydropower production. This mix altogether gives 31% renewable electricity production share in the UK (biomass included).

The UK also has ambitious goals when it comes to greenhouse emission cuts. According to the Department for Business, Energy & Industrial Strategy UK (2017), the UK wants to cut 80% of the emissions in 2050 compared to the 1990 level by implementing the so-called Carbon Budgets. The UK already managed to cut 42% of the emissions

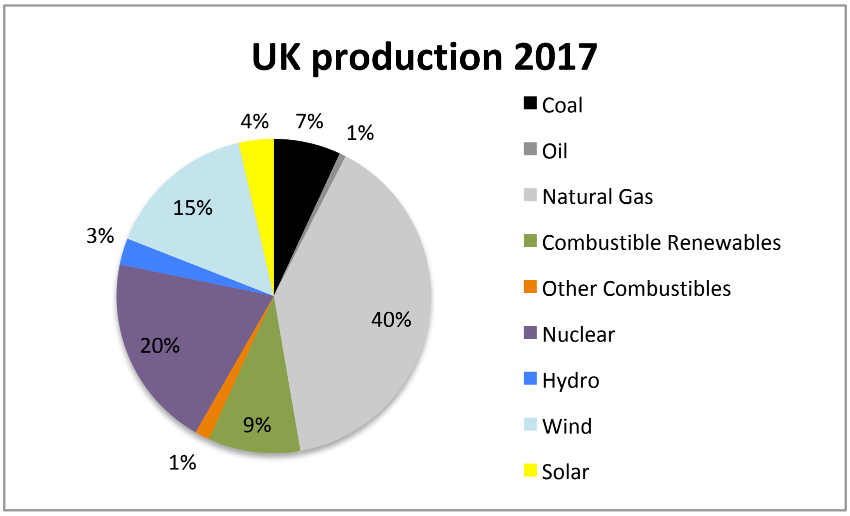

Figure 5: Breakdown of UK electricity production in 2017
Data source : IEA (2019)

since 1990 and thus outperformed the target for emission budget for the period 2008-2012. Increasing wind, solar and nuclear production share will allow further emission cuts in the power sector as planned. According to the Department for Business, Energy & Industrial Strategy UK (2018), the renewable electricity production share should increase in the base scenario to 54% and the nuclear to 33% in 2035. The UK seems to meet its targets. The UK low carbon transition plan: a national strategy for climate and energy (Department of Energy & Climate Change UK, 2009) set a target of increasing renewable electricity production share from 6% in 2009 to 31% in 2020. Figure 5 shows that this was already achieved in 2017.

Similar to Germany, the UK will also face challenges linked to increased intermittent power generation. Biomass energy storage, demand-side management and increased transmission capacity with neighbouring countries including Norway can address these challenges. (Fragaki, Markvart and Laskos, 2018) This paper developed a model for calculating storage needs in case the UK was supplied solely by wind and solar production. They used historical weather data for a 30-year long period and calculated different scenarios of curtailment and necessary storage capacity. The model was not intended to calculate the most economically efficient solution in terms of the cheapest ratio between curtailment and the storage capacity. The main conclusion from the scenario calibrated to the current situation is that a storage equivalent to 30 days consumption is needed if 30% curtailment is allowed. (Approximately 25TWh storage) If the volatility were addressed by international transport, the total of 53 TWh would need to be imported throughout a year and 146 TWh exported or curtailed. These are huge numbers, and we have to keep in mind that the UK is not planning to phase out nuclear energy as Germany does. Thus, the real power exchange need will be smaller. However, it is apparent that the planned interconnection between Norway and the UK, North Sea Link, with the capacity of 1 400 MW will help the UK's electricity market to deal with increasing production volatility created mainly by increasing wind production share. (Statnett, 2019b)

Energy UK, a trade association for the UK's energy industry, created a report analysing the attitude of main stakeholders towards integration to neighbouring electricity markets. (Energy UK, 2016) Most of the interviewed stakeholders hold a positive attitude towards further integration. The mentioned benefits are larger price stability, supply security, easier supply/demand balancing, source diversity and lower prices for consumers. (Each GW of the interconnection might bring 1-2% price reduction on the UK's wholesale market.) Some of the stakeholders raised concerns about the fairness of the conditions for producers, for example, higher carbon prices in the UK than in the EU and different transmission network use charges.

1.4 Research question

The previous sections described different interests of various stakeholders when it comes to the construction of undersea cables connecting the Nordic market and the rest of the European market. The debate about real consequences on the domestic market is convoluted and often biased. The impact of these interconnections is difficult to predict in the future because of many unknown features of the future energy markets. Analysis of historical data is, however, feasible. Therefore, this master's thesis presents a model for calculating price changes and welfare effect on the Nordic market under a hypothetical scenario that the undersea cables to Germany or Britain were already built in the past.

The rest of the thesis is organised as follows: Chapter 2 provides a literature review where the different model approaches are presented, and it presents results from relevant studies focused on the effect of the Nord Link and Nord Sea Link cables on the electricity market. Chapter 3 presents the methodology for answering the research question, it describes the data available and argues the appropriate architecture of the model designed to calculate the price change, redistribution effect from consumers to producers and welfare effect from the trade on Nord Pool day-ahead electricity spot market. Chapter 4 presents the results and validates them by comparison to the outcomes of previously published estimates, explains why the outcomes may differ and provides possible implications of those differences. Finally, Chapter 5 concludes the whole work and sums up the contribution to the topic.

Chapter 2

Overview of model approaches

The grid expansion and offshore wind power development in the North Sea are subjects of various studies with different model approaches. A paper by Pfenninger, Hawkes and Keirsteada (2014) provides an overview of these approaches. They divide energy system models into four categories:

- Optimisation models
- Simulation models
- Qualitative and mixed method models
- Electricity market models

This division is rather artificial, and the models used in practice can be defined as a combination of the categories mentioned above. However, it helps to get familiar with the main types of models and their purposes. Pfenninger et al. (2014) also use another dichotomy of the models, namely planning models and operational models based on their purpose. (Simply said the purpose of planning the energy system or of finding out how it should operate.)

2.1 Optimisation models

We can divide the optimisation models into two classes. One class, the optimisation planning models, are used for long-term investment decisions of the capacity expansions. One such model is *The Open Source Energy Modeling System* (OSeMOSYS), which is described in Howells et al. (2011). This model is publicly shared on GitHub free of charge. It is intended to suggest the optimal energy system as a whole from resources extraction to energy service provision. Different time slices define the time resolution, for example, seasons of the year plus day/night resolution (e.g. "winter night" makes one slice). The input is often aggregated on country-level data. The output is the capacity installation for each technology in a long-term perspective. Such large general models are not equipped for answering the research question of this master's thesis.

According to Zakeri et al. (2016), another class of optimisation models, optimal dispatch models, can work with hourly-time resolution data on consumption and variable supply from renewable power sources. One such model is the EMPS (multi-area power-market simulator) model, which is taking into account many relevant variables, such as the amount of water in the reservoirs on plant-level, marginal and start-up cost of the thermal power plants, stochastic production of the intermittent power sources, transmission capacity between regions and hourly demand profiles for each region (Sintef, 2019). This model is used in Statnett's socioeconomic analysis of the cables (Statnett, 2013b) that is presented in the next subsection. These models are also intended to suggest an optimal system with minimised costs.

2.1.1 Statnett's socio-economic analysis

Probably the most relevant publication to the aforementioned research question is Statnett's report of the socio-economic analysis of the benefit from the cables to the UK and Germany, which was used as general background and basis for the license application. (Statnett, 2013b) This analysis focuses on the benefits of the day-ahead spot market trading. The report also mentions other benefits such as facilitating of decarbonisation of power sources in other countries, energy security arguments and possible profits from trading on future reserve capacity market. This thesis, however, focuses on the direct effect on the day-ahead electricity market. The social surplus given by the trade between two markets is given by the change in consumer and producer surplus (change in price and volume bought and sold on the domestic market) and the congestion revenue. Congestion revenue is the gain given by electricity power flowing from a cheaper market to a more expensive market, and it can be defined as the price difference multiplied by the volume of electricity transmitted between the markets. Whenever there is a price difference between the markets, it means that the capacity of the cable is used at its maximum and it does not allow transporting more energy in order to make the prices equal. In other words, the cable is "congested", and that is the source of the origin of the term "congestion revenue". This revenue will be equally split between the cable owners. In both cases, Norwegian Statnett owns 50% of the cable. To calculate the welfare effect (change in producer and consumer surplus), Statnett uses two different models called The EMPS (multi-area power-market simulator) model and BID (Better Investment Decisions) model. The EMPS model is an optimisation model. These models can calculate overall welfare on the electricity market. The net gain given by the cables is calculated as the difference in welfare between the scenarios with the cables and without them. The scenarios are a simulation over 47 historical years, and they are simulated for the year 2020 and 2030. The BID[1] model benefits from a detailed description of thermal power production and hourly data resolution. The model covers the Nordic countries as well as the rest of Northern and Western Europe (e.g. France, Germany, UK, Poland and the Baltic countries). Price sequences from this model are subsequently used in the EMPS model, which describes more in detail the Nordic hydropower system. The EMPS works on 3-hour level time resolution, and it covers the Nordic and Baltic countries only. By combining those two models, the authors managed to find a design which describes both, the continental thermal-based system and the Nordic hydropower-based system.

The results from these simulations are susceptible to various inputs that are difficult to estimate. These are, for example: consumption growth, future policies regarding CO_2 that influence input prices for different production technologies, fuel prices on the global market, advances in storage technologies and the number of interconnections between the other Nordic countries and the rest of Europe. The authors of the report tried to estimate all those factors and calculate base scenario results, which are then compared with the results of simulations where some of the inputs vary.

Table 2.1 shows the results from the report for the base scenario in the year 2020. Here only the direct effects are shown, indirect effects such as increased loss in the transmission system or decreased investment need for the backup peak-load power plants are not shown, as they are not the direct effects on the spot trading. The congestion revenue is larger

[1] The original reference Statnett (2013b) does not explain in detail how the BID model works nor does it provides any further characteristics than what is reproduced in this text. Any additional information was not found in other sources.

Table 2.1: Results of Statnett's socio-economic analysis for the base scenario in the year 2020, the numbers apply for Norway only

Cable towards:	Germany	UK
Congestion revenue (Mil. €)	83	102
Loss of congestion revenue on other interconnections (Mil. €)	-21	-22
Welfare gain (Mil. €)	85	69

Source: Statnett, 2013b

for the cable towards the UK because the price difference between the UK and Norway is larger. The congestion revenues are incomes for Statnett, which pays half of the cost of the cables. Since the cables reduce the price differences, they also reduce the congestion revenue on other interconnections. The last line of the table shows the welfare gain, which represents the change in consumer and producer surplus. The welfare gain is always positive when international trade is introduced (under both import and export). However, one group of the market actors (producers or consumers) is always losing, and the other is always gaining. The welfare increase is given by the fact that the gain of one group is always larger than the loss of the other group. (Mankiw, 2011 chap. 9) The report does not use the term "welfare effect". Instead, this effect is described as *"gain for the market actors in the form of increased producer and consumer surplus"*, which might create the impression that both groups of market actors are gaining from the trade,which is not true. Over a longer period, consumers lose if the economy is a net exporter in that period. The redistribution between groups is typically much larger than the welfare effect alone. That is something that the report itself admits as well. In the base scenario, the average price in Norway is expected to increase in 2020 due to both cables by 4,9 €/MWh. The redistribution effect volume is firstly mentioned almost at the end of the analysis report on page 72. In the base scenario, the consumers in Norway are expected to lose €610 mil., while the producers are expected to gain €764 mil. These are values concerning Norwegian market actors only. The fourth chapter compares these numbers to the results obtained in this thesis. The redistribution effect for other Nordic countries is not provided in the analysis. The report mentions Sweden's market gains from the cables, which are predicted to be approximately as large as the Norwegian gains (ca. €150 mil. base scenario 2020). However, due to the fact that Sweden will lose trading revenue on pre-existing interconnections, the total socio-economic gain for Sweden (base scenario 2020) is predicted to be only around €40-50 mil. Finland is affected only marginally with small overall socio-economic loss (since Finland is a net importer and the prices are expected to increase).

2.1.2 Doorman and Frøystad

A paper by Doorman and Frøystad (2013) presents results from an analysis of the different scenarios of interconnection with the UK. They also use the EMPS operational optimisation model. Also here, the hydropower reservoirs are appropriately taken into account. The stochastic inputs include water inflow, wind and solar generation and temperature, which projects into demand. Those are modelled from historical data from 1951 to 1990. The time resolution used is approximately 5 hours. The hydropower production is modelled on plant level, and other production is more aggregated. The model covers the Nordic countries, UK, Germany and Benelux, and in a simplified way, the neighbouring countries. The results are presented in two scenarios, a 2010 scenario with the use of actual characteristics of the power system and a 2020 scenario where the information about the future system was collected from several reports. Here, only the 2020 scenario is presented as it is more relevant for the results in Chapter 4. The description of this scenario reflects the current situation quite accurately except for the fact that the Nord Link cable is already assumed as a part of the transmission grid. The two scenarios come in 3 outlines: no connection, connection between Southern Norway and Southern UK (which resembles the North Sea Link) and connection between Southern Norway and Scotland (which is also a highly discussed project nowadays, but no concession has been given yet). This thesis focuses on the North Sea Link, so the results from this outline are presented here.

The results from North Sea Link model in 2020 scenario show an increase of the price in Southern Norway by 3 €/MWh, increase in producer surplus in Norway by about €265 mil., decrease in consumer surplus in Norway by about €235 mil. and welfare increase by about €30 mil. (These numbers are very rough since they are hardly readable from the graph.) The congestion revenue from the cable alone (here named as merchant revenue) is expected to be €45 mil., so if Norway received half of this revenue through the Statnett's 50% share of the cable ownership, it would represent €22,5 mil./year. Therefore, this cable would not be commercially profitable to build. (Meaning that the congestion revenue over time would not cover the construction costs.) It would not even be socioeconomically profitable in this study (taken into account welfare effect and lower congestion revenue from other interconnections in all affected countries). The cable to Scotland would be socioeconomically profitable since it is shorter and the cost of construction would be lower, but it would still not be commercially profitable.

