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# The Nordic Electricity Market: An Empirical Analysis of Security through Trade

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**Abstract**

With the expansion of renewable energies, policy makers face the decision of investing into back-up generation capacity or into an expansion of the transmission capacity. As electricity is a homogeneous good, it is unique in the way that it is likely to be subject of two-way trade, within a time period, as short as a day. This feature is usually not covered in generic two-way trade models. Using the model developed by Antweiler (2016*a*), this thesis analyses the drivers behind the extensive two-way trade in the Nordic electricity market. While the model was developed to fit the U.S. and Canadian market, its application to the Nordics is a first step towards modelling the Nordic electricity trade. Furthermore, the model also assesses the value of a potential extension of the transmission capacity. By utilising monthly trade data in the period from November 2011 to September 2017 across the Nordic countries, it finds that a higher load ratio is correlated with a higher export: the opposite effect of the findings on the North American market. A comparison between self-sufficient jurisdictions and a fully integrated market further shows the potential size of possible reductions in back-up capacity following from an expansion in transmission capacity.

Keywords: Electricity, Security, International Trade, Hydro power, Scandinavia

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# 1 Introduction

A recently developed theory and international trade model from Antweiler (2016*a*), suggests that two-way trade in electricity can be used as an insurance for periods in which the marginal costs of electricity generation are relatively high in one jurisdiction and relatively low in a neighbouring jurisdiction. Furthermore, the idea of trade as an insurance also covers situations in which a jurisdiction is being able to reduce its back-up capacity, by relying on its neighbouring jurisdictions' generation capacities as a back-up. The model has been developed with the approach to allow for two-way trade within a single period. The driver behind two-way trade in the model is the presence of convex marginal cost curves of electricity generation. While it has been applied empirically to the U.S. and Canadian electricity markets, yielding results supporting the theory behind the model, it is yet to be applied to other electricity markets. A large share of the U.S. and Canadian jurisdictions are characterised by convex marginal cost curves of electricity generation. However, this assumption does not hold for all electricity markets. The Nordic[1] electricity markets are characterised by a high share of renewable energy sources including a high share of hydro energy. In this setting marginal cost curves of electricity production are not convex but constant instead. The Antweiler model is one of the most recent models on cross-border electricity trade with a unique approach on the way the trade is modelled. Applying the model towards the Nordics is a first step in order to find the drivers behind electricity trade in countries which do not possess convex marginal cost curves, for which, to my best knowledge, no similar model has been developed.

Growing up in the northern part of Germany, renewable energies, especially in the form of wind energy have been present in my everyday life throughout most of my life. As the northern part of Germany is sparsely populated, with little industry being present, the demand for long-distance transmission capacity is high, due to local demand not meeting supply in times with a lot of wind. In recent years transmission capacity has been one of the most discussed topics in the European electricity markets. The main topics of the discussions are the planning of the so called "Nord-Süd-Stromtrasse", a transmission line connecting the wind turbines in Northern Germany with Southern Germany (Frankfurter Allgemeine 2016) and the planning of a transmission line connecting Northern Germany with Norway (TenneT 2017).

Furthermore, congestion of transmission lines has also been a topic in the Nordic markets. There is for instance a case of Sweden in 2006 being accused of limiting its capacity in transmission to Denmark, thereby influencing the prices. Following a Danish complaint at EU-level, a restructuring of the bidding areas took place in 2011, leading to a more integrated market with higher competition (European Commission 2009).

In recent years the electricity related public focus has been on both renewables as well as transmission capacity. The higher shares of intermittent renewable energy in generation capacity lead to a more unpredictable supply side of electricity. Securing a stable flow of electricity can be handled by either investing into back-up capacity, which can be ramped-up on short notice, or by engaging in trade with neighbouring jurisdictions, using each other's capacities as back-ups. Back-up capacity could for instance be in the form of thermal power generation units. Engaging in trade with countries with a different demand or supply pattern allows to smooth out peak-demand and -supply. Given the nature of electricity being grid bound, trade in electricity requires a transmission network. In this way, the decision makers face a trade-off between

[1] The Nordics refers in this thesis to Denmark, Finland, Sweden and Norway.

investing into back-up capacity or into transmission capacity.

The Antweiler theoretical framework and model incorporates both of these elements by arguing for two-way trade as an insurance as well as by quantifying the benefits from an interconnected U.S.-Canadian grid. With imperfections still present in the Nordic electricity market, and also in other parts of Europe, it is highly interesting to analyse the market with the tools provided by Antweiler. These will allow me to gain insights on the level of trade between the countries in the Nordics, as well as on the drivers behind the trade. Furthermore, a comparison of the results with the Antweiler findings might lead to insights which can be useful for both the U.S.-Canadian market as well as for the Nordic countries, which are part of the Nord Pool electricity exchange.

While the North American empirical study, undertaken by Antweiler, derives its insights mostly from variations in demand across states, due to season- and time zone differences, the Nordic market is more homogeneous from a demand side due to being geographically closer, as both the seasonal patterns (latitude) as well as the diurnal patterns (longitude) are expected to be similar to each other. The supply side on the other hand is more heterogeneous in the Nordic market, due to its very broad portfolio of energy sources, including renewables, hydro power and nuclear energy. While hydro power is characterised by being able to be stored to some degree, other renewable energy sources such as wind and photovoltaics are characterised by being intermittent. Furthermore, the distances between the individual jurisdictions are smaller than for most cases in the USA and Canada. This creates an interesting case, since the setting is significantly different from the North American setting.

While the Antweiler model due to its assumptions based on convex marginal cost curves is not a perfect fit for the Nordic electricity market, it is a starting point for further research on the Nordic electricity market. In this way, the Nordic countries and their trade in electricity are worthwhile being researched using the Antweiler model, thereby identifying the potential for trade as insurance and the determining factors behind two-way electricity trade. The purpose of this paper is to generate an overview of the Nordic power market, analysing electricity trade and its drivers. Following the delimitation, the next chapter will give an overview over the current electricity production in the Nordics as well as a broad introduction to the market design in electricity markets. Thereafter the literature review will cover the state of the research in electricity trade and transmission expansions. In chapter 6 I will explain the theory behind the Antweiler model and then apply it in the following chapter. The thesis ends with a discussion of the results, their robustness and the conclusion, including suggestions for further research.

# 2 Delimitation

The research focus in this paper is on the four Nordic countries Denmark, Finland, Norway and Sweden. These countries do all have a relatively high share of either renewable energies or hydro power plants or both in their electricity generation portfolio. In this way, they can be used as a case for a setting with renewable energies as the main electricity source. From the renewable energies, especially hydro energy plays a major role in the Nordic electricity market, with a share of close to 50% of the installed capacity in the region being hydro power plants. Hydro power also takes a special role among the renewable energies, as it to some extent can be stored.

It could be argued, that the entire Nord Pool market, also including the Baltic countries, should be considered for this thesis, since they all trade at the same exchange. I have decided to limit the focus to the Nordic countries. In this way, the Baltic countries will not be considered, as their entry and connection to the Nordic electricity market only happened in recent years, which would have limited the amount of consistent data. The time frame of the data, from November 2011 to September 2017, is chosen on the background of consistent data, as this is the time period in which the bidding areas have had their current size. For instance, did Sweden until October 2011 only consist of one pricing area, before it changed to its current form of four different pricing areas (Unger et al. 2017).

Please take note, that the countries which are part of this study do also trade with countries outside of the studied area. The COMTRADE database has country level data on electricity trade, showing imports and exports both in USD as well as in megawatt hours (MWh)[2]. The HS commodity code for electrical energy is HS271600. Table 8 in the appendix shows the trade of the countries researched with external countries, not being part of the researched group, in 2016. The share of trade with outside countries ranges from 16% to 38% in 2016. In this way, the share is quite significant and does also influence the trade behaviour within the group of countries being researched. In this study, the trade with other countries is left outside. This is due to the fact that it is quite unlikely to find a country which does not trade with other countries than the ones being studied, due to the high integration of electricity grids in continental Europe. The over-the-counter trade in electricity, which is not taking place via the Nord Pool market, but directly between sellers and buyers, is also not included in the analysis of this thesis. Furthermore, this thesis does not take empirical electricity prices or market power of market participants into account. Neither does it include cost of installing transmission capacity and of maintaining generation capacity, even though these factors can have some impact on the obtained results.

[2] Table 7 in the appendix contains an overview over the prefixes used in this thesis.

# 3 Electricity markets

In order to understand the dynamics of cross-border trade in electricity, I will in this part introduce the main characteristics and the unique features of the electricity markets, focusing on the Nordic electricity market.

## 3.1 Market forms

In today's world, there are three dominant forms of electricity market designs: *bilateral markets*, *exchanges* and *pools*. In bilateral markets the buyer and the seller trade with each other directly. In order for trade to take place, the information on transactions is given to a transmission system operator, who ensures that enough capacity is available for all transactions to take place at any given time.

Electricity trade via an exchange is more coordinated. The exchange is often run by the transmission system operators. By collecting and aggregating the price-quantity demand bids and supply offers from all market participants, a market clearing price is found, which all cleared offers receive.

Pools are similar to exchanges in the way they coordinate all market participants. However, the pool takes on a more active role with generation scheduling. As a consequence, bids and offers are more complex, also including factors such as start-up costs and no load costs for generators. In these cases, the pool provides side payments to ensure that the operators of generation capacity do not occur economic losses from supplying electricity (Perekhodtsev and Blumsack 2009). Following these classifications, the Nord Pool power market is an electricity exchange.

## 3.2 Energy sources

| **Type** | **firm / variable** | **type of fuel** | **flexibility** | **low-carbon** | **$CO_2$ emissions[5] (kg per kWh)** |
|---|---|---|---|---|---|
| coal | firm | fossil | medium | no | 0.95 |
| natural gas | firm | fossil | high | no | 0.55 |
| biomass | firm | renewable | medium | yes; regrowth of biomass compensates emissions | |
| nuclear | firm | nuclear | low | considered as zero-emission energy sources | |
| hydro with dam | firm | renewable | very high | | |
| solar | variable | renewable | very low | | |
| wind | variable | renewable | very low | | |
| geothermal | firm | renewable | high | | |

**Figure 1:** *Characteristics of the main energy-generation technologies*
Source: European Parliament (2016)

The electricity market is characterised by having multiple generation sources that all deliver the same good: electricity. Figure 1 gives an overview over the most common sources of electricity production and some of the key characteristics in order to understand the differences in the various forms of production. The first column shows whether the electricity flow is *firm* or *variable*, which describes whether it is able to be switched on and off on demand (*firm*) or if other factors such as wind and sunshine determine when the generator is able to produce (*variable*). The third column, *flexibility*, gives an overview over how quickly the electricity generation source can be turned on or off. Here hydro with dam is the most flexible, with nuclear power having the longest time horizon with regards to changes in the generation load, while the *variable* sources have close to no *flexibility*. It should though be noted that there can be some variation within each category, due to differences in the technological level of the generation units. These two features are highly relevant as they to some degree influence the cost structure of electricity suppliers and the decision making with regards to balancing supply and demand.

## 3.3 Supply and demand

In order to avoid blackouts or an oversupply of electricity, demand must always meet supply instantaneously, as it is not very efficient to store electricity, given the current level of technology. While it is possible to store electricity, it always leads to a loss of energy when transforming energy from one form to another. The supply side of electricity production can be separated into two parts, the base load and the peak load[3]. The base load is the load which meets the minimum demand at every point in time for a certain time horizon. Following from this, suppliers who supply the base load are ensured that their generated electricity finds a buyer, and that there will not be any need to ramp generators up or down. Peak load on the other hand is the residual load, occurring at times when demand is higher than the base load. As the peak load often follows a diurnal pattern, it needs to be provided by generation technologies, capable of being ramped-up or -down on short notice and without incurring high costs during change of the load level.