The lower congestion revenue, welfare gain and generally lower effect on the Norwegian market than what was found in Statnett's (2013b) analysis could be partially explained by the different data set used. Doorman and Frøystad (2013) used historical data from 1951 to 1990 to model the average precipitation rate, which has a direct effect on electricity supply in Norway. The changes in climate make Norway wetter (Hanssen-Bauer et al., 2017). The data from Meteorlogisk institutt (2019a) show that the average precipitation in Norway after the period 1941-1990 increased by roughly 9% compared to that period. Doorman and Frøystad (2013) admit that using newer data would lead to larger production values. However, Statnett's (2013b) analysis corrected the power balance estimate in 2020 upwards to reflect the changes of the climate (higher production and lower consumption) following a study devoted to this topic, which they undertook together with Norwegian Meteorological Institute.

Surprisingly, the analysis of the base year 2010 shows that Norway would be a net importer of electricity and the Norwegian prices would be reduced. This result is given by the fact that 2010 was an exceptionally dry year in Norway with average precipitation reaching only 82,9% of the long-term average. This value is the fourth lowest since 1950. (Meteorologisk institutt, 2019a) That led to exceptionally high prices in Norway that year – 50 €/MWh according to Doorman and Frøystad (2013).

2.2 Simulation models

Pfenninger et al. (2014) describe simulation models as models, which focus more on system evolution. They can consist of more sub-models (some of them are again optimisation models). Those sub-models interact with each other in time, meaning that the result from one is used as an input for another one. Such models can, for example, calculate the possible cross-border trade, emissions, and supply and demand.

2.2.1 The Enerallt model

Zakeri et al. (2016) develop such model to provide an analysis of market coupling of the Nordic countries with Germany. They use market-based multi-region energy system model, Enerallt. This simulation model is not supposed to design an optimal system from the social planner's perspective as the optimisation models do. It is rather intended to find out how the market actors will interact under given circumstances. The model actors are allowed to learn from the past periods and change their decisions in time. Those decisions are then taken as inputs for the optimisation model of a free market where the supply meets the demand similarly to real-world spot market such as Nord Pool. In that sense, it is also possible for this model to be classified as a mixed-method model. However, the optimisation only occurs on the common power market level; the regional models are simulation models. This is a normal setup for a simulation model according to Pfenninger et al. (2014). Enerallt in the study of Zakeri et al. (2016) works with hourly data, and it focuses particularly on hydropower and combined heat and power production, as those are important sources in the Nordic countries. The model is calibrated on 2014 data, which is the base year. The results after calibration show relatively small error (max 11% on monthly level) compared to the historical data. The results show that compared to the base year 2014 the Nordic system price would increase by 2,3% in 2020 without the Nord Link interconnection and by 3,5% with the Nord Link. Since all the other parameters remained the same, the cable would be responsible for 1,2% increase of the Nordic system price in 2020. That is approximately 0,36 €/MWh. For the year 2030 with Nord Link scenario, the Nordic system price is predicted to decrease by 0,3% compared to the 2014 price. The data on changes in social welfare is not given explicitly, but it may be read out of provided graphs. In 2020, the Nord Link cable would reduce consumer surplus by about €30 mil., increase producer surplus by about €220 mil., and increase congestion income by about €50 mil. All changes combined, the total socioeconomic welfare increase given by the Nord Link cable would be around €250 mil. These results are for Norway only. The market changes as a result of the Nord Link cable in 2020 for all Nordic countries (in this instance, Norway, Sweden, Finland and Denmark) would be consumer surplus decrease by about €100 mil., producer surplus increase by about €290 mil., and congestion income increase by about €20 mil. All changes combined, the total socioeconomic welfare increase in the Nordic countries given by the Nord Link cable would be around €210 mil.

2.3 Mixed method models

Mixed method models combine simulation and optimisation approaches. The simulation models, as described in the previous sub-section, can also contain some optimisation-based sub-models, so the boundary is not clear.

2.3.1 The-MA model

An example of this category is another very relevant study carried out by Thema consulting Group for BKK, Lyse Energi, Agder Energi, Statkraft and Vattenfall. (THEMA, 2012) This report is devoted to the impact of new interconnections as well as the construction of more renewable sources in the Nordic countries. THEMA uses The-MA (The Market Analyser) their own model, which they describe as a market simulation model. However, in the detailed description stays that this model *"minimises total system cost under a set of constraints"*, which is a property of optimisation models. As the description states, this model also consists of more sub-models interacting with each other. Therefore, this model is presented in this section as a mixed-method model. The The-MA model has many advantages, it uses fine hourly time resolution, power production is modelled on plant-level including detailed information on hydro reserves and combined heat and power production, it takes into account the volatility of intermittent sources; the modelled market is divided into price-zones as the real market is; transmission lines are modelled on line by line basis; and demand is divided into industry and other sectors. The model includes the Nordic countries as well as several West and Central European countries. The report presents results from four different scenarios depending on the power production surplus in Nordic countries (low – 2 TWh / high – 36 TWh) and the price of flexibility on the market (price for regulating services – low/high). These scenarios were designed to cover possible developments on the market, which were unknown at the time the report was written. Since then, the development of the market has become more clear. In 2018, the Nordic surplus was 7 TWh according to NVE (2018), and the price of regulating services is high due to the high price of fossil fuels and CO_2 permissions. Therefore, the results presented here represent a linear combination of low-surplus-high-regulating-prices scenario and high-surplus-high-regulating-prices scenario as the 7 TWh surplus lies between 2 TWh and 36 TWh scenarios.

By combining the two scenarios mentioned above, the congestion incomes for Norway in 2020 were estimated to be €51 mil. for the cable towards Germany and €54 mil. for the cable towards the UK. Both cables together would reduce the congestion revenues on other interconnections by €20 mil.

The price effect was estimated to be 2,13 €/MWh for both cables together. The change in consumer surplus was estimated to be €-316 mil. and the change in producer surplus €372 mil. The welfare effect would, therefore, be €56 mil.

The report also mentions the benefits in the form of lower seasonal volatility on the Nordic market, but the monetary value of this benefit is not presented. Besides, the cables will, according to the report, have a positive effect on climate by allowing to reduce the price of CO_2 quotas and thus allowing political acceptance of setting the quota lower in the long run. Similarly to the Statnett's report (2013b), this report claims that the profits for owners of the cable could be higher if part of the capacity was reserved for the selling of regulation services in case the revenue of providing those services would be higher than the revenue from day-ahead trading. With the increasing capacity of RE sources in the future, the market for regulating services will presumably grow. Along with those non-quantified benefits, there are mentioned non-quantified costs as well. These are higher investment costs in the internal transmission network and the cost of the intervention to nature.

The congestion revenues are expected to partly reduce grid tariffs. The analysis suggests that through this mechanism, the 31% of those profits would be redistributed to the energy-intensive industry, 26% to the other industry, 12% to public services and 31% to the households. The effect on price and redistribution between consumers and producers given by the cables will also supposedly be reduced by new power capacity instalments (mainly in the form of wind power), which will be more feasible due to the cables themselves.

2.4 Electricity market models

According to Pfenninger et al. (2014), the electricity market models focus on particular market-related questions within the field of electricity trade. Since the research question of this master's thesis is somewhat narrow – namely to find the price change and the changes in consumer and producer surpluses after the introduction of cables towards Germany and the UK – the use of large energy system models would be redundant. Instead, electricity market model focusing particularly on the most relevant part of the electricity market is presented. A similar approach was used in a paper by Dillig, Jung and Karl (2016). They used historical data on supply and demand curves on German day-ahead spot electricity market in order to answer a question of what would the spot price be without renewable production supply. Taking into account all equilibrium prices and volumes for each hour of the years 2011-2013, they determined the marginal cost curve of non-renewable production, and then they reconstructed average price without the renewable supply on the market. They concluded that the price reduction induced by renewable power production would be more or less equal the renewable surcharge levied on small consumers. The large consumers, who are exempted from paying these renewable surcharges, enjoy roughly 50% electricity price reduction thanks to the renewable power supply.

2.5 Literature review summary

The results across studies differ substantially. Table 2.2 displays the most relevant results from the literature review. The results obtained in this thesis will be compared to the results from the literature review in Chapter 4.

Table 2.2: Overview of the most relevant results from the literature review

Author	Statnett	Doorman and Frøystad	Zakeri et al.	THEMA
Publication year	2013	2013	2016	2012
Model name	EMPS	EMPS	Eneralt	The-MA
Model type	Optimisation dispatch		Simulation	Mixed
Modelled year	2020			
Nord Link cable				
Price increase €/MWh			0,36 (NRC)	
Cong. revenue on cable mil. €	83 (NO)		50 (NO)	51 (NO)
Δ CS mil. €			-100 (NRC)	
Δ PS mil. €			290 (NRC)	
Δ Welfare from trade mil. €	85 (NO) 85 (SE)		190 (NRC)	
Nord Sea Link cable				
Price increase €/MWh		3 (NO-south)		
Cong. revenue on cable mil. €	102 (NO)	22,5 (NO)		54 (NO)
Δ CS mil. €		-235 (NO)		
Δ PS mil. €		265 (NO)		
Δ Welfare from trade mil. €	69 (NO) 69 (SE)	30 (NO)		
Both cables combined				
Price increase €/MWh	4,9 (NO)			2,13 (NO)
Δ CS mil. €	-610 (NO)			-316 (NO)
Δ PS mil. €	764 (NO)			372 (NO)
Δ Welfare from trade mil. €	154 (NO)			56 (NO)

NRC = Nordic Countries, NO = Norway, SE = Sweden

Chapter 3

Methodology and data [1]

3.1 Motivation

The purpose of this master's thesis is to find out how the undersea cables towards Germany and the UK will affect the Norwegian electricity market. To answer this question, an electricity market model has been developed. Calculating the price change and change in consumer and producer surpluses caused by import or export is rather a simple task if the price elasticity of demand and supply is known and constant over time. That is not the case with electric power. The major part of electricity produced and consumed in Norway is traded on day-ahead spot electricity market where the supply and demand curves change each hour. Depending on the time of the day, day of the week and season of the year, the intersection of supply and demand curves changes its position along these curves and the price elasticity of both supply and demand changes with it. The easiest way to show the development of the supply and demand curves over time is to bind the single hourly time frames into a movie. The animated Figure 6 shows the hourly changes of supply and demand curves on the Nord Pool day ahead market in the 17th week of the year 2018. The full almost 15 minutes long video covering the whole year 2018 is available

[1] Significant part of the source code of the applied model was developed as part of the seminar "701016 Statistical Programming Languages" taken on my exchange at Humboldt-Universität zu Berlin, where I developed my programming skills in the R language in order to be able to design the model for this master's thesis. The preliminary version of the code was presented and tested on a small sample of the data as part of the report submitted within this seminar. Consequently, part of the reasoning and arguments, data description and preliminary results for a given data sub-sample were published in spring 2019 in this report named *"The effect on the domestic price of electricity in Norway as a result of further integration to German electricity market"*. This report and the source code was written solely by the author of this thesis, me, Dalibor Vágner.

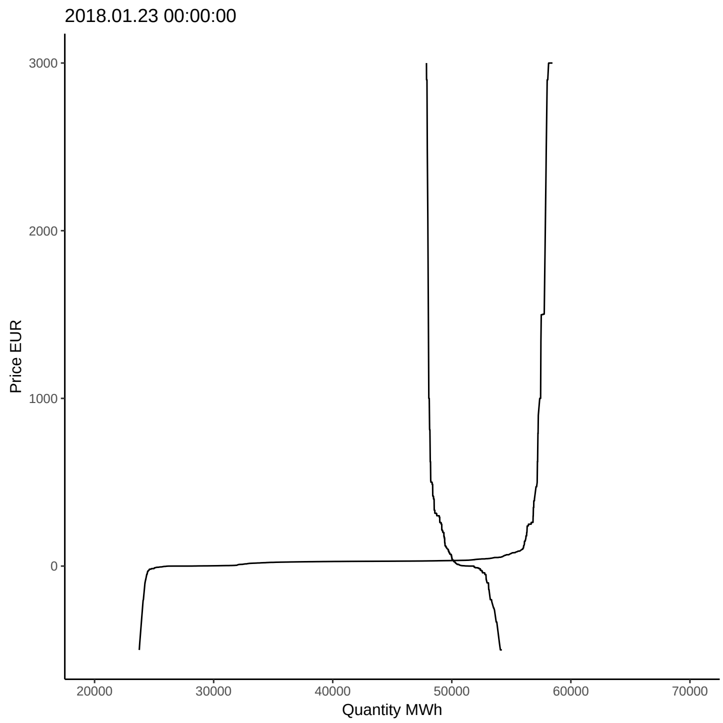

Figure 6: Animated representation of hourly changes in supply and demand curves on the Nord Pool day ahead market in the 17th week of the year 2018
Original data source: Nord Pool 2019b

on this link[2] with password "NordPool2018".

Figure 7 gives an illustration of how the position of the equilibrium is important. It shows the supply and demand curves on Nord Pool day-ahead market. The left graph represents the market in the morning from Sunday to Monday on 01.01.2018 between 01h and 02h when the equilibrium price was 24 €/MWh, and the equilibrium quantity was 39 GWh. The price in Germany at that time was negative, -30 €/MWh. Having the cable already in function on this particular hour would allow import 1,4 GWh of very cheap German electricity. The red shifted supply curve represents this hypothetical import. However, since the equilibrium lies on an extremely elastic part of the demand curve, the price on the Nordic market would change only very little. It would decrease by 0,4 €/MWh. The subsequent change in consumer and producer surplus would be little as well. The right-hand graph shows the situation on Thursday 01.03.2018 between 08-09h in the morning when the equilibrium price was the highest of the whole year 2018, namely 198 €/MWh. The quantity traded at that hour was 63 GWh. That morning was exceptionally cold in the whole Europe, with measured temperature in Oslo -13,6°C

[2]https://vimeo.com/328940405 password: **NordPool2018**

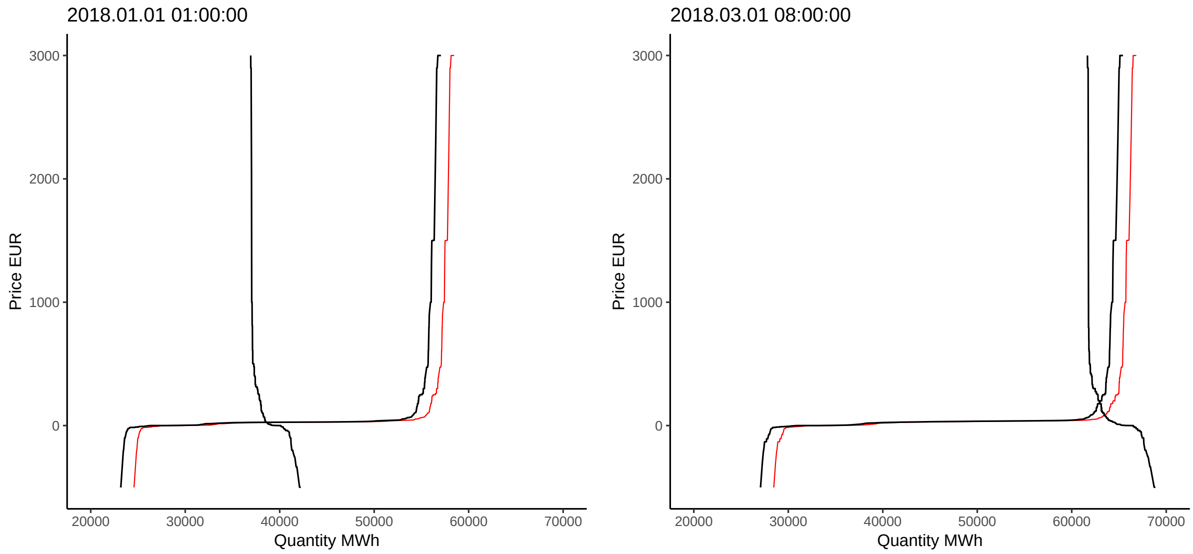

Figure 7: Nord Pool day-ahead spot market on 01.11.2018 at 01-02h and on 01.03.2018 at 08-09h. The red line shows the situation after hypothetical import of 1400MWh
Data source: Nord Pool (2019b), own calculations

(Meteorologisk institutt, 2019b). In that particular morning, the day-ahead price in Germany was around 40 €/MWh. Having the Nord Link cable already in operation by that time, 1,4 GWh could be imported to the Nordic market. The red shifted supply curve again represents this hypothetical import. Since the equilibrium lies on a relatively steep part of the demand curve, the new equilibrium price would be much lower. The new equilibrium price after importing 1,4 GWh would be lower by 111 €. A subsequent change in producer and consumer surplus would be substantial as well.

3.2 Data description

3.2.1 Data on Norwegian market

Having access to the actual supply and demand curves data for each hour allows calculating the price change and welfare change caused by hypothetical import an export quite accurately. The Nord Pool website (Nord Pool, 2019b) provides the supply and demand curves for each hour since July 2014. This data covers the whole Nord Pool area, the common market for Norway, Sweden, Denmark, Finland and the Baltic countries. In 2017, 146 TWh of the electricity produced in Norway was sold on Nord Pool day-ahead market. (Nord Pool, 2019c) That represents 98% of the Norwegian production in that year. (SSB, 2018) Since Norway is fully integrated into the Nordic market, any export and import to and from Norway will influence the day-ahead Nord Pool spot price, which is the main indicator of the price in Norway.

The Nord Pool market is divided into 15 price zones, 5 of them are located in Norway. The supply and demand curves provided publicly represent the whole Nord Pool market and indicate the so-called system price, which might differ from the zonal prices if the transmission capacity between the zones is binding. Both cables will connect to the Norwegian zone NO2 and put additional pressure on the transmission capacity to and from this bidding zone. The data from Nord Pool (Nord Pool, 2019c) show that the average price difference in 2018 between the NO2 zone and the neighbouring zones (NO1 and NO5) was 0,9% and 0,8% respectively. In 2018, the average difference between the NO2 zone price and the system price was 2,7%. These numbers show that different prices in these zones are quite rare and that the transmission capacity between those zones is sufficient most of the time. Statnett is planning grid reinforcement projects together with the construction of the cables so that the transmission capacity between the zones also remains sufficient after the cables are finished (Statnett, 2013a). Therefore, using the supply and demand curves data for the whole Nord Pool area is reasonable.

The data is provided (Nord Pool, 2019b) in downloadable excel files where each file represents 24 hours. The data for each hour consists of thousands of data points that make price-quantity pairs, which create the supply and demand curves for one particular hour. This means that one excel file contains the data for 24 supply and demand curves. Each excel file has approximately 1 MB or 2 MB depending on the file type. Thus, to cover one year on hourly resolution requires approximately 350-700 MB of data. The data needs to be adjusted before it can be used for market analysis as explained in the Nord Pool's explanatory note (Nord Pool, 2016). Namely, volumes for accepted block orders and volumes of import and export need to be added to each volume value of the respective curve. The data is available from July 2014 until now.

3.2.2 Data on German and UK market

Supply and demand curves for the day-ahead market in Germany are not publicly available. Moreover, even with access to this data, using it would be pretty complicated for two reasons:

First of all, the main German spot market operator EPEX SPOT operates in Germany, Austria, France, UK, The Netherlands, Belgium and Switzerland and it couples these markets together. (EPEX SPOT, 2019) The association of European transmission system operators publishes in its last Yearly Statistics & Adequacy Retrospect inventory of all cross-border transmission lines and cables with their maximum capacities (Entso-e, 2016). An easy calculation shows that Germany had in 2014 altogether 83 high-voltage cross-border transmission lines with a total capacity of 55,9 GW. On the other hand, Northern Europe was at that point in time connected to mainland Europe with 12 undersea cables of total capacity 5,7 GW. In that sense, the day-ahead market bids from actors in other countries are relevant for the price in Germany as well, since these markets are highly integrated with large cross-border transmission capacities. Furthermore, EPEX SPOT is not the only day-ahead spot exchange operating on German territory. Another day-ahead spot exchange operator EXAA based in Austria allows market actors to also bid for the German area. Another reason why the usage of supply and demand curves for Germany would be challenging is that not all the electricity traded in Germany is traded on the day-ahead spot market. According to the data provided on the EPEX SPOT website, there was traded 29 TWh of electricity on this platform in the common bidding area for Germany and Austria in August 2018. According to the IEA (2019), 55 TWh of electricity was produced in Germany and Austria in August 2018, meaning that roughly half of electricity that was actually produced was traded on this platform. Bilateral agreements and OTC trading are more common in mainland Europe compared to the Nordic market, especially compared to Norway. Using supply and demand curves just for the day-ahead market would, therefore, exclude large amounts of electricity traded bilaterally and over-the-counter.

The situation in the UK is similar. EPEX traded in the UK 62 TWh in 2015 (Next Kraftwerke, 2019) and Nord Pool traded 111 TWH in 2017 on the UK territory. Both exchange operators do not publish the data on supply and demand curves. UK produces annually roughly 320 TWh of electricity (IEA, 2019) meaning that roughly half of it is not traded on one of those day-ahead markets.

Since the main focus of this master's thesis is the Norwegian electricity market, the model is designed in such a way that the data on supply and demand curves for Nord Pool spot market is sufficient. The interaction with the German and UK market is based on the price information only. Therefore, the day-ahead prices for Germany and the UK on the hourly level are needed. This price data can be downloaded from Entso-e website for both countries. (Entso-e, 2019). In the case of Germany, the data is provided for the single price area covering Germany, Austria and Luxembourg until 30.09.2018. From 01.10.2018, the price zone changed and the data is provided for the zone covering Germany and Luxembourg only. The Entso-e transparency platform for data was launched 06.01.2015 meaning that the data for the first five days of the year 2015 is not provided on this platform. Therefore, the data for those five days was collected from another source (Fraunhofer ISE, 2016).

3.3 Model description

3.3.1 Theoretical model

The changes in consumer and producer surpluses by international trade are depicted in Figure 8.

Export q is, according to the economic theory (Mankiw, 2011), modelled by shifting the

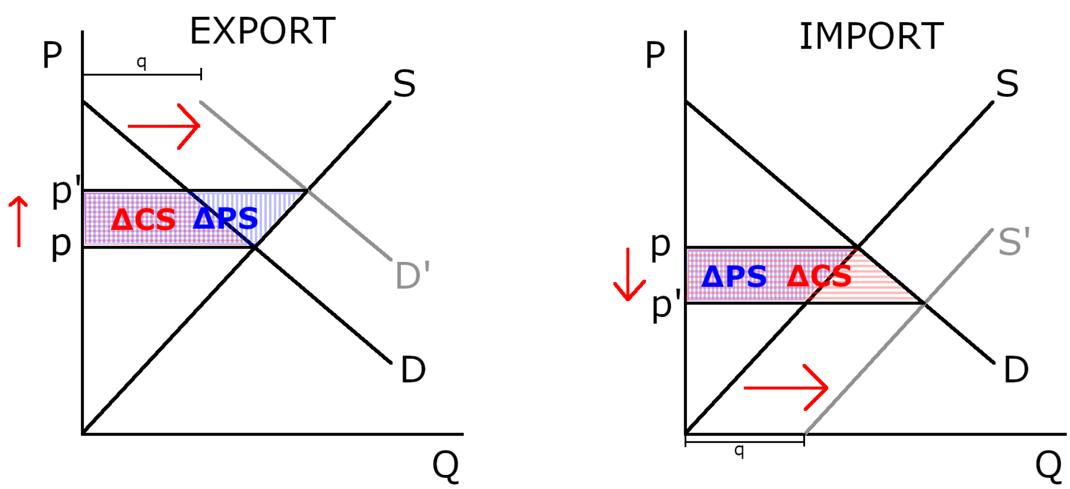

Figure 8: Changes in consumer and producer surpluses given by international trade

demand curve to the right by the amount of q. The new equilibrium finds place where the original supply curve S and the shifted demand curve D' intersect. The price increases from p to p'.

Change in consumer surplus ΔCS can be formally written as:

$$\Delta CS = \int_{p'}^{p} D(P)dP \tag{1}$$

Where p is the original price, p' is the new price and $D(P)$ is the demand quantity function of the price P. Since under export $p' > p$, the value of ΔCS is negative. On the left-hand graph of Figure 8, consumer surplus is reduced by the amount equal to the area marked with red horizontal lines. (Area between the price axis, original demand curve, horizontal line at the original price and horizontal line at the new price)

Change in producer surplus ΔPS can be formally written as:

$$\Delta PS = \int_{p}^{p'} S(P)dP \tag{2}$$

Where p is the original price, p' is the new price and $S(P)$ is the supply quantity function of the price P. Since under export $p' > p$, the value of ΔPS is positive. On the left-hand graph of Figure 8, producer surplus is increased by the amount equal to the area marked by vertical blue lines. (The area between the price axis, supply curve, horizontal line at the original price and horizontal line at the new price)

The welfare gain ΔW is given by the equation:

$$\Delta W = \Delta CS + \Delta PS \tag{3}$$

Since the absolute value of ΔPS is larger than the absolute value of ΔCS, ΔW is positive. On the left-hand graph of Figure 8, it is represented by the area of the triangle bounded by the supply curve, the original demand curve and the horizontal line at the new price.

Import q is modelled by shifting the supply curve to the right by the amount of q. The new equilibrium finds the place where the original demand curve D and the shifted supply curve S' intersect. The price decreases from p to p'.

Change in consumer surplus given by equation 1 is positive, since under import $p' < p$. On the right-hand graph of Figure 8, consumer surplus is increased by the amount equal to the area marked with red horizontal lines. (Area between the price axis, demand curve, horizontal line at the original price and horizontal line at the new price)

Change in producer surplus given by equation 2 is negative, since under import $p' < p$. On the right-hand graph of Figure 8, producer surplus is decreased by the amount equal to the area marked by vertical blue lines (the area between the price axis, original supply curve, horizontal line at the original price and horizontal line at the new price).

The welfare gain given by equation 3 is positive since the absolute value of ΔCS is larger than the absolute value of ΔPS. On the right-hand graph of Figure 8, it is represented by the area of the triangle bounded by the original supply curve, the demand curve and the horizontal line at the new price.

3.3.2 Applied model

The model used in this master's thesis was written in programming language R and the whole source code with detailed comments on each operation is provided in public repository on GitHub here[3] as well as in the Appendix B of this text. The model is designed as a loop going through all the hours in a given year and calculating the results for that particular year in the end.

3.3.2.1 Price change calculation

For each hourly data file, the model reconstructs the original price one the day-ahead Nord Pool market by finding the intersection of the supply and demand curve. The model simulates on cable at a time, so that the reconstructed domestic price is then compared to the day-ahead spot price in that particular hour on either the German or British market. So:

$$\begin{aligned} &\text{if} \quad p_d > p_f \quad \text{then} \quad S' = S + q \\ &\text{if} \quad p_d < p_f \quad \text{then} \quad D' = D + q \end{aligned} \tag{4}$$

If the domestic (Norwegian) price p_d is larger than the foreign (German/British) price p_f, then the import is realised by creating the shifted supply curve S' by adding the quantity q to every single quantity value of the original supply curve S. The quantity q is given by the transmission capacity of the modelled cable. Since the model works with an hourly resolution of the data, a transmission capacity 1 400 MW will allow to transport 1 400 MWh in a given hour. The export is realised similarly by shifting the demand curve if the foreign price is larger than the domestic one. Subsequently, the new price p'_d is

[3] https://github.com/DaliborV/Masters_Thesis_Script

found at the intersection of either S' and D or S and D'. At this point, the new price p'_d can overshoot the original price difference between the countries. If the original price difference is too small, clearly not all the export/import given by transmission capacity can be realised. That is why:

$$\text{if} \quad p_d > p_f \wedge p'_d < p_f \quad \vee \quad p_d < p_f \wedge p'_d > p_f \quad \text{then} \quad p'^{NEW}_d = p_f \tag{5}$$

If the new domestic price p'_d overshoots the difference between original domestic price p_d and the foreign price p_f, then the price change stops at the foreign price level p_f. At this point, the price change is bounded by the original price at the foreign market. However, the foreign market is likely to react to the import/export, and the foreign price starts to converge towards the Norwegian price. Thus the original foreign price cannot serve as a correct boundary. We cannot model the exact response of the foreign market since the data on supply and demand curves there is not available, so the new foreign price is unknown, and that is why the robustness parameter c allows us to model different scenarios of the sensitivity of the foreign market as follows here:

$$\text{if} \quad \frac{p'_d - p_d}{p_f - p_d} > c \quad \text{then} \quad p'^{NEW}_d = p_d + c * (p_f - p_d) \tag{6}$$

In other words, the parameter c defines the percentage of the original price difference which can be used for price change on the domestic market. For example, if the parameter is $c = 0,8$; the original foreign price is $p_f = 50$; and the original domestic price $p_d = 40$, the new price can increase, if the transmission capacity is sufficient, to 48 maximum as it is the sum of the original domestic price and product of the original price difference and the robustness parameter c as shown in the equation 6; or in the following equation with numbers:

$$48 = 40 + 0,8 * (50 - 40) \tag{7}$$

As the results will show, the number of instances when the robustness parameter is binding is relatively small, so that the price change is mostly limited by the transmission capacity and the *if* conditions of equations 5 and 6 are not fulfilled.