Using the characteristics of electricity sources from figure 1, the different electricity generation technologies can be ordered with respect to their suitability as either base or peak load. Leaving emission and cost out of the picture, the base load should be supplied by a *firm* electricity source in order to secure a continuous supply. Ideally the base load is supplied by a *firm* electricity generation technology with a high *flexibility*. This would allow *variable* electricity sources to be integrated into the supply system by being able to adjust the supply from the base load. Following these criteria, a hydro power dam is the ideal source for a base load, as it is a *firm* source with a very high *flexibility*. Other good sources based on these two criteria are geothermal and natural gas, while coal has a medium high level of *flexibility*, though depending on the level of technology. Nuclear energy however has the lowest *flexibility* of the *firm* electricity sources. One of the reasons behind the widespread use of nuclear energy is that *flexibility* is not the highest priority with regards to its purpose as a base load. When taking marginal cost of electricity production and emission into account it outperforms both natural gas and coal. Wind power and photovoltaics are due to being *variable* electricity sources not appropriate as electricity generation technologies supplying the base load. However, due to their low marginal cost of producing electricity and being zero-emission electricity sources, they provide well as flexible electricity peak load sources. Due to wind and photovoltaic power being variable, back-up peak load capacity would be needed to be installed. This could be in the form of gas or coal generation plants. Furthermore, hydro power is also used as a peak load in some jurisdictions, due to its ability to be highly flexible. By being able to predict wind and sunshine with some accuracy a day ahead, renewables

[3]In some cases, the load levels are categorised into three or four categories. For simplicity, I will refer to only two load levels, the base load and the peak load.

can substitute for some of the base load, given that the base load electricity generation technology has a high enough *flexibility* in order to accommodate a temporary decrease in output. Due to low *flexibility* and relatively high costs related to changing the load of electricity production for some generation technologies, it might not be economically viable to adjust the base load as a response to variable electricity production from renewable generation technologies. Intermittent generation from renewables can also substitute other peak load generation technologies instead of affecting the base load generator.

The increasing share of *variable* electricity generation technologies who due to their marginal costs of virtually zero outperform the other electricity generation technologies, lowers the incentive of suppliers to provide sufficient back-up capacities in the form of thermal generation plants, as they are less frequently able to dispatch electricity, while the installation of the capacities requires a fixed investment and maintenance costs. This has put some pressure on policy makers in order to secure that demand is met. On the demand side, one measure in order to ensure that demand meets supply, could be *demand response*. This is implemented by increasing prices in times of high demand, in order to ensure that demand meets supply. Empirical evidence does though point towards consumers' demand being relatively price inelastic in the short run, reacting rather to the average price in electricity than to the instant marginal cost (Ito 2014). Other than through *demand response*, international trade in electricity can also lower the costs of back-up capacity, as jurisdictions can share the back-up capacity. The use of other jurisdictions' capacity as back-up capacity works best when jurisdictions have a low correlation in demand.

In order to further understand the mechanisms of the electricity market, I will now introduce the marginal cost structure of the various sources of generation technology and building on that introduce the price setting via uniform price auctioning in electricity market exchanges, such as the Nord Pool.

## 3.4 Market entry and exit

The most prevalent method of electricity price setting in Europe is the sealed-bid uniform price auctioning. In order to illustrate the price setting mechanism the marginal cost of electricity generation technologies should be ordered in merit-order, which means from the lowest marginal cost to the highest marginal cost. This ordering can be seen in figure 8 in the appendix. For the uniform price auction to take place all the sellers and buyers in the market provide their prices for a given level of electricity. A seller could for instance offer the first unit for €3, the second and third unit for €5 each and the fourth unit for €7. A buyer on the other hand could bid €7 for the first unit, €5 for the second and €2 for the third. In this example, the amount dispatched would be two units of electricity, as the demand and supply curves intersect at two units with a price of €5. A market participant could also decide to participate on both the buying and the selling side. An electricity utility could for instance decide on using their generators with the highest marginal cost if the market price is high enough and sell to the market, while buying from the market when the market price is lower than their marginal costs. In an electricity exchange all the prices from sellers and buyers are aggregated and from these the aggregated demand and supply curves are created.

In a uniform price auction, a subcategory of multi-unit auctions, the price is set at the intersection of supply and demand. There is only one price for all participants in the market, regardless of the prices they individually have offered electricity for or were willing to buy electricity for. The sellers' and buyers' bids however determine who is going to dispatch and who is going to receive how many units of electricity, following a *lowest bid first* approach for suppliers and *highest bid first* approach for consumers (Nord Pool Group 2017*g*). It is though not an efficient market, as suppliers could engage in mutual agreements thereby creating a higher margin. Furthermore, this auction type also allows for a supplier to exercise his market power, in the case where the sum of the other suppliers' capacities cannot fulfil the market demand (Kaplan and Zamir 2015). By having the auctions for supply and demand in the electricity markets designed in this way, it leads to the outcome that the generation technologies with the lowest marginal costs of production have a competitive edge, as they are more likely to dispatch when offering electricity at their marginal cost. This is also shown by figure 8 in the appendix. The effect of the renewable energy sources, wind and photovoltaic, is that they shift the merit-order curve to the right, as they operate at marginal costs which are virtually zero. Due to the shift of the supply curve, the equilibrium price will decrease, when the variable energy sources are able to generate electricity, assuming prices set at the marginal costs due to competition. In their study analysing the merit-order effect, Clò et al. (2015) find that taking generation of 1 GW of wind and photovoltaic energy on to the grid reduces the electricity price with €4.2/MWh and €2.3/MWh respectively.

# 4 The Nordic-Baltic electricity market

Starting with Norway in the beginning of the 1990's the Nordic countries have deregulated their electricity markets. With Eastern and Western Denmark joining in 1999 and 2000, respectively, all of the Nordic countries had deregulated their electricity market and formed a common non-mandatory electricity exchange, the Nord Pool Spot. Prior to deregulation, the market in the individual countries was run by a large state owned-utility in each country. By deregulating the market, the transmission and the generation of electricity have been separated, with the transmission being operated by transmission system operators (TSOs) and generation taking place through utilities (Fridolfsson and Tangerås 2009).

## 4.1 Nord Pool

The Nord Pool Spot is owned by the national transmission system operators of the respective countries (Nord Pool Group 2017*c*). It allows for day-ahead trading and intraday trading. When trading at the Nord Pool Spot, the buyers and sellers are also secured the transmission capacity, in order to receive the electricity they bought or sold. In this way, there is no separated auctioning for transmission capacity in the Nord Pool area. The Nordic-Baltic Market consists of the countries, Denmark, Finland, Norway, Sweden, Estonia, Latvia and Lithuania. This thesis limits its focus to the countries, Denmark, Finland, Norway and Sweden. This is due to them being closest geographically and having been in the Nord Pool Spot the longest. Furthermore, these four countries have different profiles when it comes to electricity generating units, which makes it interesting to analyse their trade patterns. The Nord Pool market has around 360 members, who either buy or sell electricity at the electricity exchange, or do both. In 2015 the amount of electricity traded was 380 TWh in the Nordic-Baltic electricity market. Of these 380 TWh 374 were traded in the day-ahead market and 6 TWh were traded in the intraday market (Nord Pool Group 2017*c*). The market participants are utilities who produce the electricity, distributors operating the local distribution and large consumers, who buy directly from the electricity exchange.

Figure 2 shows the Nord Pool area in light blue. The four countries researched in this thesis are separated into twelve individual bidding areas, with two in Denmark, one in Finland, five in Norway and four in Sweden.

## 4.2 Price setting

In the day ahead market, the *Elspot*, the members of the Nord Pool Spot market participate in an auction on electricity for every hour of the next day. The deadline for the orders is at 12:00 CET the day ahead of the delivery. Aggregating the bids and offers to a supply and a demand curve, the 24 system prices for every hour of the following day are found at the intersection of the pairs of aggregated demand and supply curves and announced at around 12:42 CET. The intersection represents the system price, that is the price which would be applicable to the entire Nord Pool market in the absence of transmission capacity bottlenecks. In order to ensure no congestion at the interconnections, different prices can be applied to the different bidding areas, thereby allowing to regulate demand. The physical delivery takes place as agreed on in the contracts.


**Figure 2:** *Nord Pool bidding areas*
Source: Nord Pool Group (2017*a*)

In this way, the day-ahead market ensures that supply meets demand, due to the inability to store electricity. Furthermore, transmission constraints are taken into account when trading at the Nord Pool exchange. In this way, the price already includes direct and indirect costs of potential bottlenecks (Nord Pool Group 2017*b*). In addition to the day-ahead market, the Nord Pool market also facilitates an intraday market, the *Elbas*. While the majority of trade takes place in the day-ahead market, the intraday market allows suppliers and buyers to trade in almost real-time, up to one hour prior to physical delivery. This allows to maintain the balance in the grid in the case of an unforeseen event, such as unexpectedly high wind or problems with an important generation facility. With the high share of wind energy installed in Denmark and Sweden, the market has become more unpredictable, thereby creating a higher need for the intraday electricity market (Nord Pool Group 2017*f*). Another market operated by the Nord Pool Group is the financial market for electricity contracts. While the intraday and the day-ahead market contracts result in a physical delivery of electricity at maturity, the financial market contracts are settled with cash. The reference price for the financial contracts is the system price, so in this way producers and buyers of electricity can use the financial contracts in order to hedge their risk exposure towards changes in the electricity price (Nord Pool Group 2017*d*).

## 4.3 Grid interconnection

In order for trade to take place, it is necessary for the different bidding areas to be connected via an electricity grid. The interconnector capacity limits the amount of trade that can take place, as there are limits to the amount of electricity that can flow through the interconnector, at any given point in time. The Nordic electricity market is characterised by having a relatively high interconnector capacity, leading to few issues of congestion. This can be checked empirically by looking at the difference in the price of the system price and the price in the bidding areas. This is due to the fact that price differences are used in order to relief interconnectors, thereby ensuring no congestions on the transmission network.

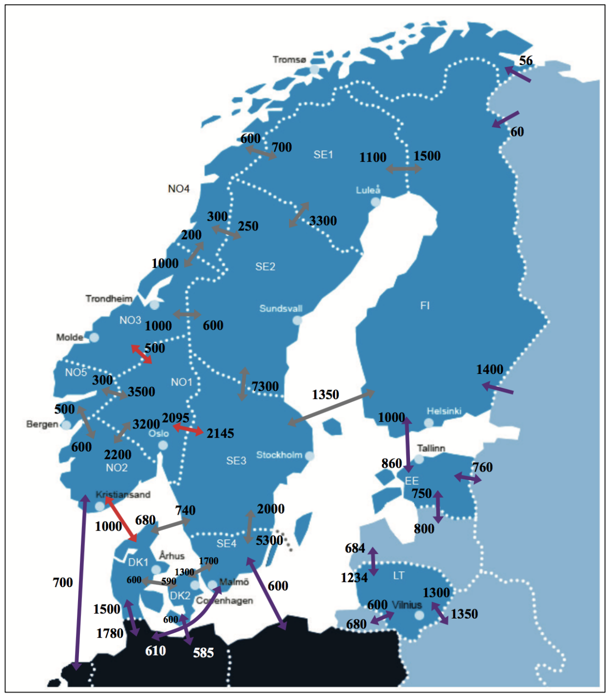


**Figure 3:** *Net transmission capacity*

Note: The red arrows show transmission lines which were congested more than 50% of the time 2013.