3.3.2.2 Welfare effect calculation

When it comes to welfare changes calculation, the model applied cannot calculate the definite integral of the supply and demand curves from their function forms as it is shown in the previous section (equations 1 and 2), since these curves are defined by discrete steps given by price/quantity data points. Figure 9 shows the area corresponding to the change

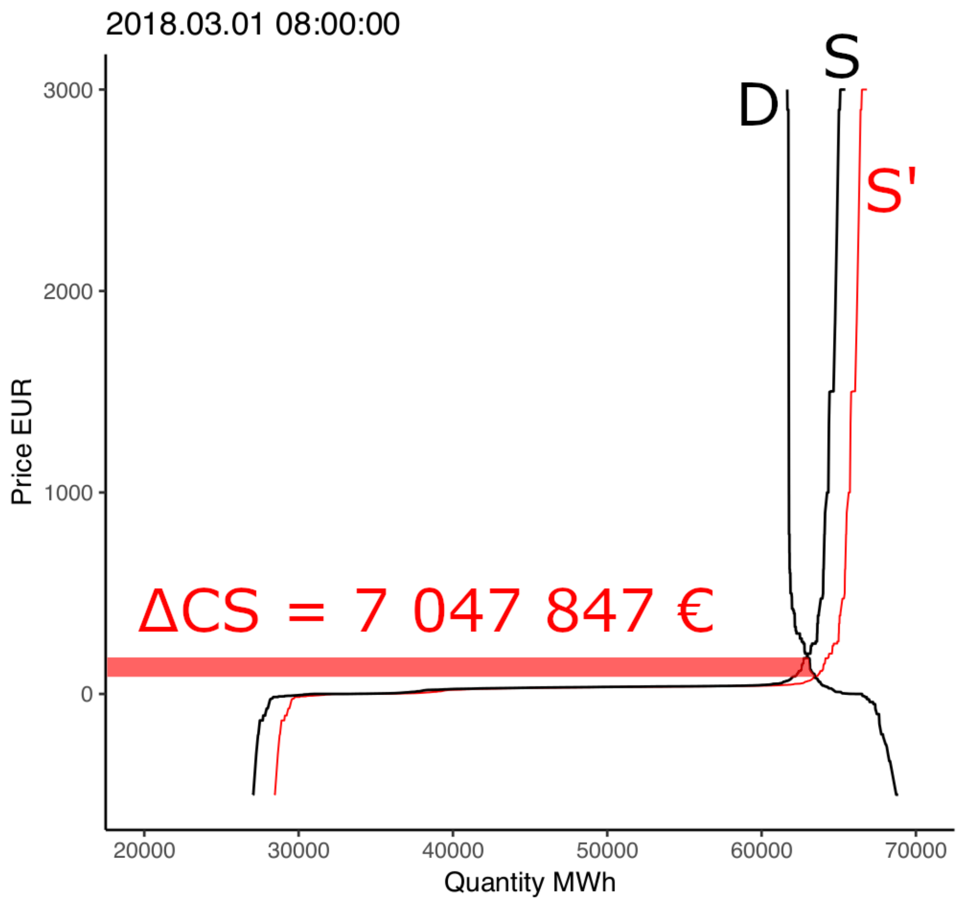

Figure 9: Change of consumer surplus after importing 1 400 MWh at 8:00-9:00 on 1.3.2018
Data source: Nord Pool (2019b), own calculations

of consumer surplus which needs to be calculated in the situation of simulated import of 1 400 MWh during 8:00-9:00 on 1.3.2018. This graph shows the largest consumer surplus increase from all the simulated hours of 2018. The area depicted on the picture was calculated by the following formula:

$$\sum_{n=1}^{I-1} (p_{i+1} - p_i) * q_i \tag{8}$$

Where I is the number of steps on the demand curve between the original price p_d and the new price p'_d; i is the index number of each price-quantity step; p_i is the price level at the i-th step; and q_i is the quantity associated with this step. In other words, the model sums the rectangles given by the quantity and price differences of the steps on the demand curve. The only challenge is that the script either includes, or excludes the whole step into the area as it is depicted in Figure 10, meaning that the yellow labelled rectangles on this figure are either included or not depending on the actual position of the intersection of the curves S and D and S' and D. If the intersection lies closer to the blue/green coloured area, the rectangle is included, if it lies closer to the outside of the coloured area, it is not included. In the case illustrated in Figure 10, the top yellow rectangle would be included and the bottom one not. This error is corrected by the following formula:

$$\Delta CS^{NEW} = \Delta CS + [(p_d - p'_d) - (p_I - p_1)] * \frac{\sum_{i=1}^{I} q_i}{I} \tag{9}$$

The correction formula can be explained on the Figure 10; it subtracts the height of the

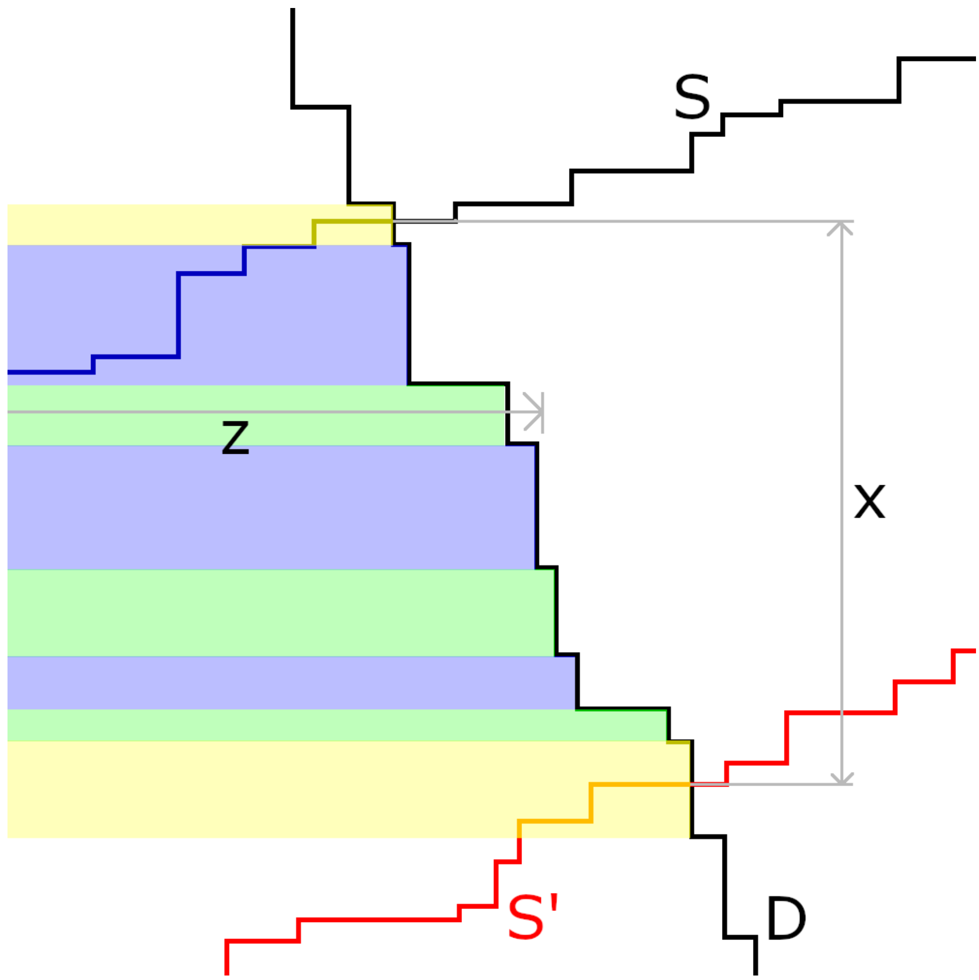

Figure 10: Detail explaining the consumer surplus change calculation, fictional data

actual distance between p_d and p'_d (here marked as X) from the height of all rectangles used for calculating the ΔCS. This difference is then multiplied with the average quantity between the intersections S and D and S' and D, here marked as Z. This product is subsequently added to the original ΔCS to make new corrected ΔCS. Using the average quantity instead of the quantity associated with the price where the error occurs (yellow rectangle) creates a negligible error. The calculation of ΔCS under import and ΔPS under both import and export is analogous.

Such calculations are done for each hour of the year and then the summary statistics for the whole year are calculated.

3.3.2.3 Model limitations

The response of the foreign market is not based on the actual supply and demand curves on that market, but it is rather simulated by the robustness parameter, which works as if the foreign supply and demand curves were linear. This simplification causes a bias of the price change upwards. The exact mechanism of this bias, and examples of this, are described in the Chapter 4. For small transmission capacities and large price differences between markets, this bias is negligible. Therefore, this model is not suited well for calculating the effect of interconnections of much larger transmission capacity than the assumed 1 400 MW cables.

Another source of upward bias in the result might be the fact that this model neglects the energy loss in the cable, but this loss is more important for the calculation of the congestion revenue since in most of the hours it will be projected there. One more physical restriction, which is neglected in the model, is power ramping. The model simply assumes that the flow of electricity can be changed immediately to follow the price pattern. However, Statnett (2013a) assumes that when the construction of the cables is finished, the ramping regime will allow the change of the power flowing in the cable by 1 000 MW/h.

Chapter 4

Results

The table with all results as produced by the original code is attached in the Appendix A.

4.1 Results introduction

The script of the model was programmed to go through all the years with complete data (2015 to 2018), do the calculations with different transmission capacities (700, 1400, 2100 and 2800 MW) and different values of the robustness parameter (1; 0,8 and 0,6). The calculations took around 18 hours on regular PC. This section presents and discusses the results.

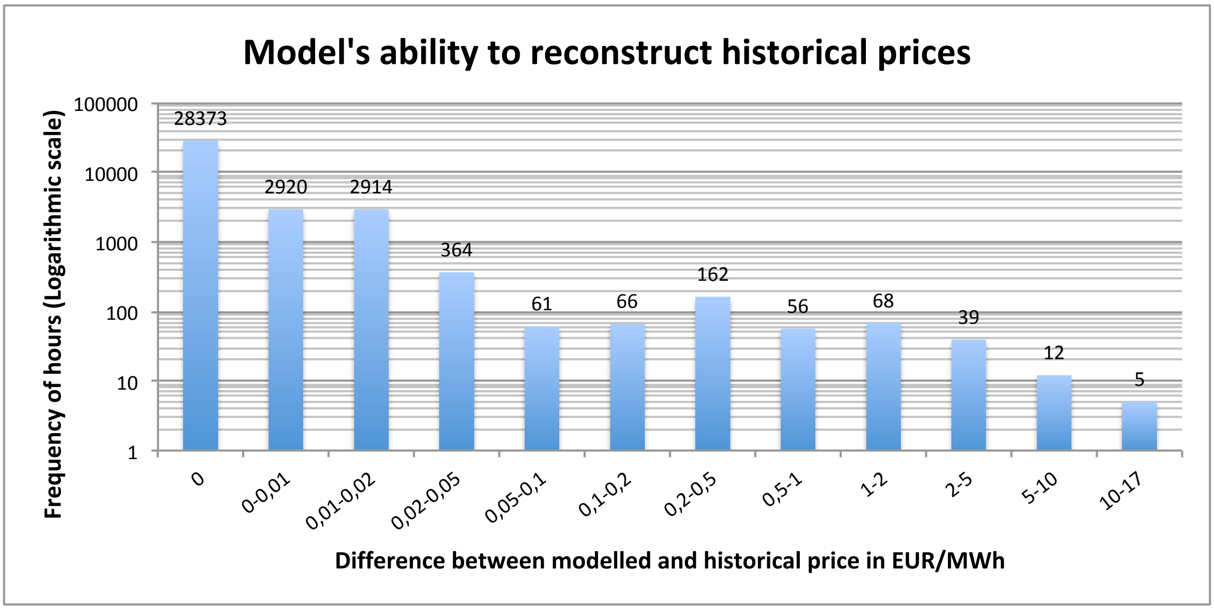

Figure 11: The blue columns represent the frequency of differences between modelled and historical prices through all the hours of the years 2015-2018. The grey lines represent the logarithmic scale of the Y-axis

First of all, we will have a look at the reconstructed original domestic price p_d on the Nord Pool market and compare it with historical data to see if the intersections of supply and demand curves give correct price information. The results show that the historical price was modelled quite accurately. In 2018, the average price difference between estimated and historical price was 0,005 €/MWh. In 2017 it was 0,049 €/MWh, in 2016 0,003 €/MWh and in 2015 0,011 €/MWh. Figure 11 depicts how often the reconstructed prices are different from the historical prices and how large the difference is (note the logarithmic scale of the Y-axis). In total, out of the 35 040 hours of the years 2015-2018, the price was estimated exactly in 28 373 instances. At those hours when the price was different, the absolute value of the difference was smaller than 0,02 €/MWh in 88% of those cases. Therefore, we can conclude that the model reconstructs the price accurately. The difference is most probably given by the fact that finding the intersection of two curves defined by discrete steps always needs some level of approximation and Nord Pool uses different algorithm to find this intersection.