Source: Nordic Energy Regulators (2014)

Figure 3 shows the net transmission capacity installed in the Nord Pool area in 2013. The numbers next to the arrows show the maximum capacity of the transmission lines in megawatt (MW). These numbers should be held up against the peak demands and production in the different bidding areas, in order to see the level of interconnection. An overview of the average demand and production in the different bidding areas can be found in the appendix in table 19. Note that the data in the table is based on daily observations. As peak demand and supply can occur at a higher frequency, the actual peaks and minimum will be more extreme than the values based on daily observations. The red arrows show the transmission lines which were congested more than %50 of the time during 2013. These are the transmission lines between *DK1-NO2*, *NO1-NO3* and *NO1-SE3*.

The 2014 Nordic Market Report (Nordic Energy Regulators 2014) provides some stylized facts about the grid interconnections, their utilization and the amount of congestion. For the year 2013, the entire Nord Pool market had the same price in 23.4% of the time, which means that in only 23.4% of the time, the transmission capacity was sufficient for the market to freely allocate demand and supply. The report also states that there in 50% of the time were only two different prices in the Nordic bidding areas. The high share of wind energy in the Danish bidding areas has led to negative electricity prices for more than 30 hours in 2013. Due to the need for a balanced electricity grid an unexpected high production from a *variable inflexible* source could lead to a situation in which a negative price is needed in order to maintain the balance. Figure 4 gives an overview over different combinations of bidding areas and the amount of time they had a single price. The four Swedish bidding areas had a single price in 92% of the time, while the Swedish bidding areas and the Finnish bidding area together had a single price in 78% of the time in 2013. The northern Swedish and northern Norwegian bidding areas, *NO3, NO4, SE1* and *SE2* who all have hydro power as their main generation technology, had a single price in 83% of the time. The other combinations of bidding areas all had a single price in less than 40% of the hours in 2013. As price differences indicate insufficient transmission capacity for the market to freely allocate loads, the data shows that the installed transmission capacity is not able to meet the demand in capacity needed for a single market price to occur constantly.

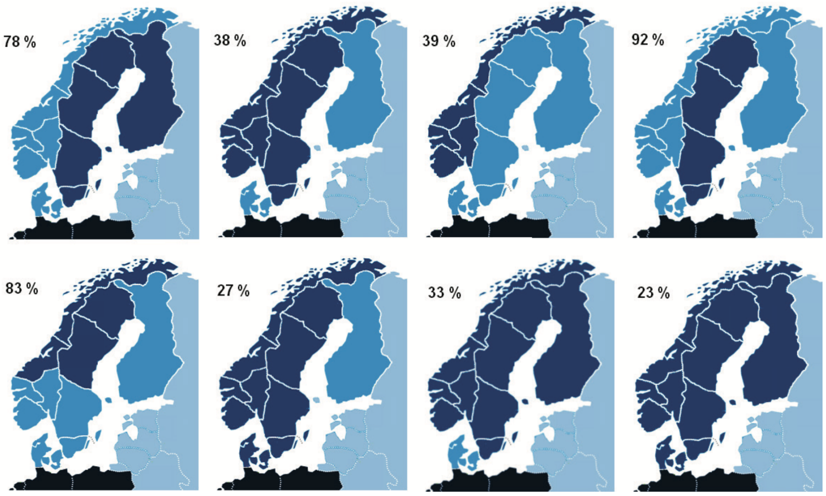


**Figure 4:** *Equal price areas 2013*

Note: The dark blue areas show the areas who had equal prices for the percentage of time shown in the left corner.
Source: Nordic Energy Regulators (2014)

## 4.4 Country profiles

In this section I will give a description of the energy production capacities in the countries Denmark, Finland, Norway and Sweden. Energy production capacities are measured in Watt. For instance, would a generation unit with the size of 60 Watt be able to power a 60 Watt light-bulb, if it was running at full capacity.

As can be seen from figure 5 and figure 6, the twelve bidding areas each have a production portfolio different from the others. Starting with the combined production capacity of the twelve bidding areas, hydro power makes up around half of the installed capacity in Denmark, Finland, Sweden and Norway together, with thermal making up a quarter, nuclear and wind power making up approximately an eighth of the total installed capacity each. The two Danish bidding areas *DK1* and *DK2*, are characterised by their relatively high shares of both wind and thermal generation units. The thermal energy is mainly from fossil gas and fossil hard coal (ENTSOE 2017*b*). The production capacity of bidding area *SE4* is similar to the Danish bidding areas'. The bidding area is located in the south of Sweden, geographically closest to Denmark. A difference to the Danish bidding areas is though the share of hydro energy in *SE4*, whereas the Danish bidding areas have an almost identically big share in other renewables such as photovoltaics. Finland, which only consists of one bidding area has the most diversified installed capacity, including nuclear as well as

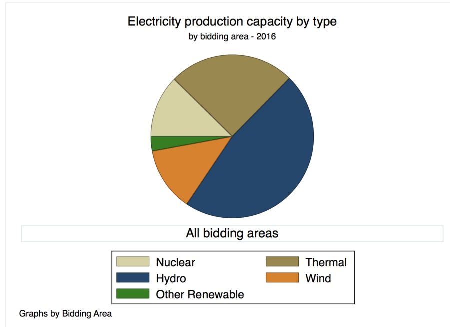


**Figure 5:** *Composition of electricity generation capacities of all bidding areas*
Source: Author with data from ENTSOE (2017*b*) and Svensk Energi (2016)

thermal and wind electricity generation technologies. The Norwegian production portfolio for the bidding areas *NO1-NO5* is characterised by hydro power being the main source of energy, with *NO1* having no other energy generation type. For the other four Norwegian bidding areas, the share of hydro is over 80% for all of them, with the remaining production capacity being thermal and wind. The four Swedish bidding areas *SE1-SE4* are the most diverse within a country in this group. *SE1* and *SE2* consist of a portfolio similar to the Norwegian bidding areas, with hydro power being the dominant capacity, and as mentioned above, bidding area *SE4* is similar to the Danish bidding areas. The last Swedish bidding area, *SE3*, home to Sweden's capital, Stockholm, differs from the other Swedish bidding areas, by incorporating nuclear power plants into its generation capacity portfolio. Notice that figure 5 and 6 show the capacity and not the actual production. As a result, the composition of electricity production in the bidding areas will be different from the capacity portfolio, depending on the load factor of the generation units. Furthermore, production and usage can also differ due to cross-border trade in electricity.

## 4.5 The role of hydro

As hydro accounts for close to 50% of the installed electricity capacity in the countries researched, the main features of this electricity generation technology will be introduced.

The two main types present in the Nordic countries are river power plants and storage power plants. River power plants, which are also called run-off-river power plants are installed directly into a running river. They generate electricity by converting the kinetic energy from the running water via turbines into electricity. The water is however not stored, such that the electricity produced highly depends on the amount of water the river is holding. In this way, river power plants have limited flexibility with regards to controlling the amount of power generated, as it depends on the precipitation as well as on the meltdown of the ice and snow during the spring.

The other main source are storage power plants, which make up the main share of the Norwegian hydro production. Here the influx of water comes from melted ice and snow as well as from precipitation. Unlike the river run-off power plants, the water is stored in reservoirs behind dams at different heights in the mountains. In order to increase efficiency, the reservoirs are connected via pipelines. By letting water flow through the pipelines from the upper to the lower reservoir, thereby going through a turbine, electricity is

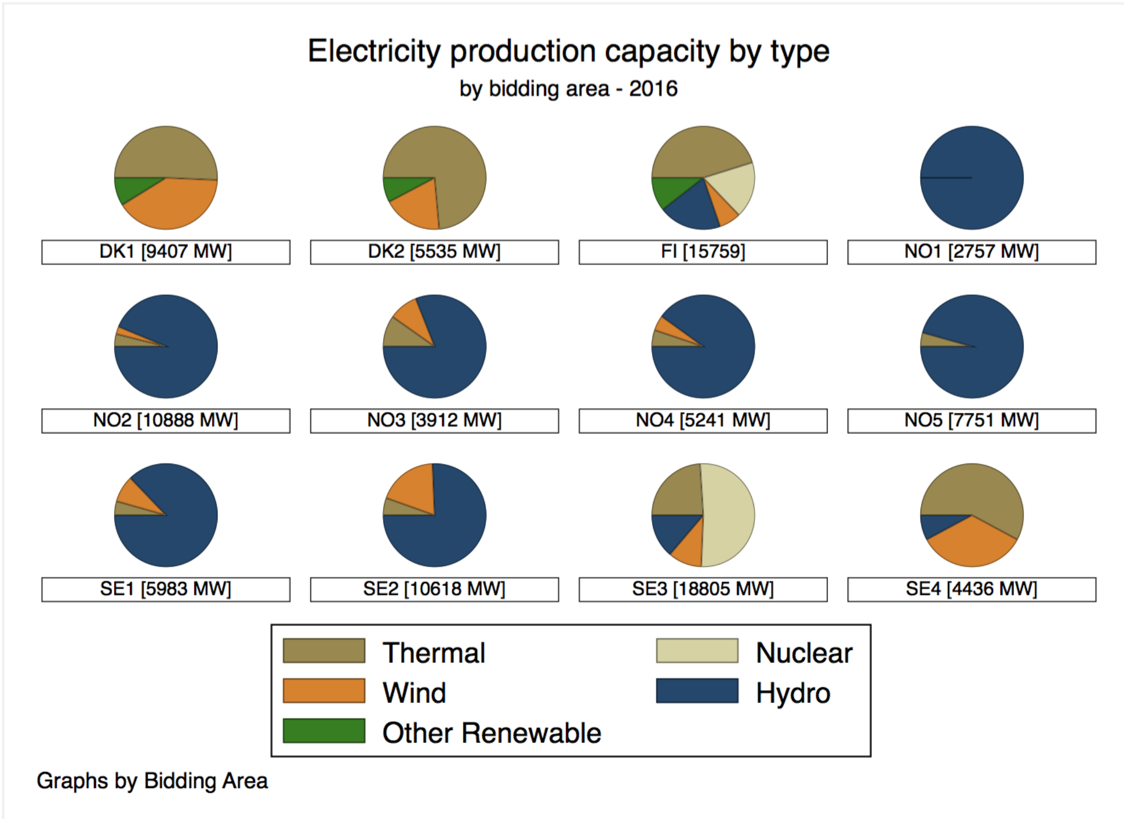


**Figure 6:** *Composition of electricity generation capacities by bidding area*
Source: Author with data from ENTSOE (2017*b*) and Svensk Energi (2016)

generated. Being able to control the flow of water, storage power plants are highly flexible, being able to increase or decrease their electricity production with very short notice. However, also storage power plants can only produce as long as there is sufficient water in the reservoirs. Due to their storage capacity, storage power plants are able to provide the base load in some cases, while also being able to provide the peak load in other cases, due to their flexibility.

While storage can come from natural influxes such as melted ice and snow, and perception, pumped storage power plants use energy in order to pump water from a lower to an upper basin. While some energy is going to waste by pumping the water up, it allows to store energy. In this way, an oversupply from an intermittent energy source, such as wind energy could be stored via pumped electricity storage power plants and then be used when needed.

There are multiple reasons for choosing a run-off river plant over a storage power plant, despite the storage power plant having higher flexibility. These include situations in which a jurisdiction cannot stop the flow of the river, due to it running through a jurisdiction downstream depending on a constant flow and situations in which it is not possible to construct a dam due to the location (Wagner and Jyotirmay 2011).

Figure 10 to figure 12 in the appendix show the characteristics of the hydro power production in Finland, Norway and Sweden. There is a seasonal pattern, with reservoirs filling up during the summer and autumn due to meltdown of snow and ice and precipitation, while production is highest in the winter months, when electricity demand in the Nordic countries is at its highest. Following from this, the reservoirs are at their lowest at the end of the spring. For Finland the hydro generation though peaks around May, which is when the inflow is the highest too. This could be due to relatively lower ratios of storage capacities to influx in the Finnish storage power plant reservoirs.