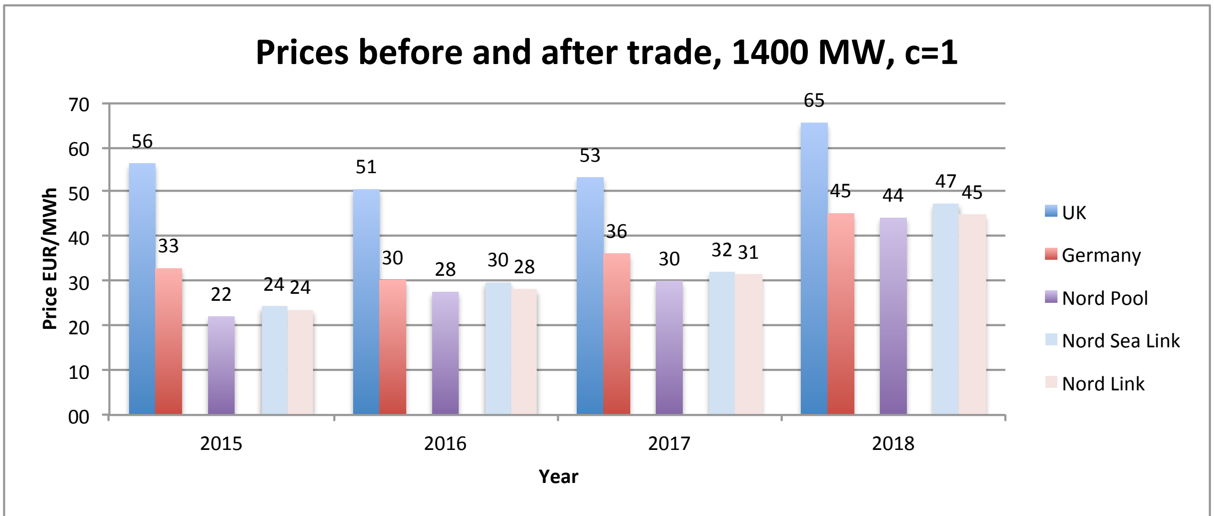

Figure 12: Prices on the markets before and after interconnection

Figure 12 illustrates what happens with the domestic price on Nord Pool after import/export is realised. The Figure shows a modelled scenario with transmission capacity equal to 1 400 MW and robustness parameter $c = 1$. The left blue column represents the average price in the UK and the left red column represents the average price in Germany. The middle violet column represents the original average reconstructed price on the Nord Pool market. The right light-blue column shows the price on the Nord Pool market with modelled Nord Sea Link cable (towards the UK) and the right light-red column shows the

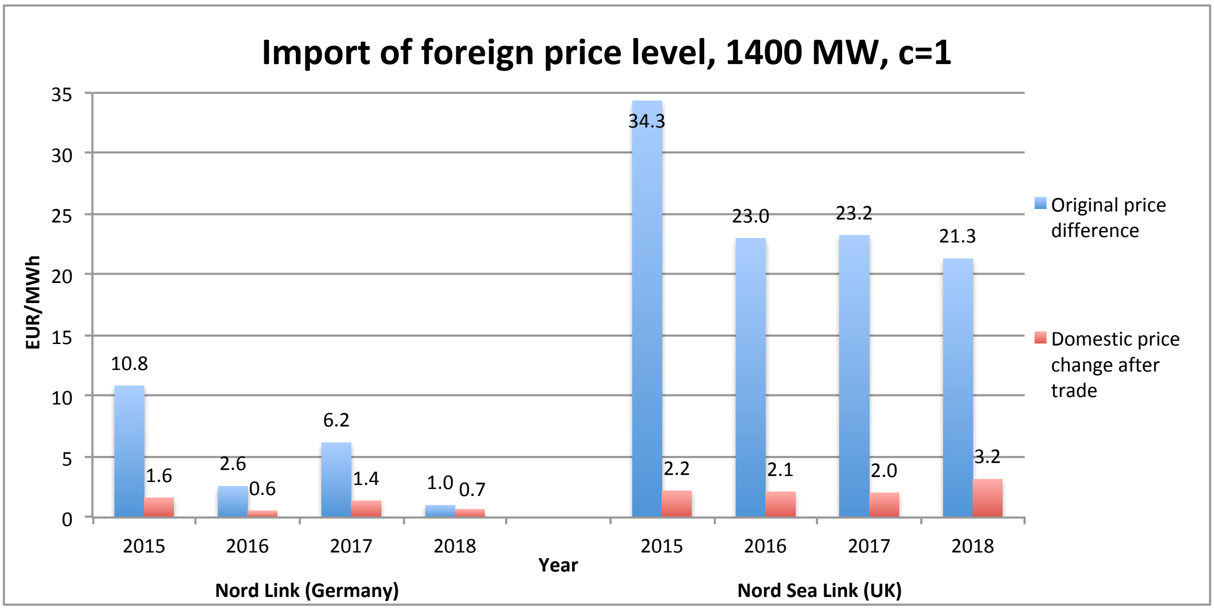

Figure 13: Price changes compared to the price level on the other side of the cable

price on the Nord Pool market with modelled Nord Link cable (towards Germany). We can see that, generally, the higher the price on the other side of the cable, the higher the price change. However, the limited transmission capacity does not allow to import the price level on the other side of the cable by far. Maximal price change in this scenario is 3,17 €/MWh. For better illustration of how the markets interact, Figure 13 compares the differences between foreign price p_f and domestic price p_d before trade and the differences between original domestic price p_d and the new domestic price p'_d. We can see that in case of trade with the UK, domestic prices generally increased more than in the case of trade with Germany since the UK had generally higher prices. However, since the shape of supply and demand curves and the distribution of price differences across time play an important role in the new price creation, the domestic market reacts differently across years. In the left-hand part of Figure 13, we can see that the price increased more in 2018 than in 2016 even though the average price difference was larger in 2016. In the right-hand part of this figure, the effect is even more visible. The domestic market reacted strongest in 2018 even though this year the difference between Nord Pool price and the UK price was the smallest. The properties of the supply curve can explain this paradox. The graphs in Chapter 3 show the shape of the demand curve which becomes increasingly inelastic as the price increases. That has two consequences. First, any import has generally lower price response than export because, under import, the equilibrium moves from more inelastic part of the supply curve to more elastic. In contrast, under export the equilibrium moves to a more inelastic area where the price response is higher. Secondly, for generally higher price level, the response is stronger because the equilibrium generally lies on more inelastic part of the supply curve. That is the case of the year 2018 when the average price on the Nord Pool market was 44 €/MWh, while in 2016 it was only 28 €/MWh. That is why the price response in 2018 is much larger than in 2016.

4.2 Robustness parameter discussion

The previous section gave some insight into the results. Nevertheless, further discussion is necessary before drawing any conclusions. This section will focus on the role and meaning of the robustness parameter c. As explained here in the previous chapter, this parameter simulates elasticity of the foreign market. It determines how close the new domestic price p'_d can approach the original foreign price p_f each of the modelled hours. This restriction is not binding most of the time, because the price differences between the markets are so large that the new domestic price after trade approaches the foreign price only slightly. However, in the few cases when the price differences are small, this parameter is important to simulate the response of the foreign market. Table 4.1 shows how often the robustness

Table 4.1: Frequency of instances when the robustness parameter c is binding

Year	Total # of hours	Parameter c	# of hours when c is binding: Nord Link (DE)	# of hours when c is binding: Nord Sea Link (UK)
2015	8 736	1	1 199	228
		0,8	1 334	272
		0,6	1 558	319
2016	8 784[1]	1	2 507	500
		0,8	2 834	578
		0,6	3 345	675
2017	8 760	1	1 669	269
		0,8	1 900	320
		0,6	2 289	390
2018	8 760	1	2 952	621
		0,8	3 294	703
		0,6	3 774	833

1) The year 2016 has 366 days and thus 8 784 hours

parameter c restricts the price change. The second column shows number of hours in a given year. This number slightly differs because the year 2016 has 366 days (it is a leap year) and the year 2015 lacks the data for one day. The fourth and fifth column shows the

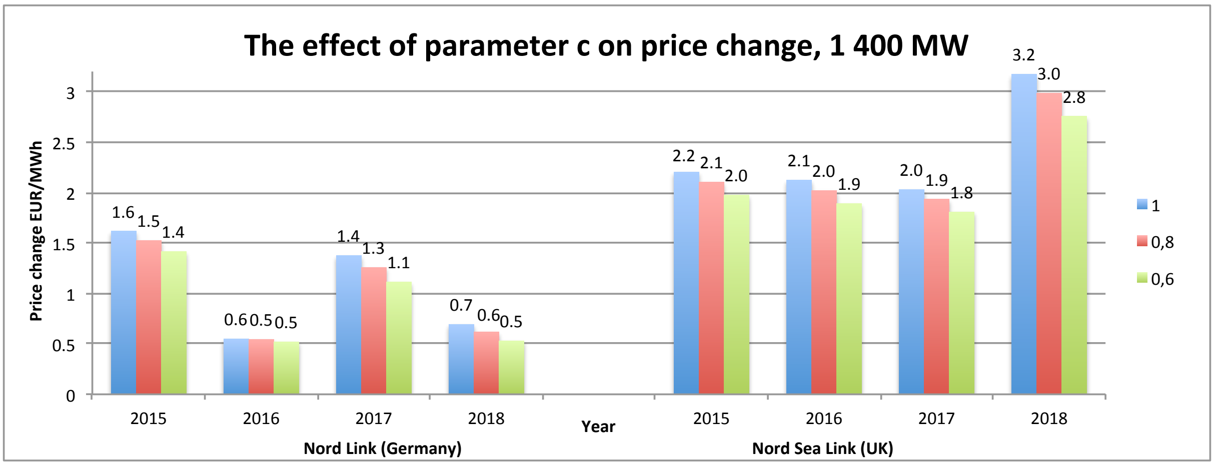

Figure 14: The effect of the parameter c on the domestic price change

number of hours when the parameter c is binding. Since the price differences are smaller with Germany, the number of times when the domestic price gets too close to the foreign price is higher and thus the parameter is binding more often. There is also clear trend that the lower the parameter, the higher the frequency since the lower parameter means that the price movement is stopped earlier. The shape of supply and demand curves and the timing of the differences on hourly level play also an important role here because some of the variation does not follow previously mentioned patterns.

The parameter c influences the price change on the domestic market. Figure 14 depicts this relationship. Generally, the parameter does not influence price difference to a great extent. Nevertheless, the results show that the price change would be overestimated if it was not part of the model. The correct value, which should be used, is unknown. However, it is possible to argue that the German market is larger than the Nord Pool market. Besides, it is very well interconnected to the rest of Europe as explained in Chapter 3. Therefore, it is reasonable to assume rather lower elasticity corresponding to the robustness parameter $c = 0,8$. The UK market is slightly smaller than the Nord Pool market, and the interconnection to other markets is far weaker than in Germany. Therefore, we chose the robustness parameter $c = 0,6$ as the default scenario for analysis of the Nord Sea Link cable. The results presented in the next sections are the results of the scenarios with $c = 0,8$ and $c = 0,6$ for the German and UK market, respectively.

It is also apparent that the robustness parameter is far from being a perfect estimation of the reaction of the foreign market. Namely, the day-ahead supply curves of the foreign spot market are likely shaped similar to the supply curves of the Nord Pool market.

That means that in the case of export from Norway (import to the foreign market), the price reaction will be stronger than in the case of import to Norway (export from the foreign market). The mechanism is similar to what was previously described in chapter 3. The new equilibrium on the foreign market moves to the more elastic part of the supply curve under import while it moves to the more inelastic part under export. However, the robustness parameter does not differ under import and export. It simply assumes linear curves and models the response the same in both cases. In that sense, using this parameter causes upward bias of the price change on the Nord Pool market. The bias is much smaller than if the parameter was not used at all and it is generally small if this parameter is used in a small number of instances. Therefore, we could argue that the bias is negligible in case of the Nord Sea Link (UK) cable. Nevertheless, the bias could be relevant in case of the Nord Link (DE) cable in 2018, when the parameter was used in 38% of the hours (for $c = 0,8$).

4.3 Transmission capacity discussion

The model was designed in such a way that the transmission capacity can be changed as a parameter. This section will discuss how a further increase of transmission capacity between Nord Pool and Germany, and Nord Pool and the UK affects the Nord Pool market. This analysis is important because, alongside the cables that are already under construction, there is a discussion about more undersea cables. The Statnett is at least assuming one more cable to Scotland in the future in its long-term market analysis. (Statnett, 2018) Figure 15 shows how the scenarios with different transmission capacity

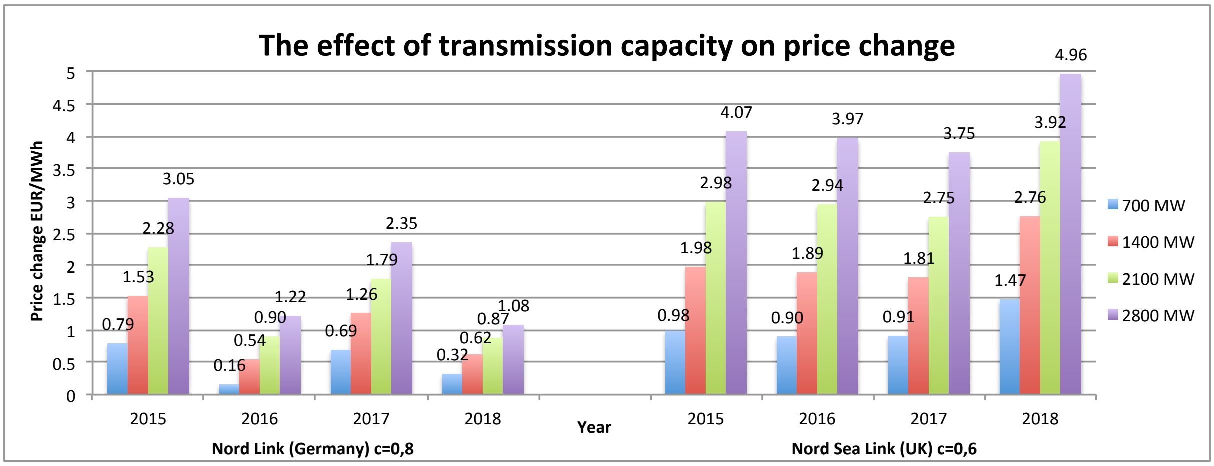

Figure 15: The effect of the transmission capacity on the domestic price change

change the domestic price on the Nord Pool market. We can see that the price differences increase almost proportionally to the transmission capacity. This price change is given by the large price differences between markets, especially in the case of Nord Sea Link cable towards the UK. Here, even the capacity of 2 800 MW (which is double of the planned Nord Sea Link cable) would lead to increase representing just 12% of the original price difference in 2015, 17% in 2016, 16% in 2017 and 23% in 2018. Meaning that from the perspective of transmission system operators, it would be profitable to build interconnection of much higher transmission capacity than it is planned now. In the case of the cable towards Germany where the prices are not so high, the construction of interconnections with substantially larger capacity than 2 800 MW would not make economic sense. This is because the modelled domestic price after the trade gets already quite close to the German average price.