As it cannot be assumed that the depletion of the reservoirs takes place uniformly, some reservoirs might have storage levels close to zero. In this case, the hydro power generation is no longer part of the available generation technologies. This reoccurring annual scenario leads to a change in the merit-order curves of the bidding areas in which hydro power reservoirs reach low levels during the spring. In this way, the trading advantage that comes with hydro power diminishes, leading to a period in which the direction of trade to a higher degree is determined by other factors, such as the intermittency of renewables.

## 4.6 Merit-order curves

The ENTSOE (2017*a*) data on generation by production type allows to identify the role of the various generation technologies installed in the bidding areas. The data shows the actual generation by production type, allowing to identify a pattern of generation. As trade between bidding areas takes place, the technologies should not be viewed as technologies of countries in electricity autarky as the construction of generation technology is built with the market interdependence in mind.

The Danish bidding areas, *DK1* and *DK2* are characterised by having a high share of renewable energies in their generation technology portfolio. For the generation by production type, this means that a base load providing a constant output is not present in the Danish data. Rather the production forecasts for wind and sunshine determine the generation of electricity from biomass, coal and gas generation plants. This leads to merit-order curves which are convex, shifting to the right, depending on the amount of electricity produced from the variable energy sources, wind and photovoltaic. This effect can be seen in figure 8 in the appendix, which shows a scenario with production from renewables and a scenario without production from renewables.

The Finnish bidding area is the most diverse with respect to generation technologies, as it consists of nuclear, hydro, thermal as well as renewable energies in the form of wind and biomass. The base load is provided by the nuclear power plants. The residual load is then provided following the low cost first approach, with wind energy being implemented when available. In order to meet demand, the load is balanced with the other generation technologies including hydro and thermal generation. As the hydro source comes from run-of-river as well as reservoirs, it is only to some degree flexible. Following from the generation technologies used in the Finnish bidding area, the merit-order curve can be classified as being convex.

Norway consists of five bidding areas, of which one is different from the others. The bidding area *NO1* generates its hydro energy run-of-river as well as from reservoirs, with the share of both being around 50% of production. Due to the reservoir hydro energy being variable on demand, the run-of-river electricity acts as the base load, with the reservoir energy being used as the peak load source, due its *flexibility*. For the bidding areas *NO2-NO5* the share of production by generation type is close to 100% generation from hydro energy, with minor shares of wind and thermal generation. In these bidding areas the majority of the hydro power comes from storage power plants. The Norwegian merit-order curves are due to their high share of hydroelectricity constant with a marginal cost of production close to zero and hence not convex.

For the Swedish bidding areas, the European Network of Transmission System Operators for Electricity (ENTSOE) source does not provide data on a bidding area level. Since the different bidding areas do not act in autarky, a description of the generation on a country level also provides some information. The base load in Sweden is produced by the nuclear power plants, which are located in the bidding area *SE3*. Hydro power from reservoirs, predominantly present in *SE1* and *SE2* and to a smaller extent in the bidding areas *SE3* and *SE4* acts as the flexible peak load, responding to the difference in demand and the production from nuclear and wind energy. The merit-order curve for Sweden as whole is somewhere in between the Norwegian and the Danish ones. Due to a high share of wind, hydro and nuclear production it stays rather flat, though it also has a significant amount of thermal production capacity installed, mainly in *SE3* and *SE4*.

Using installed capacity, table 11 in the appendix shows the share of installed capacity by generation type in the bidding areas in 2016. In order to define whether bidding areas resemble convex or constant merit-order curves, I have defined a threshold value of 20% thermal energy generation capacity. This variable is chosen as the variable defining the structure of the merit-order curves, due to wind, renewables, hydro and nuclear all representing rather low marginal costs, thereby not creating convexity in a merit-order curve. Bidding areas with more than 20% of their installed generation capacity being thermal are characterised as having convex merit-order curves, while the residual bidding areas are characterised as having constant merit-order curves. Following this threshold value, the bidding areas with convex merit-order curves are *DK1, DK2, FI, SE3* and *SE4*. Bidding areas with constant merit-order curves are *NO1, NO2, NO3, NO4, NO5, SE1* and *SE2*.

Applying the classification with 20% thermal energy production being the threshold value in order to classify a jurisdiction as convex, on to the data from Table TA-7 in the technical appendix of the Antweiler paper (Antweiler 2016*b*), only two of the U.S. states would have non convex merit-order curves[4]. Using data from Statistics Canada (2015), nine out of 13 Canadian provinces/territories are classified as having convex merit-order curves, while the remaining four resemble merit-order curves closer to being constant. The North American data-set hence has approximately 10% of jurisdictions with constant merit-order curves, while the remaining 90% can be categorised as being convex. In the Nordics, five out of twelve bidding areas are categorised as having convex merit-order curves, with seven out of twelve being categorised as having constant merit-order curves. This comparison shows that there is a significant difference in the structure of the merit-order curves.

## 4.7 The North American market

The U.S. electricity market is separated into eight interconnection areas in which free trade can occur, while trade between them is limited due to prohibitive tariffs (Antweiler 2016*a*). The separation has been regulated by the North American Electric Reliability Corporation (NERC) and Federal Energy Regulatory Commission (FERC) (WECC 2017). Traditionally wholesale electricity markets were supplied by vertically integrated utilities, who own the generation facilities, the transmission network and the distribution network. The trade usually took place via bilateral transactions and power pools. Due to the Order No. 888 from 1996, which was promoting open access to non-discriminatory transmission services, it led to the creation of independent system operators (ISOs). The Order No. 2000 further encouraged utilities to join regional transmission

[4]The data is generation data and not capacity data, it does however indicate the installed capacities

organizations (RTOs). Both RTOs and ISOs manage markets in which sellers and buyers can place bids, similar to the Nord Pool. Large parts of the U.S. still operate with the traditional vertical integrated model, though two thirds of the load are served in RTO and ISO regions (FERC 2017).

# 5 Literature review

The model upon which this thesis is built, the model for cross-border trade in electricity by Antweiler (2016*a*), is a model on international trade in a homogeneous good. As such it contains elements from earlier international trade models. The literature on international trade does not consider the case of two trade participants trading a homogeneous good in both directions within the same time frame. Despite the model's roots within the international trade literature, I will narrow the focus of the literature review down, focusing on trade in electricity, a sub-category within international trade.

## 5.1 International trade in electricity

Antweiler develops a model which captures two-way trade in homogeneous goods. By introducing a model for homogeneous goods, the model differentiates itself from the former literature on trade, which is mainly focusing on two-way trade in heterogeneous goods.

Examples of such theories are the Ricardian model of international trade and the Heckscher-Ohlin model. In the Ricardian model, trade takes place for two countries, in two goods, with labour as the only factor determining production. In this case, relative advantages in labour productivity determine which country is going to produce and export which good, while importing the other good. The Heckscher-Ohlin model incorporates two goods, two countries and two factors, labour and capital. In this model, the relative factor endowments determine which country is producing and exporting which good, while importing the other good (Ohlin 1933). Both models are hence built upon trade in heterogeneous goods, while the Antweiler model incorporates trade in homogeneous goods. Furthermore, the trade determining factors in the Ricardian and the Heckscher-Ohlin model are static in the short-run, while trade direction in the Antweiler model is dynamic, able to change within a single time period. By allowing the model to work for homogeneous goods, it is suitable of modelling trade in electricity, with the novel motive of trade as insurance. The model is based on two main assumptions. These are convex marginal cost curve for electricity generating utilities and stochastic demand with correlation across jurisdiction.

According to Antweiler, the model has some parallels to Blum et al. (2013), in the way it is able to describe the frequent entry and exit of firms as exporters. On the same note, it also connects with Blonigen and Wilson (2010) on its explanatory power regarding cyclic dumping. More than just to introduce a new model, the article also tests the model empirically, using data from trade in electricity between the U.S. states and Canadian provinces and territories. In this way, the Antweiler paper provides both a model as well as empirical results based on the model. The main finding is that a higher load ratio decreases a jurisdictions competitive advantage with respect to electricity trade, thereby making it less likely to export. Furthermore, it also finds that it is economically viable to establish a continental supergrid[5] given technological progress in long-distance transmission. Having such a wide approach, from marginal cost curves of electricity producers to the viability of a continental supergrid, the paper can be used to be held up against research in various different fields of energy and resource economics.

Some of the earlier models and literature on international trade in electricity can be found when reviewing

[5]A fully integrated grid connecting the U.S. and Canadian interconnections into one grid.

the paper by Gately (1974). The findings from the paper identify benefits of linking the electricity grids of four Indian states in the Southern Electricity Region. Using a game-theoretical approach, he analyses whether a set-up can be reached, in which it is in each state's interest to cooperate. The model is though focusing on the investment aspects and distribution of potential gains rather than on operational aspects, such as the direction of trade. A literature review from Anderson (1972) shows, that a lot of the electricity related research in the 1940's to 1970's focused on the investment side. The overview shows how different models have been implemented over time. These models are mainly linear programming and dynamic programming models, applied in order to find the optimal allocation of the different electricity plant types, as well as hydro storage and discharge over time. In the 1990's a time in which deregulation of the electric markets was starting, Ferrero et al. (1997) published a paper, analysing the effects of deregulation and the role of a power pool in the deregulated market. The model they use is based on a linear incremental cost function. Applying a game-theoretical model, Ferrero et al. reach the conclusion that deregulation would increase the benefits of operating a power pool. The results in the paper show that increasing competition will decrease operational costs and that it, given a big enough power pool, is beneficial to sell into the pool at marginal costs, rather than staying outside of the pool. Most of the current literature is focusing on the effect on price when engaging in international trade and to a lesser extent on potential capacity savings and increased security through trade.

Research into the Scandinavian electricity market has for instance been undertaken by Von Der Fehr and Sandsbråten (1997), who in their article analyse the trade opportunities between thermal-based and hydro-based electricity industries. They model four different scenarios based on daytime/nighttime and summer/winter. In their study, they find that a completely liberalised regime would lead to a reduction in thermal-based capacity and an increase in hydro system capacity. More recent research can be found in the works of Amundsen and Bergman (2006) who look at the Scandinavian market and analyse why it works so well, also under stress. By comparing the Nord Pool market with the Californian Power Exchange (CALPEX), they are able to find the main drivers behind the success of the Nord Pool market. These are for instance the market design, the dilution of market power and the political support, but also the high share of hydro power. Another study from Amundsen and Bergman (2007) focuses on the market integration of the Norwegian and Swedish market and concludes that the Nordic wholesale market is well integrated, whereas there still is room for improvement regarding the retail market.

## 5.2 Transmission and grid expansion

The Antweiler paper has been cited by four other papers[6] which mainly work with quantifying the benefits from creating a continental supergrid, which could lead to some significant reductions in generation capacity. Beiter et al. (2017) contribute to the literature related to the Antweiler article. In their journal article, Beiter et al. discuss the full integration of the U.S. and Canadian electricity grid using a model from the National Renewable Energy Laboratory's Regional Energy Deployment System (ReEDS) which allows them to look at the effects on numerous factors in scenarios limiting the transmission capacities to today's level as well as unrestricted scenarios. The model is hence comparable to the parts of the Antweiler paper, quantifying the impact of a fully integrated grid. The paper by Nikandrova and Steinbuks (2017) connects to the Antweiler

[6] As of: 31.10.2017

model as well, also relating to the Antweiler finding of the economical viable supergrid, leading to a potential reduction in capacity.

Wolak (2015) takes competitiveness benefits into account when looking at transmission expansions. He argues that transmission expansions lead to higher competition in the market, leading to market clearing prices closer to the marginal costs suppliers face. Using data from Alberta, he argues that competitiveness benefit should be taken into account during the planning process of transmission expansions. In this way, the literature agrees on the viability of transmission and grid expansions. Timilsina and Toman (2016) apply a dynamic least-cost simulation model in their study of the South Asian region. Their findings show the potential for savings in electricity supply costs, in the case of unrestricted electricity trade following initial investments into cross-border interconnection transmission capacity. Abrell and Rausch (2016) look in their study into transmission infrastructure expansions on the backdrop of the European decarbonisation plans. For their research, they apply a multi-country, multi-sector, general equilibrium model. Their findings show that the efficiency in abatement of carbon dioxide is dependent on the level of renewable energy production. The aggregate welfare of European countries increases following their model. Denmark, Germany and Switzerland would occur welfare losses as a consequence of a transmission grid expansion, due to loss of their current role as wheeling countries, through which electricity has to flow.

## 5.3 Contribution to the literature

The literature related to Antweilers model mainly narrows its relationship with the Antweiler model down to the benefits of a supergrid. The model itself is however not used in a different setting within the current literature. This leaves a gap which can be explored, as the U.S.-Canadian trade in electricity is only one of many examples of cross-border electricity trade. The theoretical model developed in the Antweiler (2016*a*) paper fits well onto the U.S.-Canadian trade between bidding areas with convex merit order curves. As the literature review has shown the amount of current research in the Nordic market is limited. Applying the Antweiler model onto the Nordic market is not optimal given the marginal cost curve structure in these jurisdictions. Hence, this thesis is a first step towards an identification of the drivers behind the electricity trade in the Nordics.

The thesis will contribute to the literature by answering the following two questions. "Which factors drive the electricity trade in the Nordic market applying the scope of the Antweiler (2016*a*) model?" and "How would further investments into transmission-capacity impact the need for back-up generation capacity?"

In an approach to fill some part of the gap, this thesis will contribute to the current research. By applying the Antweiler model on the Nordic countries, the setting and the possible conclusions that can be drawn change significantly. The main additions to the current research follow from the different setting when looking at the trade between Denmark, Finland, Norway and Sweden. Most importantly the market between these four countries is within the same interconnection, such that every jurisdiction is on the same grid. Furthermore, the portfolio of energy generation capacity is varying from jurisdiction to jurisdiction, though with a high share of renewable energies and hydro power, leading to different merit-order curves compared to the North American jurisdictions.

The renewable energies create higher variance on the supply side than a portfolio based on thermal and nuclear power would. Hydro power on the other hand can to some degree be stored, thereby adding another element to the composition of generation technologies. On the demand side, the Nordic setting also differs from the North American setting by being geographically closer, which presumably leads to a higher positive correlation in demand across jurisdictions. In this way, it can be assumed that two-way trade in the countries researched by me, is relatively more supply side driven, whereas the North American trade is relatively more demand side driven. This is based on the background of the expected variance between jurisdictions occurring on the demand side for the North American market and relatively more on the supply side for the Nordic market. Lastly, energy is traded via a common electricity exchange, the Nord Pool. All these factors add to the relevance of applying the model developed by Antweiler to this new setting, which by itself can make a case for an electricity model, with a relatively high share in renewables and strong positive correlation between jurisdictions.

# 6 Theory

Referring back to the literature review, a lot of models in international trade, as well as in electricity trade, have been developed. In order to answer my research questions, I will apply the model developed by Antweiler (2016*a*), which has been specifically designed for the application on electricity markets. One of the main features of the model, which makes it able to be applied to electricity markets, is its ability to estimate both one-way and two-way trade.

## 6.1 The Antweiler model

The model used to answer my research questions has been developed by Antweiler and been published in 2016. Setting it apart from the former literature, it is able to describe the behaviour of electricity producers, entering and exiting the electricity export markets multiple times within a period as short as day. In the journal article the theory is developed and four estimation equations are built upon the theoretical framework. In the following section the main assumptions and estimation equations of the model will be discussed, with a focus on the main estimation equation of the model, estimating exports with a set of factors describing the production and demand patterns across jurisdictions. The model is built up upon two main assumptions. The first one is that the marginal cost curve for production of electricity in each jurisdiction is convex. This is necessary in order to encounter a situation in which trade occurs in two directions within a single time period. The second main assumption is that demand is stochastic and correlated across jurisdictions.

## 6.2 Cost curves

In the paper, the cost curves are modelled with the following equation:

$$c(q(t)) = c_0 + c_1 q(t) + c_2 q(t)^2/2 \tag{1}$$

in which the quantity produced follows a function of time. The marginal cost curve is found to be:

$$\frac{\delta c}{\delta q} = c_1 + c_2 q(t) \tag{2}$$

Using a convex cost curve, the marginal costs also increase for higher outputs. This can be observed in the merit-order curve in figure 8 in the appendix, which resembles the marginal costs, due to the least-cost first approach, which the market design leads to.

## 6.3 Load ratio

The Antweiler model links the marginal cost curves with the load ratios of a given jurisdiction. The reasoning behind this is that the utilities with the lowest marginal cost curves would serve the market first and only after that would capacity with higher marginal costs be ramped-up. Following from this, a relatively high load ratio indicates the usage of marginally relatively expensive generation technologies, as these are dispatched last. As the market price in a unilateral price auction is found at the intersection of demand and the marginal costs of supply, assuming a competitive market, the high load ratio indicates high prices in the market. In a deregulated market, the high prices would hence create a higher incentive to import electricity from a jurisdiction with lower costs. A low load ratio on the other hand would come with low marginal costs and potential for exports. In the main equation of the Antweiler model, the load ratio enters as an independent variable:

$$\frac{q_{it}}{K_{it}} \tag{3}$$

The load ratio is defined as the actual load divided by the installed capacity. Installed capacity in the Antweiler model is found using the maximum generation in a month, from a 36-month rolling time frame. Antweiler argues that this approach is superior to *name plate capacity*, as it only takes the capacity actually being used into account.

## 6.4 Exporting decision

In the model, the decision whether to export or not depends on the difference in marginal cost curves, as well as a difference in fixed costs. Antweiler illustrates this with figure 7, which shows in which situations a country would be exporting or importing. The two axes refer to a cost independent from the quantity produced $c_1$ and to a cost increasing with produced quantity $c_2$, respectively. The y-axis shows the part of the marginal cost equation related to the costs independent of the load ratio. By showing the difference in the $c_1$ terms of the *home* and *foreign* jurisdiction, it shows the advantage one jurisdiction has over the other, independently of the load ratio. The higher the value of the difference, $c_1^f - c_1^h$ the more likely is the home jurisdiction to export. The x-axis represents the difference in marginal costs related to the load ratio in the two jurisdictions. On this axis, the difference in $c_2^f q^f - c_2^h q^h$ consists of two factors, the load ratio, as well as the individual cost functions. An increase in the load ratio, represented by $q$, decreases a jurisdiction's likelihood to export, following from the convex marginal cost curves. However, not only the load ratio but also the cost structure in a jurisdiction, here represented by $c_2$, influences its overall competitiveness. In this way, a jurisdiction might have a lower load ratio and still have a disadvantage, due to its generation technologies. Hence, the composition of electricity generation units and the therefrom following cost curves determine which jurisdiction will be at a trade advantage, given their respective load ratios. Another feature of the Antweiler model is the *No Trade Region*, at which no trade takes place. In the description of his model, Antweiler introduces the transmission costs that occur when engaging in cross-jurisdictional trade in electricity, represented by $g|x|$, which is which is a linear increasing function of the absolute amount of electricity traded. Antweiler assumes that the importer and the exporter share the costs equally. By implementing the trading costs, it creates a threshold which needs to be overcome, in order for trade to be economically viable. This threshold is visualised by the *No Trade Region*.

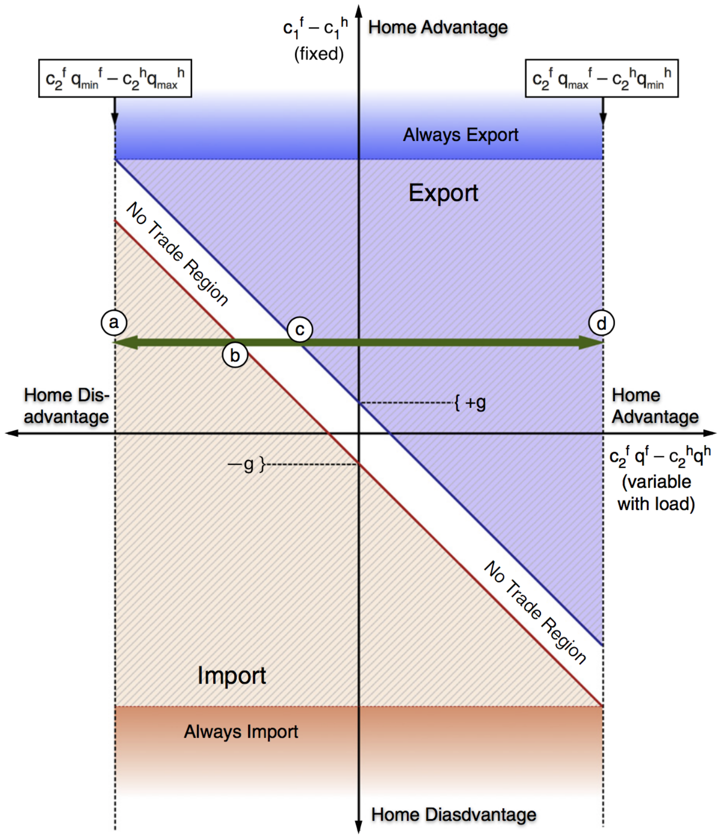


**Figure 7:** *Electricity trading patterns*
Source: Antweiler (2016*a*)

## 6.5 Demand variability

The exporting decision does not only depend on the countries' electricity supply and marginal costs, but also on the demand for electricity. If all countries experience similar patterns for electricity demand, this limits the opportunities for international trade, as jurisdictions with a high correlation in demand experience high demand and low demand periods simultaneously and hence cannot use each other's excess generation capacity. For the model, Antweiler models demand variability to be stochastic with correlation across jurisdictions. Correlation in demand can be related to multiple factors, including daily and weekly electricity usage as well as seasonal differences in electricity usage. In this way, jurisdictions which are geographically close with respect to the longitude will have similar diurnal and weekly patterns. On the other hand, a difference in latitude could lead to reverse seasons or different annual electricity peaks, due to different usage patterns. This could for instance be a jurisdiction with an electricity demand summer peak due to air conditioning, trading with a jurisdiction with a winter peak due to heating demand.

The Antweiler model's main equation includes the countries correlations on the demand side, by setting up the *Demand Variability* term:

$$\sqrt{(\frac{s_{jt}}{K_{jt}})^2 - 2\rho_{ijt}\frac{s_{jt}s_{it}}{K_{jt}K_{it}} + (\frac{s_{it}}{K_{it}})^2} \tag{4}$$

The *Demand Variability* consists of multiple parts. The $(\frac{s_{jt}}{K_{jt}})^2$ is the standard deviation of demand in the bidding area of the importer divided by the generating capacity of the importer while $(\frac{s_{it}}{K_{it}})^2$ represents the exporter's standard deviation in demand and generation capacity. $\rho$ represents the correlation coefficient between the demand of the importer and exporter. Following the equation, a high standard deviation increases the value of the expression, while a high correlation decreases the value of the expression.