It is also needed to say that the price changes estimated under the 2 800 MW scenario in the German case are biased upwards since the robustness parameter c gets activated in the model more often. Especially in the year 2018, it is binding in 55% of the hours in this 2 800 MW scenario. Therefore, the real price change in the 2 800 MW scenario with Germany would presumably be lower. Higher transmission capacity results in higher frequency of the cases when c is binding. Subsequently, this results in higher bias stemming from the movement of the equilibrium along the supply curve on the foreign market. That is why we would probably observe a more diminishing effect of the transmission capacity in the German case in reality.

4.4 Welfare effect discussion

After the discussion in previous sections, this section focuses on the welfare effect of trade under the default scenario. That is to say the transmission capacity equal to the capacity of the cables under construction (1 400 MW each) and the robustness parameter is equal to 0,8 in case of Germany and 0,6 in the case of the UK. Figure 16 shows the results of CS and PS changes and welfare effect calculation under the default scenario. The redistribution effect from consumers to producers on the Nord Pool market is strikingly large in comparison to the overall welfare increase, which is almost invisible on the graph. The redistribution effect is between 21 to 66 times larger than the welfare increase itself.

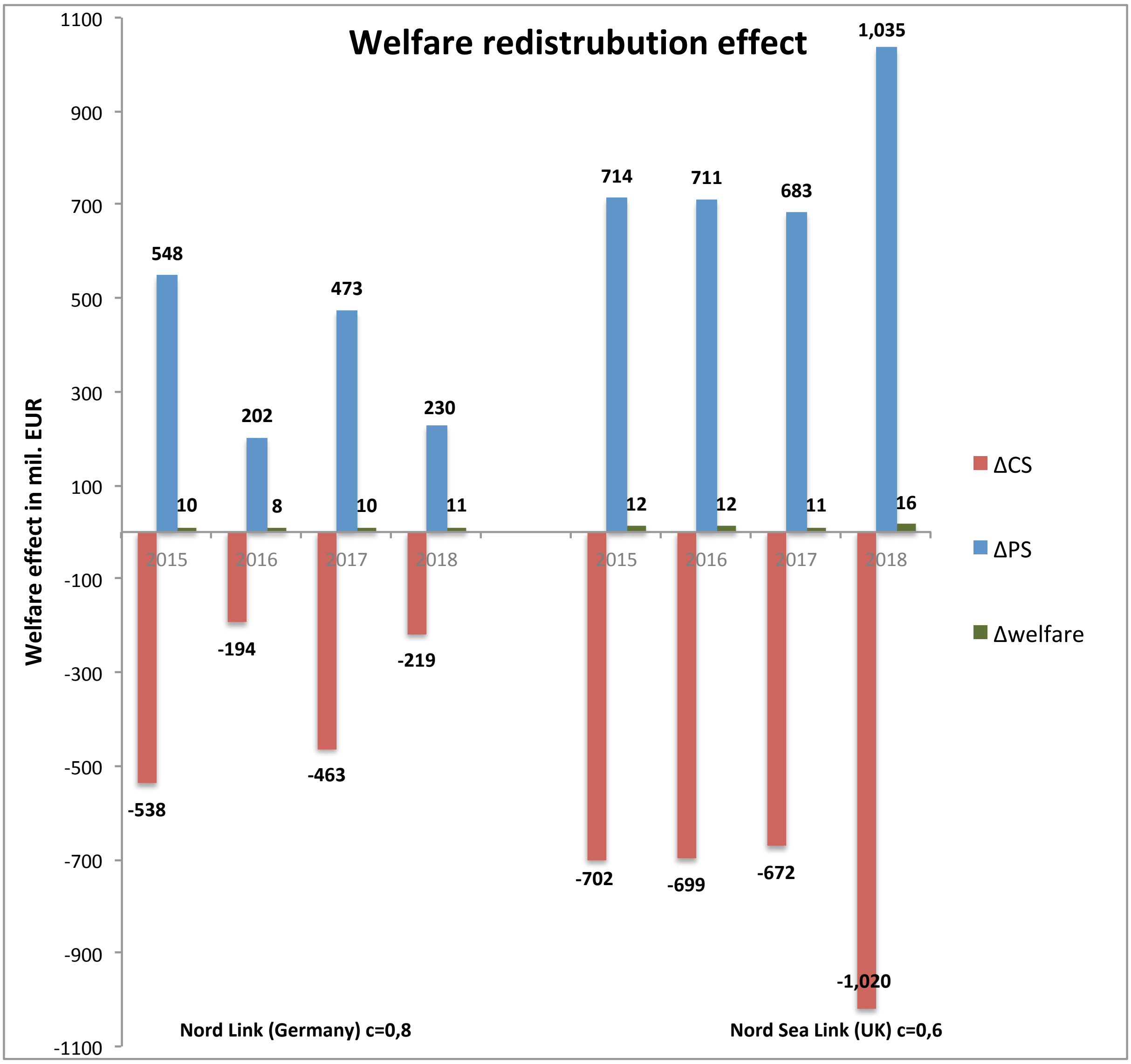

Figure 16: Redistribution and welfare effect on the domestic market

Since the numbers presented in the table 16 are difficult to imagine without any context, it should be said that €1 000 mil. is approximately 6% of the total Nord Pool market value in 2018, or 8% of the market value in 2017. That means that the estimated welfare redistribution effect given by those cables is in the magnitude of units of percentage points of the total market value.

4.5 Comparison with the literature

4.5.1 Price

Our analysis suggests, that the Nord Pool spot market price would increase by, on average (over all four years), 1 €/MWh in the case of the Nord Link cable. Last year (2018), the increase would be 0,62 €/MWh. (This year is most relevant for the 2020 scenario in the literature review.) This result lies somewhat in between results of the literature review. The paper by Zakeri et al. (2016) suggests only 0,36 €/MWh in the Nordic countries, Statnett's analysis (2013) claims 4,9 €/MWh for both cables and THEMA's (2012) conclusion is 2,13 €/MWh increase in Norway for both cables.

Our model shows an average price increase of 2,1 €/MWh in case of the Nord Sea Link cable. The result for the last year (2018) show a 2,8 €/MWh increase. Doorman and Frøystad (2013) suggest 3 €/MWh price increase in Southern Norway in 2020, which is very close to our result for 2018. We cannot simply sum the price increases from the two scenarios and compare them with the results from both cables combined. Despite that, we can conclude that our price difference results are in line with Statnett's (2013) analysis.

4.5.2 Change in PS and CS

When it comes to the welfare effect analysis, the results differ slightly more. The estimated average ΔCS for Nord Link is €-354 mil., while the 2018 change is €-219 mil. Zakeri et al. (2016) found €-100 mil. change. Those numbers apply for the whole Nord Pool. The estimated average ΔPS for Nord Link is €363 mil. and the 2018 change is €230 mil. Zakeri et al. (2016) found €-290 mil. change. Those numbers apply for the whole Nord Pool.

In the case of Nord Sea Link, the average ΔCS is €-773 mil. The 2018 change is €-1 020 mil. Doorman and Frøystad (2013) found the change of CS to be €-235 mil. for Norway only, which represents roughly half of the Nord Pool market. The average ΔPS for Nord Sea link is €786 mil. The 2018 change is €1 035 mil. Doorman and Frøystad (2013) found the change of PS to be €265 mil. for Norway only.

Statnett's and THEMA's analysis' calculated ΔCS and ΔPS for both cables together. They found ΔCS to be €-610 mil. and €-316 mil., respectively and ΔPS €764 mil. and €372 mil., respectively. Those numbers represent the changes of the Norwegian market only, meaning that the numbers for the whole Nord Pool market would be approximately twice as large. In that sense, our results are closer to the Statnett's results even though we cannot just simply add the results from our two cables and compare them with the results for both cables combined.

We conclude this subsection with the statement that the redistribution effect found by our model is somewhat larger than that found in the literature review. The possible explanation could be that the analyses presented in the literature review calculated the scenarios for the year 2020, while this thesis is based on older data. The price differences between the Nordic countries and the UK and Germany tend to decrease (see Figure 13). In that sense, a mildly larger redistribution effect in this thesis is expected.

4.5.3 Welfare change

Lastly, we will compare the welfare gain from the trade. Here, our results show a gain of approximately €10 mil. in all the years for Nord Link cable and approximately €13 mil. gain for the Nord Sea Link Cable in all the years for the whole Nord Pool. Statnett's analysis claims this effect to be roughly €170 mil. for Nord Link cable and around €140 mil. for the Nord Sea Link cable in the whole Nord Pool. Doorman and Frøystad found the welfare increase €30 mil. in Norway only for the Nord Sea Link cable. Zakeri et al. suggest an increase of €190 mil. in Norway only for the Nord Link cable. And finally, THEMA's analysis shows the increase of €56 mil. in Norway only for both cables.

It is apparent that our results of the welfare increase from trade are much lower than all the results presented in the literature review. This difference cannot be explained just by the difference in the year of scenarios. The model in this thesis used real data on actual supply and demand curves on the market and straightforward calculation of the changes in surpluses given by the microeconomic theory. Therefore, we claim that our result is trustworthy despite the inconsistency with previously published literature.

Chapter 5

Conclusion

This thesis presented a simple electricity market model to answer a question how would the planned undersea cables connecting electricity markets in Norway, Germany and the UK affect the Nordic electricity market if they were already in operation in the past. This model benefits from the usage of hourly data on supply and demand curves on day-ahead Nord Pool market. This approach does not allow to make any prediction in the future. However, it allows to calculate the change of price and welfare effect given by those hypothetical interconnections in the past quite accurately. The results are compared with the predictions of four different models. The price increase of roughly 1 €/MWh for Nord Link cable and roughly 2 €/MWh for the Nord Sea link cable lies in line with the predictions in the literature. The results show that the price reacts to the import and export more when the overall price level is high due to the shape of the supply curve characterised by increasing inelasticity with increasing price. The redistribution effect from consumers to producers was found to be larger than what is suggested in the literature. However, this difference is quite mild and could be possibly explained by a different base year of the previously published studies and this thesis. Moreover, the welfare effect of the trade was found to be significantly lower than what is presented in the literature despite the larger redistribution effect found. We claim that the results calculated directly from the historical supply and demand curves are a useful compliment to the results from extensive predictive models published in the literature. This is because the calculation of the redistribution effect with the use of those models is methodically challenging (Statnett, 2013a).

Even though the results show larger redistribution effect and smaller welfare effect increase than the previously published studies, this thesis by any means questions the project of building Nord Link and Nord Sea Link as a whole. This thesis focused on one particular aspect of these interconnections linked to the direct effect on the Nord Pool day-ahead market. Energy security arguments; effect on climate; reserve capacity market potential; congestion income and the subsequent effect on the grid tariffs; long-term impact on production capacity investments; impact on the budgets of local municipalities (as often owners of the power plants); impact on tax revenue; and other relevant topics were not discussed in this thesis.

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Appendix A

Table 5.1: The table of results as generated by the original code

	Year	capacity_MW	robustness	avg_price_change	avg_org_nor_price	avg_ger_price	avg_new_nor_price	avg_ger_nor_price_diff	avg_ABS_ger_nor_price_diff	avg_perc_diff_weighted	avg_percent_diff_nonweighted	sum_PS_change	sum_CS_change	sum_welfare_change	country
1	2015	1400	1.0	1.617	22.010	32.844	23.627	10.834	12.824	28.592	28.031	580855850	-569817781	11038069	DE
2	2016	1400	1.0	0.550	27.597	30.184	28.147	2.587	6.095	49.542	49.559	204920398	-196040232	8880166	DE
3	2017	1400	1.0	1.378	30.001	36.164	31.379	6.163	10.757	35.810	36.534	518434670	-507826553	10608117	DE
4	2018	1400	1.0	0.694	44.175	45.196	44.869	1.021	8.571	52.862	52.456	258367601	-246503324	11864277	DE
5	2015	1400	1.0	2.205	22.013	56.331	24.218	34.318	34.333	9.321	8.291	796585751	-783253353	13332397	UK
6	2016	1400	1.0	2.123	27.571	50.576	29.694	23.005	23.593	16.520	14.954	798880419	-784578754	14301665	UK
7	2017	1400	1.0	2.032	29.978	53.224	32.011	23.245	23.338	12.137	11.584	768265326	-756101005	12164321	UK
8	2018	1400	1.0	3.173	44.137	65.459	47.309	21.322	21.549	21.088	19.608	1193193109	-1174979977	18213132	UK
9	2015	1400	0.8	1.527	22.010	32.844	23.537	10.834	12.824	25.586	25.142	548340095	-537910873	10429222	DE
10	2015	1400	0.6	1.415	22.010	32.844	23.425	10.834	12.824	22.173	21.856	507855660	-498177887	9677773	DE
11	2016	1400	0.8	0.543	27.597	30.184	28.140	2.587	6.095	43.327	43.447	202015347	-194116801	7898546	DE
12	2016	1400	0.6	0.522	27.597	30.184	28.119	2.587	6.095	36.210	36.393	193827151	-186976055	6851097	DE
13	2017	1400	0.8	1.259	30.001	36.164	31.260	6.163	10.757	31.836	32.487	473188475	-463447261	9741214	DE
14	2017	1400	0.6	1.112	30.001	36.164	31.113	6.163	10.757	27.188	27.749	417793265	-409133559	8659705	DE
15	2018	1400	0.8	0.617	44.175	45.196	44.792	1.021	8.571	45.646	45.387	229540590	-218746306	10794284	DE
16	2018	1400	0.6	0.532	44.175	45.196	44.707	1.021	8.571	37.497	37.365	197552699	-188186913	9365786	DE
17	2015	1400	0.8	2.104	22.013	56.331	24.116	34.318	34.333	8.583	7.715	759672168	-746983071	12689097	UK
18	2015	1400	0.6	1.977	22.013	56.331	23.990	34.318	34.333	7.728	7.045	713554554	-701624711	11929843	UK
19	2016	1400	0.8	2.022	27.571	50.576	29.593	23.005	23.593	14.999	13.732	760500325	-747302399	13197925	UK
20	2016	1400	0.6	1.892	27.571	50.576	29.462	23.005	23.593	13.276	12.332	710901972	-698960569	11941403	UK
21	2017	1400	0.8	1.934	29.978	53.224	31.912	23.245	23.338	11.339	10.918	730730956	-719210339	11520617	UK
22	2017	1400	0.6	1.809	29.978	53.224	31.787	23.245	23.338	10.394	10.121	683192783	-672442050	10750733	UK
23	2018	1400	0.8	2.986	44.137	65.459	47.122	21.322	21.549	19.223	18.107	1122393796	-1105303543	17090253	UK
24	2018	1400	0.6	2.756	44.137	65.459	46.892	21.322	21.549	17.111	16.368	1035450201	-1019702142	15748059	UK
25	2015	700	0.8	0.789	22.033	32.823	22.822	10.791	12.808	17.085	16.769	281428669	-278636272	2792397	DE
26	2015	700	0.6	0.748	22.033	32.823	22.781	10.791	12.808	14.910	14.667	266710736	-264056392	2654343	DE
27	2015	2100	0.8	2.276	21.986	32.862	24.263	10.876	12.840	32.713	32.153	823248141	-800003345	23244796	DE
28	2015	2100	0.6	2.076	21.986	32.862	24.062	10.876	12.840	28.148	27.778	749982337	-728766219	21216118	DE
29	2015	2800	0.8	3.045	21.961	32.877	25.006	10.916	12.855	39.246	38.596	1109250322	-1067607076	41643246	DE
30	2015	2800	0.6	2.722	21.961	32.877	24.683	10.916	12.855	33.445	33.038	990073823	-953042249	37031574	DE
31	2016	700	0.8	0.160	27.603	30.158	27.763	2.555	6.099	31.125	31.117	59267523	-56805032	2462491	DE
32	2016	700	0.6	0.188	27.603	30.158	27.791	2.555	6.099	26.532	26.595	69704105	-67519035	2185070	DE
33	2016	2100	0.8	0.898	27.589	30.206	28.487	2.617	6.091	52.028	52.227	335286228	-319431995	15854233	DE