## 6.6 Bilateral trade in electricity

Building upon the main assumptions introduced above, Antweiler sets up the main estimation equation. This equation describes the factors determining the amount of electricity a jurisdiction exports over a time period.

$$ln(\frac{X_{ijt}}{K_{ijt}}) = \mu_{ij}+\alpha_0+\alpha_1 ln(\frac{q_{jt}}{K_{jt}})-\alpha_2 ln(\frac{q_{it}}{K_{it}})-\alpha_3 ln(D_{ij})+\alpha_4 ln\sqrt{(\frac{s_{jt}}{K_{jt}})^2 - 2\rho_{ijt}\frac{s_{jt}s_{it}}{K_{jt}K_{it}} + (\frac{s_{it}}{K_{it}})^2}+\alpha_5 T_t+\varepsilon_{ijt} \tag{5}$$

**Table 1:** *Antweiler main estimation equation variables*

| *Variable* | *Description* |
|---|---|
| $\frac{X_{ijt}}{K_{ijt}}$ | Export/Joint capacity of importer and exporter |
| $\mu_{ij}$ | Comparative advantage differential |
| $\frac{q_{jt}}{K_{jt}}$ | Importer load ratio |
| $\frac{q_{it}}{K_{it}}$ | Exporter load ratio |
| $D_{ij}$ | Distance |
| $\sqrt{(\frac{s_{jt}}{K_{jt}})^2 - 2\rho_{ijt}\frac{s_{jt}s_{it}}{K_{jt}K_{it}} + (\frac{s_{it}}{K_{it}})^2}$ | Demand variability |
| $T_t$ | Time trend |
| $\varepsilon_{ijt}$ | Error term |

The main equation (5) consists of multiple parts which are shown in table 1. The dependent variable, is normalised, by dividing the electricity export from exporter to importer with the harmonic average capacity[7] of the two jurisdictions. The comparative advantage differential represents the differences in the installed capacity of the jurisdictions. It is separated into nuclear, hydro and renewables, with the residual being thermal. The exporter and importer load ratios are established by dividing the produced electricity with

[7] $K^{fh} \equiv 2K^f K^h/(K^f + K^h)$

the maximum capacity in the respective bidding areas and is hence in the interval [0;1]. For the distance Antweiler uses the population-weighted harmonic averages based on the population for the different postal areas in the bidding areas. The demand variability captures the correlation between bidding areas, as well as the standard deviations in demand for the two bidding areas engaging in trade. A time trend is included in order to capture infrastructure changes over time.

Following the theory, the $\alpha_1$ coefficient is expected to be positive, as a higher load ratio in the importing jurisdiction due to convex marginal cost curves leads to higher marginal costs. All else being equal, this should improve the competitive position of the exporting jurisdiction regarding their export opportunities, which is why I do expect the variable to be positive. For the $\alpha_2$ coefficient, the expected value is negative. As the exporting jurisdiction produces more electricity, its marginal costs increase, due to the convex marginal cost curve. The higher marginal cost decreases the exporters competitive position, making them, all else being equal, less likely to export, given a higher load ratio. For the distance variable, the coefficient $\alpha_3$ is expected to be negative, as there are some losses occurring during transmission. Furthermore, the distance variable also indirectly captures costs and fees related to border crossing. All else being equal, a higher distance leads to more borders being crossed and higher transmission losses. The coefficient $\alpha_4$, capturing the demand variability, is expected to be positive, leading to an increase, following a decrease in correlation or an increase in standard deviations of demand. In this way, lower correlation leads to more opportunities for trade, expressed by a higher export over joint capacity.

# 7 Data

The data used comes from two main sources. The main data sources are the Nord Pool Group (2017*e*) and the ENTSOE (2017*b*). The data from the Nord Pool Group is on Denmark, Finland Norway and Sweden for the period 1999 - 2017 on a bidding area level. However, it is the case that the bidding areas only have been in their current form since 2011. Due to that, I am mainly using data from November 2011 to September 2017. The data from ENTSOE (2017*b*) is annual data on the installed generation capacities by type, on a bidding area level.

## 7.1 Overview

The main data of this thesis is the trade between the twelve Nord Pool bidding areas in the four Nordic countries, Denmark, Finland, Norway and Sweden. The data that I was able to retrieve from the Nord Pool ftp servers delivers hourly and daily observations on: *prices, trade, generation* and *demand*.

Studying the individual bidding areas, it becomes apparent that some are net importers while others are net exporters and yet others change over time, being net exporters in some periods and net importers in others. The figures 13 and 14 in the appendix show the trade between the twelve bidding areas resulting in 20 trade pairs. The data is presented in $\frac{GWh}{Month}$ on the y-axis, and shows the export from the first named bidding area to the second named bidding area. Table 9 in the appendix gives an overview over the electricity production and demand in the bidding areas. Table 10 in the appendix is also related to the production and the demand. Here the first four columns are based on the production over demand, thereby indicating which bidding areas are importers and which bidding areas are exporters on average. Furthermore, the column named *swap* identifies how often a bidding areas has changed from being an exporter to an importer or vice versa, from one month to the next.

### 7.1.1 Trade data

The data from the (Nord Pool Group 2017*e*) is characterised by showing the trade flow from one bidding area to its neighbouring bidding area. In this way, it is not always clear who the buyer and the seller of the electricity is, as the data only shows physical electricity flows from one bidding area to its neighbouring bidding areas. This is however a feature of the market pool and cannot be bypassed. In this way, electricity being sold from for instance $DK2$ to *SE3* will be registered both as an import and as an export in at least one bidding area in between, through which the electricity has to flow.

### 7.1.2 Distances

For the distances between jurisdictions, Antweiler uses population weighted harmonic averages based on populations and geographic locations of postal codes. The approach in this thesis, is to find the linear distance between the most populous cities in the bidding areas measured in km. Amundsen and Bergman (2007) point out that there are no costs incurred by trading across borders, though they do argue that different prices in the individual bidding areas reflect the congestion charges. Furthermore, the physical transmission of electricity leads to electricity losses, increasing with distance (Prentiss 2015).

## 7.2 Data handling

The estimation of the main regression follows the methods Antweiler uses in his journal article (2016*a*).

In this way data has been aggregated to monthly levels, for each trading pair's imports as well as exports seen from both perspectives. Demand and supply for the individual bidding areas have also been aggregated to the monthly levels. This leads to two observations for each trading pair at every point in time entering the data-set. For instance, would there for the trade between *DK2* and *SE4* in June 2013 both be an observation showing the export from *DK2* to *SE4* and an observation showing the export from *SE4* to *DK2*.

For the demand correlations and standard deviations Antweiler (2016*a*) uses a rolling 36-month window. Given that my data only covers 71 months in total, I have decided to use a rolling 24-month window.

Regarding capacity, Antweiler looks at generation data, instead of the installed capacity. He argues that this is superior to nominal capacity. The reason for this is, that some countries are having a lot of back-up capacity, for instance for their renewable generation units, which might never be used. In order to find the maximum capacity available, I found the highest monthly generation over a rolling time period. My approach is similar to the one named for the correlations and standard deviations, and I am therefore also here using a rolling 24-month value, finding the maximum value in this period.

For the comparative advantage variable, the thesis uses annual data on the capacities installed in Denmark, Finland, Norway and Sweden, sorted into renewable energy, hydro energy, nuclear energy and thermal energy. The data source of the data is ENTSOE (2017*b*) for Denmark, Finland and Norway, while I retrieved Swedish data from Svensk Energi (2016). The data is on the installed capacity on a per bidding area level. Though for some of the Danish, Finnish and Norwegian bidding areas, data was only available for the period 2015-2017. Due to rather little change over time in relative installed capacity, I have chosen to use 2015 data for the time period 2011-2014 in the case of missing data. For the Swedish bidding areas data was only available from 2013-2017. Here I applied the 2013 data on to 2011 and 2012.

### 7.2.1 Frequency of observations

The data provided ranges in the frequency of observations from hourly data, up to annual data. In this subsection, I will discuss the benefits and drawbacks of using the different frequencies.

The benefit of working with high frequency data, such as hourly data, is that you get a very detailed picture of the trade flows. However, having small time intervals can make it difficult to detect trends and other insights from the data, which develop over a longer time horizon. Too low frequencies of observations, for instance monthly, though make it difficult to detect some of the daily patterns as they get lost in the aggregation of trade.

The decision on whether to proceed with daily observations in trade, hourly observations or even further aggregating the daily data, is made based on the trading patterns of the two market participants. Since the trading direction can change within a day, some information would be lost when aggregating the data of each jurisdiction to a month or a year. As Antweiler uses monthly data, I follow his approach.

## 7.3 Differences to the Antweiler model

In this section I will point out the differences in the data compared to the Antweiler model, which should be kept in mind when comparing the regression results.

While it cannot be seen directly from the data, the main difference is that the main assumption of convex marginal cost curves has to be relaxed, when applying the model to the Nord Pool market. This is due to the high share of bidding areas, who produce a significant amount of their electricity in hydro plants. With almost one hundred percent installed hydro power, merit-order curves and marginal cost curves become constant, reducing the "benefits from trade due to increasing marginal costs under higher load ratios".

A major difference in the data is the way in which the trade is registered. In the data Antweiler uses when applying the model to the North American market, he is able to identify the origin and the final destination of the electricity sold on a state to province/territory-level. The data from the Nord Pool group, shows the trade from one bidding area into its neighbouring bidding areas. For instance would electricity from the bidding Area *DK2* to the bidding area *SE3* have to go through at least the bidding area *DK1* or *SE4* in order to reach its destination. Due to the electricity market being an exchange in the countries I am researching, it can be argued that buyers and sellers as such do not exist, as everyone sells and buys to and from the market pool.

Furthermore, my data-set does not include trade with countries that are not part of the study, which creates an outside factor. This is not the case in the Antweiler paper, due to trade with Mexico being very limited (US Energy Information Administration 2013), such that it only leaves the two countries, the USA and Canada, who are part of the study.

Another difference in the data is the way the distance between jurisdictions is measured. While Antweiler uses a harmonic population-weighted average, I am using the distance from the most populous city in the exporting bidding area to the most populous city in the importing area. Distances can be found in table 12 in the appendix. Due to the shorter time-span of observations available I am using a 24-month rolling average for the standard deviations and correlations, where Antweiler uses a 36-month rolling average. The same applies to the maximum capacity, which I identify by finding the highest generation in a 24-month period around the date of interest, while Antweiler uses a 36-month period.

# 8 Empirical Analysis

For the regression model, I follow the theory developed by Antweiler (2016*a*). Applying the main regression from equation (5) on the Nordic data, I am able to compare the results to the results derived by Antweiler for the U.S.-Canada cross-border trade.

## 8.1 Bilateral trade in electricity

Table 2 gives an overview of the data, being used for the following regressions. It only holds the load ratios and the generation technologies once, due to the fact that every importing bidding area also takes on the role of an exporting bidding area. Hence the results for importing and exporting load ratios are the same. As the load ratios and the generation technology shares are expressed as a share of a total, they are within the range [0,1]. As the variable *Export/Joint capacity* is expressed as the export over the harmonic average capacity, values higher than 1 can occur. The *Distance* variable is expressed in km.

**Table 2:** *Monthly summary statistics*

| | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Export/Joint capacity | 2840 | .101601 | (.2067061) | 0 | 1.721943 |
| Load ratios | 2840 | .7331767 | (.1586871) | .2499387 | 1 |
| Distance | 2840 | 445.5 | (232.7779) | 29 | 1091 |
| Demand variability | 2840 | .1188831 | (.0999362) | .0088545 | .4228054 |
| Hydro share | 2840 | .5982148 | (.3951366) | 0 | 1 |
| Nuclear share | 2840 | .0772443 | (.1720308) | 0 | .5252735 |
| Renewables Share | 2840 | .1238596 | (.1330765) | 0 | .492293 |
| Time | 2840 | 36 | (20.49751) | 1 | 71 |
| *N* | 2840 | | | | |

Using the data described in the summary statistics, the main estimation equation from the Antweiler model will be applied in the following regression. Table 3 shows the regression run as an ordinary least square regression (OLS), a fixed effects regression (F.E.) and a random effects regression (R.E.). The results from the North American market from the Antweiler paper can be seen in figure 9 in the appendix.

The results from the OLS regression show significance at the 99%-level for the *Importer load ratio* as well as for the *Exporter load ratio.* The signs of the coefficients though show the opposite direction of both the Antweiler results, as well as the intuition developed in the theoretical framework. Following the results from the regression, an increase in the exporter's load ratio, increases the expected amount of *Export/Joint capacity.* An increase in the importer's load ratio on the other hand decreases the expected amount of *Export/Joint capacity.* The *Distance* coefficient is significant at the 95%-level. Having a negative coefficient, it has the expected direction. A 1% increase in distance hence leads a to 1.105% decrease in *Export/Joint*

**Table 3:** *Bilateral trade estimation results*

Dependent variable: ln export over joint capacity

| | (1) OLS | | (2) F.E. | | (3) R.E. | |
|---|---|---|---|---|---|---|
| ln importer load ratio | -1.247** | (-3.02) | -1.987*** | (-6.00) | -1.983*** | (-6.04) |
| ln exporter load ratio | 1.804*** | (4.58) | 2.447*** | (7.05) | 2.444*** | (7.08) |
| ln distance | -1.105* | (-2.41) | 0 | (.) | -0.864** | (-2.65) |
| ln demand variability | 0.503 | (1.67) | 0.172 | (1.25) | 0.176 | (1.26) |
| Importer hydro share | -2.511 | (-1.08) | | | | |
| Importer nuclear share | -0.748 | (-0.23) | | | | |
| Importer renewables share | -0.235 | (-0.05) | | | | |
| Exporter hydro share | 8.390*** | (6.58) | | | | |
| Exporter nuclear share | 10.04*** | (4.03) | | | | |
| Exporter renewables share | 16.40*** | (4.66) | | | | |
| Time | -0.00170 | (-0.50) | | | | |
| Constant | -2.145 | (-1.31) | -3.253*** | (-8.66) | 1.582 | (0.84) |
| Observations | 2512 | | 2512 | | 2512 | |
| $R^2$ | 0.337 | | 0.133 | | | |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

*capacity*. Demand variability is not significant at the 95%-level. Having a positive coefficient, it though follows the theory, leading to an outcome in which lower correlation or higher standard deviations in demand or both increase *Export/Joint capacity*. The generation capacity shares are only significant for the exporter's shares, here though at the 99.9%-level. Furthermore, the importer and the exporter shares have opposite directions, which makes intuitive sense. The results show that an increase in the share of either of the three generation technologies, holding the other two constant, increases the *Export/Joint capacity*. The fixed effect and the random effect regression results have the same directions for the coefficients, and confirm the results found in the OLS regression.

## 8.2 Bilateral trade in electricity grouped by merit-order curve

In order to account for the differences in merit-order curves between the Nordic countries and the USA and Canada, I will in this section rerun the OLS regressions with the bidding areas, grouped as defined in section 4.6 into either constant (cons.) or convex (conv.) merit-order curves. Having them grouped into three groups on both the importer and exporter side, leads to nine combinations, of which one is the full regression with all bidding areas on the importer as well as on the exporter side. The trade between the *convex* bidding areas resembles the case, which is closest to the assumptions presented in the Antweiler model. The results are shown in table 4.

The results show that the opposite sign for the load ratio's coefficients is also present in all eight sub-samples of the main regression. This is especially for the sub-sample *conv.-conv.* counterintuitive, as this sub-sample resembles the North American data the closest, due to convex marginal cost curves. However, the high integration of the convex merit-order curve bidding areas into a market pool, with almost 50% hydro energy, is likely to influence the trading behaviour, even for the bidding areas which do not directly rely on hydro energy.

## 8.3 Econometric considerations

For the OLS regressions on bilateral trade in electricity I assume independence between bidding areas, but correlation between observations within a bidding area. Hence, I use the cluster for the standard errors, with respect to bidding area, when running the regression in STATA (Wooldridge 2015). The Hausman test results in table 5 show that the null hypothesis is not rejected, such that there is no significant difference in the fixed effect and random effect estimates. Due to the smaller residuals, the random effect regression should hence be preferred. In this case though the difference is rather small (Wooldridge 2015).

## 8.4 Load pooling

Following the Antweiler (2016*a*) journal article, I will in this section analyse the benefits which can be achieved by having a fully integrated electricity grid. In the section *The gains from electricity trade* in the (Antweiler 2016*a*) journal article, Antweiler analyses the benefits from pooling loads by comparing a setting in which all states, provinces and territories are connected with each other, with a setting in which every state, province and territory is self-sufficient. The benefits are achieved in line with portfolio theory due to

**Table 4:** *Monthly bilateral trade estimation OLS regression with merit order-curve grouped bidding areas*

Dependent variable: ln export over joint capacity

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | cons.-cons. | cons.-conv. | conv.-cons. | conv.-conv. | cons.-both | conv.-both | both-conv. | both-cons. | all |
| ln importer load ratio | -0.962 | -2.406 | -0.899 | -1.349* | -1.032 | -1.842*** | -2.183** | -0.790 | -1.247** |
| | (-1.72) | (-2.49) | (-1.30) | (-2.40) | (-1.73) | (-5.48) | (-3.47) | (-1.68) | (-3.02) |
| ln exporter load ratio | 1.762** | 0.756 | 4.047* | 1.783* | 1.514** | 2.614*** | 2.157** | 1.801** | 1.804*** |
| | (3.62) | (0.68) | (2.88) | (2.74) | (3.44) | (4.35) | (3.70) | (3.38) | (4.58) |
| ln distance | -0.851 | -9.005*** | -0.824 | -0.449 | -1.004 | -0.679 | -0.915 | -1.128 | -1.105* |
| | (-1.06) | (-32.27) | (-0.84) | (-0.60) | (-1.15) | (-1.21) | (-1.50) | (-1.48) | (-2.41) |
| ln demand variability | 0.410 | 0.350 | -0.221 | 0.387 | 0.453 | 0.912 | 1.534 | 0.530 | 0.503 |
| | (1.13) | (0.80) | (-0.34) | (0.70) | (1.15) | (1.48) | (2.08) | (1.60) | (1.67) |
| Importer hydro share | 2.965 | 25.68 | 17.56** | 6.090 | 2.697 | -3.643 | -3.395 | 6.000 | -2.511 |
| | (0.25) | (1.04) | (5.76) | (0.25) | (0.51) | (-1.57) | (-1.23) | (0.51) | (-1.08) |
| Importer nuclear share | 0 | -5.817 | -17.24 | -9.016 | 6.818 | -4.259 | -1.665 | 13.10 | -0.748 |
| | (.) | (-0.76) | (-0.43) | (-1.27) | (1.01) | (-1.31) | (-0.45) | (0.81) | (-0.23) |
| Importer renewables share | 18.12 | -0.231 | 6.395 | -10.17 | 11.69 | -3.575 | 0.669 | 19.89 | -0.235 |
| | (1.07) | (-0.01) | (0.70) | (-1.42) | (1.15) | (-0.75) | (0.11) | (1.23) | (-0.05) |
| Exporter hydro share | -4.248 | -20.22 | 53.92 | 0.569 | -4.056 | 10.61*** | 9.428** | 5.002 | 8.390*** |
| | (-0.33) | (-1.95) | (1.41) | (0.02) | (-0.31) | (8.10) | (4.09) | (1.83) | (6.58) |
| Exporter nuclear share | 0 | -71.42 | 20.89 | 7.650 | -9.819 | 8.190*** | 10.10* | 5.046 | 10.04*** |
| | (.) | (-2.62) | (1.58) | (1.04) | (-0.54) | (4.49) | (2.61) | (1.22) | (4.03) |
| Exporter renewables share | -10.48 | -24.52 | 51.22 | 8.987 | -5.883 | 17.22*** | 18.72** | 11.10 | 16.40*** |
| | (-0.64) | (-2.07) | (1.55) | (1.35) | (-0.37) | (5.72) | (3.19) | (2.03) | (4.66) |
| Time | 0.000135 | 0.0217* | -0.00733 | 0.00693 | 0.00108 | -0.00339 | -0.00193 | -0.00747 | -0.00170 |
| | (0.02) | (3.92) | (-0.71) | (0.82) | (0.17) | (-0.77) | (-0.47) | (-1.38) | (-0.50) |
| | 2.989 | 71.27** | -39.69 | 0.0942 | 4.031 | -2.105 | -2.192 | -7.038 | -2.145 |
| | (0.18) | (4.82) | (-2.02) | (0.01) | (0.27) | (-1.21) | (-1.18) | (-0.58) | (-1.31) |
| *N* | 1196 | 334 | 332 | 546 | 1530 | 878 | 880 | 1528 | 2512 |
| $R^2$ | 0.115 | 0.795 | 0.773 | 0.739 | 0.177 | 0.694 | 0.589 | 0.256 | 0.337 |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

non-perfect correlation between bidding areas, which allows jurisdictions to share each other's generation capacity.

Given that the thesis is analysing the trade between the individual bidding areas, the market is not in the extreme where each bidding area is self-sufficient. On the other hand, price differences in the Nord Pool bidding areas, identify situations in which transmission capacity was smaller than what would have been needed for the optimal load pooling. Evidence from the (Nordic Energy Regulators 2014) report shows that price differences were present in the Nordic markets in more than 75% of the time in 2013.

The results from the comparison between a pooled market and self-sufficient bidding areas in the Nordic market can be seen in table 6. The table shows the demand and the supply in every bidding area on a monthly level in GWh. The row *All 12 BA* shows the sum of the individual average demand and supply. The

**Table 5:** *Hausman test results*

| | |
|---|---|
| Chi-Squared | 0.57 |
| Prob-Squared | 0.9033 |

standard deviation is the sum of the standard deviations of the twelve bidding areas. The margin is based on the maximum demand, which is found as the sum of the twelve bidding areas' maximum demands. For the row *(pooled)* the average demand is the same as for *All 12 BA*. The standard deviation is however found as the standard deviation of the sum of the twelve bidding areas' demand over time. The margin is also based on the highest pooled demand. The highest pooled demand is smaller than the sum of the highest individual demands in the case of not all twelve bidding areas having had their peak demand in the same month.

The possible savings in back-up capacity amount to the difference in back-up capacity for the two scenarios. Following Antweiler, the back-up capacity is determined as the difference between the mean demand and the peak demand. It can hence be found when multiplying the standard deviation of demand with the margin. In the self-sufficient setting the back-up capacity is $5245GWh * 2.292 = 12,019GWh$ while it is $5060GWh * 2.064 = 10,445GWh$ in a fully integrated network, leading to a saving of $12,019 - 10,445 = 1574GWh$ per month. This is approximately a 13% reduction, compared to the state in which bidding areas are self-sufficient. 1,574 GWh[8] a month, correspond to a 2,157 MW generation facility running at full capacity.

The results from load pooling show that despite the Nordic countries having a high demand correlation, cross-border trade allows to reduce the amount of needed back-up generation capacity by 13%.

[8] $\frac{2157MW*24hours*365days}{12months} = 1574GWh/month$

**Table 6:** *Load pooling in the Nordics*

| Bidding area | Demand | Std.Dv. | Supply | Surplus | Margin |
|---|---|---|---|---|---|
| DK1 | 1647 | 130 | 1695 | 48 | 2.437 |
| DK2 | 1110 | 117 | 732 | -377 | 2.234 |
| NO1 | 3015 | 861 | 1925 | -1090 | 2.045 |
| NO2 | 2875 | 459 | 4196 | 1321 | 2.195 |
| NO3 | 1898 | 277 | 1419 | -480 | 2.248 |
| NO4 | 1543 | 231 | 2025 | 482 | 2.015 |
| NO5 | 1401 | 254 | 2362 | 961 | 2.593 |
| SE1 | 838 | 147 | 1791 | 953 | 2.344 |
| SE2 | 1351 | 232 | 3464 | 2114 | 2.709 |
| SE3 | 7219 | 1275 | 6949 | -271 | 2.157 |
| SE4 | 2028 | 364 | 621 | -1406 | 1.956 |
| FI | 6865 | 896 | 5417 | -1448 | 2.580 |
| All 12 BA | 31789 | 5245 | 32595 | 806 | 2.292 |
| (pooled) | | 5060 | | | 2.064 |

Note: Analysis is based on 2011-2017 period using monthly data. All but the last columns report figures in GWh per month. The column *Margin* reports the difference between the maximum demand and the average demand in units of demand standard deviation.