34	2016	2100	0.6	0.807	27.589	30.206	28.396	2.617	6.091	42.823	43.051	300810556	-287337655	13472900	DE
35	2016	2800	0.8	1.218	27.581	30.226	28.798	2.645	6.086	58.881	59.100	456671072	-430654571	26016500	DE
36	2016	2800	0.6	1.053	27.581	30.226	28.634	2.645	6.086	47.859	48.078	393924964	-372275502	21649462	DE
37	2017	700	0.8	0.693	30.003	36.127	30.697	6.124	10.772	21.524	22.090	258981204	-256240893	2740311	DE
38	2017	700	0.6	0.644	30.003	36.127	30.647	6.124	10.772	18.744	19.226	240298238	-237748806	2549432	DE
39	2017	2100	0.8	1.789	29.998	36.198	31.787	6.200	10.742	39.862	40.517	677265244	-656261012	21004232	DE
40	2017	2100	0.6	1.557	29.998	36.198	31.555	6.200	10.742	33.558	34.114	588726105	-570394696	18331409	DE
41	2017	2800	0.8	2.352	29.994	36.228	32.346	6.234	10.726	46.760	47.362	896515916	-859574698	36941218	DE
42	2017	2800	0.6	2.005	29.994	36.228	31.999	6.234	10.726	38.852	39.362	763049751	-731659673	31390077	DE
43	2018	700	0.8	0.322	44.164	45.126	44.486	0.962	8.575	34.355	33.937	119293786	-116065750	3228036	DE
44	2018	700	0.6	0.289	44.164	45.126	44.453	0.962	8.575	28.663	28.396	107317916	-104392486	2925430	DE
45	2018	2100	0.8	0.875	44.185	45.261	45.060	1.076	8.566	53.259	53.070	326325545	-304894218	21431326	DE
46	2018	2100	0.6	0.737	44.185	45.261	44.923	1.076	8.566	43.173	43.081	274151925	-256218210	17933715	DE
47	2018	2800	0.8	1.078	44.194	45.324	45.272	1.130	8.561	58.900	58.755	402873806	-368862992	34010814	DE
48	2018	2800	0.6	0.875	44.194	45.324	45.069	1.130	8.561	47.184	47.127	325382534	-297594688	27787846	DE
49	2015	700	0.8	1.017	22.034	56.341	23.051	34.307	34.322	4.794	4.241	363626698	-360457691	3169007	UK
50	2015	700	0.6	0.982	22.034	56.341	23.016	34.307	34.322	4.408	3.943	351160786	-348093326	3067460	UK
51	2015	2100	0.8	3.228	21.990	56.320	25.219	34.330	34.344	12.148	11.046	1177392297	-1148358551	29033746	UK
52	2015	2100	0.6	2.984	21.990	56.320	24.974	34.330	34.344	10.881	10.036	1087267913	-1060422217	26845696	UK
53	2015	2800	0.8	4.453	21.966	56.308	26.420	34.342	34.356	15.883	14.566	1640729154	-1586610836	54118318	UK
54	2015	2800	0.6	4.074	21.966	56.308	26.041	34.342	34.356	14.162	13.171	1499218576	-1449684928	49533648	UK
55	2016	700	0.8	0.921	27.590	50.603	28.511	23.013	23.607	9.060	8.110	343232628	-339688762	3543866	UK
56	2016	700	0.6	0.895	27.590	50.603	28.485	23.013	23.607	8.088	7.345	333382931	-330113412	3269518	UK
57	2016	2100	0.8	3.268	27.550	50.546	30.818	22.996	23.576	20.607	19.097	1241259192	-1210706637	30552555	UK
58	2016	2100	0.6	2.945	27.550	50.546	30.495	22.996	23.576	18.025	16.946	1117284402	-1090434877	26849525	UK
59	2016	2800	0.8	4.491	27.530	50.517	32.021	22.987	23.559	25.923	24.262	1722517223	-1667716394	54800829	UK
60	2016	2800	0.6	3.971	27.530	50.517	31.500	22.987	23.559	22.492	21.347	1520568234	-1473058232	47510002	UK
61	2017	700	0.8	0.948	29.992	53.248	30.940	23.256	23.350	6.255	5.979	354789493	-351802407	2987086	UK
62	2017	700	0.6	0.910	29.992	53.248	30.901	23.256	23.350	5.788	5.592	340454088	-337605879	2848210	UK
63	2017	2100	0.8	2.990	29.964	53.199	32.954	23.234	23.325	16.384	15.829	1140580872	-1113832145	26748727	UK
64	2017	2100	0.6	2.747	29.964	53.199	32.711	23.234	23.325	14.851	14.496	1047108531	-1022658148	24450383	UK
65	2017	2800	0.8	4.176	29.950	53.173	34.126	23.223	23.313	21.687	20.957	1609008040	-1558517009	50491031	UK
66	2017	2800	0.6	3.747	29.950	53.173	33.697	23.223	23.313	19.309	18.860	1441881148	-1397172924	44708224	UK
67	2018	700	0.8	1.564	44.144	65.465	45.708	21.321	21.551	11.954	11.015	582837847	-578124162	4713685	UK
68	2018	700	0.6	1.475	44.144	65.465	45.619	21.321	21.551	10.630	9.972	549673111	-545254132	4418979	UK
69	2018	2100	0.8	4.350	44.128	65.451	48.478	21.323	21.547	25.969	24.649	1649495976	-1612759098	36736878	UK
70	2018	2100	0.6	3.919	44.128	65.451	48.047	21.323	21.547	22.885	22.045	1484617785	-1451742049	32875735	UK
71	2018	2800	0.8	5.608	44.118	65.442	49.726	21.324	21.545	32.107	30.647	2144137646	-2081821351	62316295	UK
72	2018	2800	0.6	4.964	44.118	65.442	49.082	21.324	21.545	27.908	27.029	1894687122	-1840131138	54555984	UK

Appendix B

Full text of the model source code with explanatory notes

```
library(readxl)
library(xlsx)
library(ggplot2)

results = data.frame(year= character(0),capacity_MW= character(0),robustness=character(0),avg_price_change = character(0),avg_org_nor_price= character(0),avg_ger_price = character(0),avg_new_nor_price = character(0),avg_ger_nor_price_diff= character(0),avg_ABS_ger_nor_price_diff= character(0),avg_perc_diff_weighted= character(0),avg_percent_diff_nonweighted= character(0),sum_price_sell_change= character(0),sum_price_buy_change= character(0),sum_PS_change= character(0),sum_CS_change= character(0),sum_welfare_change= character(0),country=character(0))
#creates a dataframe for final results
country = "UK" #"germany" or "UK"
for (year in 2015:2018)

{

  foreign_prices = read_excel(paste("~/Desktop/electricity/data/",country,"_prices/Day-ahead_Prices_",year,".xlsx",sep = ""), col_names = FALSE)
  #loads the price data for foreign country

  for (capacity_MW in c(700,1400,2100,2800))
  {#set the transmission capacity


    for (robustness in c(1,0.8,0.6))
    {#set the parameter for robustness check


```

```
intersections = data.frame(time = character(0),original_price = numeric(0),original_quantity = numeric(0),german_price = numeric(0), new_price = numeric(0), new_quantity = numeric(0), ger_nor_org_diff = numeric(0), price_change = numeric(0), perc_diff = numeric(0), price_buy_change= numeric(0),CS_change= numeric(0),price_sell_change= numeric(0),PS_change= numeric(0),welfare_change= numeric(0))
#creates a data frame for intersections


data_files = list.files(paste("~/Desktop/electricity/data/",year,"_curves",sep=""))
for (data_file in data_files)
{

  ################################################################
  data_copy = read_excel(paste("~/Desktop/electricity/data/",year,"_curves/",data_file, sep=""), col_names = FALSE)
  #data_copy = read_excel("~/Desktop/electricity/data/2018_curves/2018-10-28.xlsm",col_names = FALSE)
  ################################################################


  for (hour in 1:24)

  {
    #extracting buy curve data:
    hour_buy = data.frame(data_copy[((which(data_copy[, hour * 2 - 1] == "Buy curve"))+1):((which(data_copy[, hour * 2 - 1] == "Sell curve"))-1), hour * 2] )
    #extracts the buy data in every second column from row 15 to the row prior to "Sell curve" in respective column (every second column -1)
    names(hour_buy) = c("column")
    #set the name of the only column in hour_buy dataframe to "column" so that it is uniform
    hour_buy_price = hour_buy$column[ c(T,F) ]
    #extracts every first value from the hour_buy dataframe which is the price value
    hour_buy_price = as.numeric(hour_buy_price)
    #converts the character values to numeric
    hour_buy_q = hour_buy$column[ c(F,T) ]
    #extracts every second value from the hour_buy dataframe which is the quantity value
    hour_buy_q = as.numeric(hour_buy_q)
    #converts the character values to numeric
    hour_buy_curve = data.frame(hour_buy_price, hour_buy_q, stringsAsFactors = FALSE)
```

```
    # makes the dataframe of quantity and price for the buy curve

    #extracting sell curve data:
    hour_sell = data.frame(data_copy[((which(data_copy[, hour * 2 - 1] == "Sell curve"))+1):nrow(data_copy), hour * 2] )
    # extracts the sell data in every second column from row of "Sell curve" to the end of dataframe
    names(hour_sell) = c("column")
    #set the name of the only column in hour_sell dataframe to "column" so that it is uniform
    hour_sell_price = hour_sell$column[ c(T,F) ]
    #extracts every first value from the hour_sell dataframe which is the price value
    hour_sell_price <- as.numeric(hour_sell_price)
    #converts the character values to numeric
    hour_sell_q = hour_sell$column[ c(F,T) ]
    #extracts every second value from the hour_sell dataframe which is the quantity value
    hour_sell_q = as.numeric(hour_sell_q)
    #converts the character values to numeric
    hour_sell_curve <- data.frame(hour_sell_price, hour_sell_q, stringsAsFactors = FALSE)
    #makes the dataframe of quantity and price for the sell curve
    hour_sell_curve = na.omit(hour_sell_curve)
    #deletes the N/A values from the dataframe

    #adjusting the curves with respect to block orders and import/export:
    hour_sell_curve[,2] = hour_sell_curve[,2]+as.numeric(data_copy[5,hour*2])
    #adding accepted blocks sell
    hour_buy_curve[,2] = hour_buy_curve[,2]+as.numeric(data_copy[4,hour*2])
    #adding accepted blocks buy
    if(as.numeric(data_copy[(which(data_copy[, hour * 2 - 1] == "Bid curve chart data (Volume for net flows)")),hour*2])>0) {hour_sell_curve[,2] = hour_sell_curve[,2]+as.numeric(data_copy[(which(data_copy[, hour * 2 - 1] == "Bid curve chart data (Volume for net flows)")),hour*2])}
    #if net flow >0 (import) - shift sell curve right (increased quantity and decreased price)
    if(as.numeric(data_copy[(which(data_copy[, hour * 2 - 1] == "Bid curve chart data (Volume for net flows)")),hour*2])<0) {hour_buy_curve[,2] = hour_buy_curve[,2]-as.numeric(data_copy[(which(data_copy[, hour * 2 - 1] == "Bid curve chart data (Volume for net flows)")),hour*2])}
    #if net flow <0 (export) - shift buy curve right (increaed quantity and increased price)

    #script for finding the intersection of curves taken from: https://rdrr.io/github/andrewheiss/reconPlots/src/R/curve_intersect.R - eddited
    curve_intersect = function(curve1, curve2) {
```

```
      {
        # Approximate the functional form of both curves:
        curve1_f <- approxfun(curve1[,1], curve1[,2], rule = 2)
        curve2_f <- approxfun(curve2[,1], curve2[,2], rule = 2)
        # Calculate the intersection of curve 1 and curve 2 along the x-axis:
        point_x <- uniroot(function(x) curve1_f(x) - curve2_f(x),
                           c(min(curve1[,1]), max(curve1[,1])))$root
        # Find where point_x is in curve 2:
        point_y <- curve2_f(point_x)
      }
    return(data.frame(x = point_x, y = point_y))
  }

  intersection = curve_intersect(hour_buy_curve, hour_sell_curve)
  #comand for finding the intersection (using the script above)

  if(country == "germany"){
    intersection = cbind(data_copy[1,hour*2],intersection,as.numeric(foreign_prices[(which(foreign_prices[, 1] == substr(data_copy[1,2], 1, 10)))+1+hour,2]))
    #adds the time info and german price at that time to the intersection result
  }else if(country == "UK"){
    intersection = cbind(data_copy[1,hour*2],intersection,as.numeric(foreign_prices[(which(foreign_prices[, 6] == substr(data_copy[1,hour*2], 1, 13))),4]))
    #adds the time info and UK price at that time to the intersection result
  }
  shift_hour_sell_curve = hour_sell_curve
  shift_hour_buy_curve = hour_buy_curve
  #copies curves which will be shiftet due to additional export/import

  if(intersection[1,2]>intersection[1,4]) {shift_hour_sell_curve[,2]=hour_sell_curve[,2]+capacity_MW}
  #if Norwegian price larger tnan foreign price, then import capacity in MW (shift sell curve right)
  if(intersection[1,2]<intersection[1,4]) {shift_hour_buy_curve[,2]=hour_buy_curve[,2]+capacity_MW}
  #if Norwegian price smaller tnan foreign price, then export capacity in MW (shift buy curve right)

  new_intersection = curve_intersect(shift_hour_buy_curve, shift_hour_sell_curve)
  #comand for finding the intersection of shifted curve

  intersection = cbind(intersection, new_intersection)
  #adds the new intersection into the result

```

```
    if(intersection[1,2]>intersection[1,4] && intersection[1,5]<intersection[1,4]) {intersection[1,5] = intersection[1,4]}
    #if original Norwegian price larger tnan foreign price and  New Norwegian price smaller than foreign price, then the new Norwegian price stops at foreign price

    if(intersection[1,2]<intersection[1,4] && intersection[1,5]>intersection[1,4]) {intersection[1,5] = intersection[1,4]}
    #if original Norwegian price smaller tnan foreign price and  New Norwegian price larger than foreign price, then the new Norwegian price stops at foreign price

    ger_nor_org_difference = intersection[1,4]-intersection[1,2]
    #calculates the difference in original prices

    price_change = intersection[1,5]-intersection[1,2]
    #clculates price change (new-old)

    perc_diff = 100/ger_nor_org_difference*price_change
    #calculates how much % of the foreign-norwegian price difference is the price change

    if(perc_diff/100 > robustness){
      intersection[,5] = intersection[,2] + robustness*ger_nor_org_difference # correction of the error, price_change corrected to ger_nor_org_difference
      #new price = orgiginal price + robustness * price change
      #does not influence the volume, only price and subsequent calculations
    }

    #recalculation price change and perc_diff
    price_change = intersection[1,5]-intersection[1,2]
    perc_diff = 100/ger_nor_org_difference*price_change


    intersection = cbind(intersection, ger_nor_org_difference, price_change, perc_diff)
    #adds the data to the result

    #EXPORT WELFARE CALCULATION:
    if(intersection[1,2]<intersection[1,4]) { #original price lower than foreign (export)
      #Producer's surpluss change:
```

```
        sub_sell_curve = hour_sell_curve[which(abs(hour_sell_curve-intersection[,2])==min(abs(hour_sell_curve-intersection[,2]))):which(abs(hour_sell_curve-intersection[,5])==min(abs(hour_sell_curve-intersection[,5]))),]
        #creates a data frame of the sell curve just between original and new price (approximately, correction follows)
        sub_sell_curve = sub_sell_curve[seq(dim(sub_sell_curve)[1],1),]
        #reverse the order in sub curve such that the difference in next step makes sense (otherwise conflict between calculating upper and lower integral for buy or sell) (order is reversed back afterwards)
        difference=data.frame(-diff(as.matrix(sub_sell_curve$hour_sell_price)))
        #calculates the quantity increase for each price
        difference = rbind(difference,0)
        #adds zero to the last missing value which was caused by diff function so that columns can be merged
        sub_sell_curve = cbind(sub_sell_curve,difference)
        sub_sell_curve = sub_sell_curve[seq(dim(sub_sell_curve)[1],1),]
        #reverse the order of sub curve again to get to original order
        PS = sub_sell_curve[,2]*sub_sell_curve[,3]
        #calculates the change of producer surplus
        sub_sell_curve = cbind(sub_sell_curve,PS)
        #ads the PS to the sub_sell_curve dataframe
        price_sell_change = sum(sub_sell_curve[,3])
        PS_change = sum(sub_sell_curve[,4])

        #Consummer's surpluss change:
        sub_buy_curve = hour_buy_curve[which(abs(hour_buy_curve-intersection[,2])==min(abs(hour_buy_curve-intersection[,2]))):which(abs(hour_buy_curve-intersection[,5])==min(abs(hour_buy_curve-intersection[,5]))),]
        #creates a data frame of the buy curve just between original and new price   (approximately, correction follows)
        #sub_buy_curve = sub_buy_curve[seq(dim(sub_buy_curve)[1],1),]
        #reverse the order in sub curve such that the difference in next step makes sense (order is reversed back afterwards)
        difference=data.frame(diff(as.matrix(sub_buy_curve$hour_buy_price)))
        #calculates the quantity increase for each price
        difference = rbind(difference,0)
        #adds zero to the last missing value which was caused by diff function so that columns can be merged
        sub_buy_curve = cbind(sub_buy_curve,-difference)
        #sub_buy_curve = sub_buy_curve[seq(dim(sub_buy_curve)[1],1),]
        #reverse the order of sub curve again to get to original order
        CS = sub_buy_curve[,2]*sub_buy_curve[,3]
        #calculates the change of producer surpluss
        sub_buy_curve = cbind(sub_buy_curve,CS)
        #ads the PS to the sub_buy_curve dataframe
```

```
    price_buy_change = sum(sub_buy_curve[,3])
    CS_change = sum(sub_buy_curve[,4])

    #Not used part of code:
    #if(abs(price_buy_change) < abs(price_sell_change)){
    #CS_change = CS_change-(abs(abs(price_buy_change) - abs(price_sell_change)))*(mean(hour_sell_curve$hour_sell_q))
    #}
    #if(abs(price_sell_change) < abs(price_buy_change)){
    #PS_change = PS_change+(abs(abs(price_buy_change) - abs(price_sell_change)))*(mean(hour_buy_curve$hour_buy_q))
    #}
    #welfare_change = PS_change+CS_change
  }

  #IMPORT WELFARE CALCULATION:
  if(intersection[1,2]>intersection[1,4]) { #original price larger than foreign (import)
    #consumer's surplus change
    sub_buy_curve = hour_buy_curve[which(abs(hour_buy_curve-intersection[,5])==min(abs(hour_buy_curve-intersection[,5]))):which(abs(hour_buy_curve-intersection[,2])==min(abs(hour_buy_curve-intersection[,2]))),]
    #creates a data frame of the buy curve just between original and new price  (approximately, correction follows)
    difference=data.frame(diff(as.matrix(sub_buy_curve$hour_buy_price)))
    #calculates the quantity increase for each price
    difference = rbind(difference,0)
    #adds zero to the last missing value which was caused by diff function so that columns can be merged
    sub_buy_curve = cbind(sub_buy_curve,difference)
    CS = sub_buy_curve[,2]*sub_buy_curve[,3]
    #calculates the change of CS
    sub_buy_curve = cbind(sub_buy_curve,CS)
    #ads the CS to the sub_buy_curve dataframe
    price_buy_change = sum(sub_buy_curve[,3])
    CS_change = sum(sub_buy_curve[,4])

    #producer's surplus change
    sub_sell_curve = hour_sell_curve[which(abs(hour_sell_curve-intersection[,5])==min(abs(hour_sell_curve-intersection[,5]))):which(abs(hour_sell_curve-intersection[,2])==min(abs(hour_sell_curve-intersection[,2]))),]
    #creates a data frame of the sell curve just between original and new price   (approximately, correction follows)
    sub_sell_curve = sub_sell_curve[seq(dim(sub_sell_curve)[1],1),]
```

```r
        #reverse the order in sub curve such that the difference in next step makes sense (otherwise conflict between calculating upper and lower integral for buy or sell) (order is reversed back afterwards)
        difference=data.frame(-diff(as.matrix(sub_sell_curve$hour_sell_price)))
        #calculates the quantity increase for each price
        difference = rbind(difference,0)
        #adds zero to the last missing value which was caused by diff function so that columns can be merged
        sub_sell_curve = cbind(sub_sell_curve,-difference)
        sub_sell_curve = sub_sell_curve[seq(dim(sub_sell_curve)[1],1),]
        #reverse the order of sub curve again to get to original order
        PS = sub_sell_curve[,2]*sub_sell_curve[,3]
        #calculates the change of PS
        sub_sell_curve = cbind(sub_sell_curve,PS)
        #ads the PS to the sub_sell_curve dataframe
        price_sell_change = sum(sub_sell_curve[,3])
        PS_change = sum(sub_sell_curve[,4])

        #correction for inelastic curves
        #if(abs(price_buy_change) < abs(price_sell_change)){
        #CS_change = CS_change+(abs(abs(price_buy_change) - abs(price_sell_change)))*(mean(hour_sell_curve$hour_sell_q))
        #}
        #if(abs(price_sell_change) < abs(price_buy_change)){
        #PS_change = PS_change-(abs(abs(price_buy_change) - abs(price_sell_change)))*(mean(hour_buy_curve$hour_buy_q))
        #}
        #welfare_change = PS_change+CS_change
      }
      #correction for imprecise sub_curve selection
      CS_change = CS_change - (price_change+price_buy_change)*(mean(sub_buy_curve$hour_buy_q))
      PS_change = PS_change + (price_change-price_sell_change)*(mean(sub_sell_curve$hour_sell_q))
      welfare_change = PS_change+CS_change


      intersection = cbind(intersection, price_buy_change,CS_change,price_sell_change,PS_change,welfare_change)

      names(intersection) = c("time","original_price","original_quantity","german_price", "new_price", "new_quantity", "ger_nor_org_diff", "price_change", "perc_diff", "price_buy_change","CS_change","price_sell_change","PS_change","welfare_change")
      #renames the columns in intersection result

      intersections = rbind(intersections, intersection)
```

```
        #writes the result into a dataframe

        #assign(paste(hour,"sub_buy_curve",sep=""),sub_buy_curve)
        #assign(paste(hour,"sub_sell_curve",sep=""),sub_sell_curve)

        #Plot generator: !!! generates shifted curve before any adjustments (parameter, stop change etc.)
        #ggplot()+
        #geom_line(data=shift_hour_buy_curve, aes(x=shift_hour_buy_curve$hour_buy_q, y=shift_hour_buy_curve$hour_buy_price), color='green',size=0.35)+
        #geom_line(data=shift_hour_sell_curve, aes(x=shift_hour_sell_curve$hour_sell_q, y=shift_hour_sell_curve$hour_sell_price), color='green',size=0.35)+
        #geom_line(data=hour_buy_curve, aes(x=hour_buy_curve$hour_buy_q, y=hour_buy_curve$hour_buy_price), color='black',size=0.5) +
        #geom_line(data=hour_sell_curve, aes(x=hour_sell_curve$hour_sell_q, y=hour_sell_curve$hour_sell_price), color='black',size=0.5)+
        #xlab("Quantity MWh") + ylab("Price EUR") + ggtitle(paste(capacity_MW,"_",robustness,"_",substring(data_copy[1,hour*2],7,10),substring(data_copy[1,hour*2],3,6),substring(data_copy[1,hour*2],1,2),substring(data_copy[1,hour*2],11,19),sep = ""))+ theme_bw() + theme(panel.border = element_blank(), panel.grid.major = element_blank(), panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))+
        #xlim(20000,70000)

        #ggsave(paste(capacity_MW,"_",robustness,"_",substring(data_copy[1,hour*2],7,10),substring(data_copy[1,hour*2],3,6),substring(data_copy[1,hour*2],1,2),substring(data_copy[1,hour*2],11,19),".pdf",sep = ""), device = "pdf", path = paste("~/Desktop/electricity/graphs/",year,"/",sep = ""))
      }
    }

    write.xlsx(intersections, paste("intersections_",country,year,"_",capacity_MW,"_",robustness,".xlsx",sep="") )

    #POSTANALYSIS:  (for the whole year)

    #calculate the change of average price (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*intersections[,8])
    avg_price_change = sum(avg_calc)/sum(intersections[,6])

    #calculate the change of the difference between foreign and Norwegian price (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*intersections[,7])
    avg_ger_nor_price_diff = sum(avg_calc)/sum(intersections[,6])
```

```

    #calculate absolute value of the change of the difference between foreign and Norwegian price (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*abs(intersections[,7]))
    avg_ABS_ger_nor_price_diff = sum(avg_calc)/sum(intersections[,6])

    #calculate the average Original Norwegian price (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*intersections[,2])
    avg_org_nor_price = sum(avg_calc)/sum(intersections[,6])

    #calculate the average changed Norwegian price (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*intersections[,5])
    avg_new_nor_price = sum(avg_calc)/sum(intersections[,6])

    #calculate the average foreign price (averaged by new Norwegian volume):
    avg_calc=data.frame(intersections[,6]*intersections[,4])
    avg_ger_price = sum(avg_calc)/sum(intersections[,6])

    #calculate the average perc_diff (averaged by new volume):
    avg_calc=data.frame(intersections[,6]*intersections[,9])
    avg_perc_diff_weighted = sum(avg_calc)/sum(intersections[,6])

    #calculate average perc_diff (averaged by hours):
    avg_percent_diff_nonweighted = mean(intersections[,9])

    #calculate sum price_change:
    sum_price_sell_change = sum(intersections$price_sell_change)

    #calculate sum price_buy_change:
    sum_price_buy_change = sum(intersections$price_buy_change)

    #calculate sum PS_change:
    sum_PS_change = sum(intersections$PS_change)

    #calculate sum CS_change
    sum_CS_change = sum(intersections$CS_change)

    #calculate sum welfare_change
    sum_welfare_change = sum(intersections$welfare_change)

    result = data.frame(year, capacity_MW, robustness)
    #crates a dataframe for result of this itteration
    result = cbind(result,avg_price_change,avg_org_nor_price,avg_ger_price,avg_new_nor_price,avg_ger_nor_price_diff,avg_ABS_ger_nor_price_diff,avg_perc_diff_weighted,avg_percent_diff_nonweighted,sum_price_sell_change,sum_price_buy_change,sum_PS_change,sum_CS_change,sum_welfare_change,country)
    #puts the results into dataframe
```

```
      names(result) = c("year","capacity_MW","robustness","avg_price_change","avg_org
        _nor_price","avg_ger_price","avg_new_nor_price","avg_ger_nor_price_diff","
        avg_ABS_ger_nor_price_diff","avg_perc_diff_weighted","avg_percent_diff_non
        weighted","sum_price_sell_change","sum_price_buy_change","sum_PS_change","
        sum_CS_change","sum_welfare_change","country")
      #renames the columns in result
      results = rbind(results,result)
      #binds the result into results dataframe
    }
  }
}
write.xlsx(results, "results.xlsx" )
#saves the results as an excel file
```