Source: Author with data from Nord Pool Group (2017*e*)

# 9 Discussion

When comparing the regression results with the Antweiler regression results, some main differences in the characteristics of the two markets should be kept in mind.

Looking at the demand side, the electricity trade in the North American market is mainly driven by differences in demand across jurisdictions. For instance, California and British Columbia have different demand patterns, as they are both affected differently by the seasons. Furthermore, the longitudinal distances are big enough, as that demand differences also occur on a diurnal pattern, due to the U.S. East Coast being three hours ahead of the West Coast[9]. In the Nordics, the correlation in demand is higher, due to the jurisdictions being geographically closer. This leads to peak demands being around the same time in all twelve bidding areas on a diurnal level as well as with regards to the seasons. The difference in demand fluctuations can be seen when comparing the monthly correlations among bidding area demand found in table 13 in the appendix with the table TA-3 found in the technical appendix of the Antweiler paper (Antweiler 2016*b*).

On the supply side the North American electricity market and the Nordic electricity market differ as well. While the supply side is rather stable in the North American market, the high share of intermittent renewable energy sources in the Nordics leads to a different situation. The supply sides influence on two-way trade in electricity is relatively larger in the Nordics than in the North American market.

As one of the main assumptions of the Antweiler model is that marginal cost curves are convex, which they are in a scenario with convex merit-order curves, this assumption does not hold for the Nordics. As the assumption does not hold, the driver behind trade incentives given higher load ratios is no longer present. In the setting with constant marginal cost curves, a higher load ratio does not increase the marginal cost of electricity generation, such that other jurisdictions no longer gain a competitive advantage from a jurisdictions higher load ratio. In a setting in which marginal costs are constant, due to a large amount of installed capacity in hydro power plants, the opposite might be the case. As Antweiler explains in his paper, a jurisdiction with marginal costs that always are lower than the marginal cost curves of their trading partners, would only export. With hydro power, there is a generation technology which has lower marginal cost curves than generation technologies such as thermal and nuclear generation. Being able to utilise the hydro power is though also dependent on factors such as precipitation and the water level of the reservoir. As such the competitive advantage from hydro power could change with a seasonal component. In this case the comparative advantage resulting from lower marginal cost curves would change throughout the year, leading to a period dominated by one-way trade and a period possibly allowing for two-way trade.

While the electricity trade in the North American market is being driven by the demand side, the Nordic market is driven relatively more by the supply side, due to high correlations in demand. Furthermore, the high share of hydro in the market influences the merit-order curves to such a degree, that the main assumption of the Antweiler model no longer holds. Taking these features of the comparison of the two markets into account, the opposite signs for the load ratios describe a different characteristic of electricity trade. The Antweiler theory describes a causal relationship between two jurisdictions' load ratios and their trade with each other. Due to the main assumption for this causality, the convex marginal cost curves,

[9] Due to separation into interconnection areas, real East Coast - West Coast trade does not take place.

not holding in the Nordic countries, the coefficients should be viewed as indicators of correlation, rather than interpreting a causal effect. Analysing the correlation, without the Antweiler theoretical framework explaining causation, the regression results show that higher export is correlated with a higher load ratio in the exporting country, and a lower load ratio in the importing country. Assuming that a jurisdiction in fact is able to utilise its hydro power, thereby having a static comparative advantage due to lower marginal costs, without the risk of depleting reservoir levels, it might be in the generating utilities' best interest to utilise the full capacity, depending on the market price for electricity. In this situation, the positive correlation between exports and the exporting jurisdiction's load ratio is hence explained by the static comparative advantage following from constant marginal cost curves. It can then be argued that a high load ratio in the importing country diminishes export opportunities as the importing country is more likely to be self-sufficient.

Unlike the regression consisting of all bidding areas, the results from some of the sub-group regression swith bidding areas grouped into *convex* and *constant* merit-order curves, would be expected to produce results in line with the Antweiler theory. Especially the sub-group, only looking at trade between bidding areas with *convex* merit-order curves, is expected to be close to the Antweiler theory. However, the regression results for load ratios do in this case also show the opposite signs. Due to the bidding areas being part of the highly integrated Nordic market, the high share of hydro power likely changes the trade dynamics of the entire market, thereby also influencing trade between bidding areas without hydro power installed.

The results from the load pooling show that investments into transmission capacity are capable of reducing the amount of overall installed generation capacity. While the analysis cannot identify where in between the two extremes the Nordic countries are to be placed, the data from the Nordic Energy Regulators (2014) market report shows, that the region in only 23.4% of the time has a single market price, corresponding to a fully integrated market. Following from this, it shows that further investments into transmission capacity would have a positive impact on the optimal allocation of electricity between bidding areas. The analysis though leaves out the costs of installing more transmission capacity, which should be held up against the savings from a reduction in back-up capacity. Leaving the financial perspective aside, investments into transmission capacity extensions can further work as a catalyser for a reduction in greenhouse gas emissions. This would be the case when higher interconnection capacity leads to a reduction in local thermal back-up capacity, allowing renewables to be implemented more efficiently into the grid.

# 10 Robustness

In order to check whether the regression results for the control variables also hold when working with the data under different circumstances I am rerunning the Antweiler model with Nordic market data on a daily level, as well as with seasonal dummy variables.

Running the regression with daily data could provide some more insights on the robustness of the coefficient estimates. In addition to this, the daily trade data can also provide more details on the trade in the Nordics. As some of the produced energy comes from intermittent energy sources, some of the directional changes in trade, which occur on a daily level, are lost when the data is aggregated to a monthly level. In this way, the data level does not only check the robustness of the coefficients but could possibly also identify further characteristics of the cross-border trade in the Nordics. In order to have the results being as comparable to the monthly regressions as possible, the methodology follows the same approach[10].

Table 14 in the appendix shows the summary statistics of the variables used in the regressions. They follow the monthly summary statistics closely, though with some minor differences with respect to the mean and the standard deviations in the variables *Load ratio*, *Demand variability* and *Export / Joint capacity.*

The regression run with daily data shows similar results to the regression run with monthly data. The table can be found in the appendix under table 15. The same coefficients are significant, with the addition of the *Importer hydro share* using daily observations, running the OLS model. The significance of the negative importer hydro share coefficient, indicates that exporters export more to countries with a relatively lower hydro share.

The regression run with daily data and bidding areas grouped into either being *convex* or *constant* can be found in table 16 in the appendix. The results from this regression are also similar to the ones for monthly data. The main variables of interest *Importer load ratio*, *Exporter load ratio*, *Distance* and *Demand variability* do not change significantly when comparing the results.

Having run the regression with both monthly and daily data, without the coefficients being affected by it, shows that the estimates are robust with respect to the chosen frequency of observations.

Another appropriate robustness check is the inclusion of seasonal dummies. As hydro power, photovoltaic power and wind power all include some seasonality, including these dummies controls for that. The results from running the OLS regressions on monthly and daily data with various seasonal dummies can be found in the appendix in table 17 and table 18 respectively. Also here, the main coefficients of the regressions are unaffected by the inclusion of seasonal dummies. It is though worth noting that the spring dummy[11] in the third regression with daily data is significant. In this regression the spring is held up against the rest of the year. Interesting about the spring is, that hydro reservoir levels reach their lowest annual level during this period of the year. The coefficient for the dummy variable is negative, indicating that the expected export during the spring is significantly lower than throughout the rest of the year.

[10]While the monthly data uses a 24-month rolling average for the demand standard deviation and a 24-month rolling maximum for the maximum capacity, the daily data uses a 365-day rolling average and 365-day rolling maximum. Even though this data only covers one year, it ensures that an annual reoccurring peak or low does not fall out of the rolling window.

[11]Spring dummy: 1 for April, May and June, 0 otherwise.

# 11 Conclusion

Using the Antweiler model in a different empirical setting shows that there are a lot of factors that are worth some further research. The main results from applying the Antweiler model on the Nordic electricity market show that a higher load ratio in the exporting country increases the export over joint capacity, all else being equal. A higher load ratio in the importing country, decreases the export over joint capacity in the exporting country, all else being equal.

With the results being the opposite direction of the results of the Antweiler (2016*a*) paper, they show how the high share of hydro power energy in all of the Norwegian bidding areas, two of the Swedish bidding areas and the Finish bidding area not being in line with the assumption of convex marginal cost curves, impacts the drivers behind electricity trade. In the absence of convex marginal cost curves trade is driven by other factors than differences in current load levels. The drivers behind the trade in the Nordics are hence different to the drivers in the North American market due to the static comparative advantage hydro power generators possess.

Furthermore, the high integration of the market into a common electricity trading exchange, leads to a situation in which producers face the entire pool, instead of just the bidding area they will physically engage in trade with. In this way, the Nordic electricity market is to a lower degree than the North American market driven by convex marginal cost curves.

Due to all these differences, the results of the Nordic market should not be compared directly to the North American market, due to rather different drivers behind the trade and due to relaxing the convex cost curve assumption when applying the model to the Nordic electricity market.

The results from the load pooling analysis paired with data on congestion and different prices throughout the bidding areas show that investments into further transmission capacity would decrease the need for back-up capacity throughout the Nordic countries. Sharing the back-up capacity with other bidding areas rather than relying on self-sufficient back-up, also opens opportunities for reductions in greenhouse gas emissions, by trading polluting back-up generation capacity off with higher transmission capacity. Not taking the investment costs held up against the savings, due to lower back-up capacity, into account, the analysis identifies a significant opportunity for capacity reductions. Furthermore, higher transmission capacities increase the degree to which intermittent energy sources, such as wind power and photovoltaics, are integrated, as the higher capacity increases the size of the potential market, thereby decreasing the risk of negative prices, due to an overproduction.

Following from the results of the thesis I will in the following present some areas which are worth some future research. As a high market integration of the bidding areas is present in the Nordics, and as bids and offers are placed at an exchange rather than being bilateral, it would be worthwhile to look at a bidding area's trade with the entire market pool. Instead of looking at export to a specific other bidding area, one could look at a bidding area's export to the market pool consisting of the residual bidding areas and vice versa for the imports. This would make the model a better fit for the actual structure of the Nord Pool area, as this is a better replication of the actual trade taking place. This is due to the decisions made by producers in the bidding areas, being not only impacted by their adjacent bidding areas, but by the entire Nord Pool, such that the aggregate demand and the aggregate supply in the Nord Pool also influence their decision making. The application of this is possible with the data available from the Nord Pool Group. This application would in addition be able to solve the issue of not being able to identify the final destination of electricity in the Nord Pool trade data, as the pool would serve as the trading partner.

Furthermore, the researched area could be expanded to the entire Nord Pool area, though with shorter time series, due to the Baltic countries joining after 2011. The Antweiler theory could also be applied to the entire European market, thereby being less affected by the high share of hydro power in the Nordics.

Another addition to the Antweiler model could be a higher focus on the impact of the hydro reservoir levels and the generation from photovoltaic and wind energy. By implementing these variables, possibly at an hourly level, trade patterns resulting from the intermittency of some of the renewable energy sources could be researched within the Antweiler (2016*a*) theoretical framework.

# 12 Bibliography


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# A Appendix

**Table 7:** *Watt prefixes*

| Prefix | Symbol | Multiplicator |
|---|---|---|
| Kilo | kW | $10^3$ |
| Mega | MW | $10^6$ |
| Giga | GW | $10^9$ |
| Tera | TW | $10^{12}$ |

Source: Author

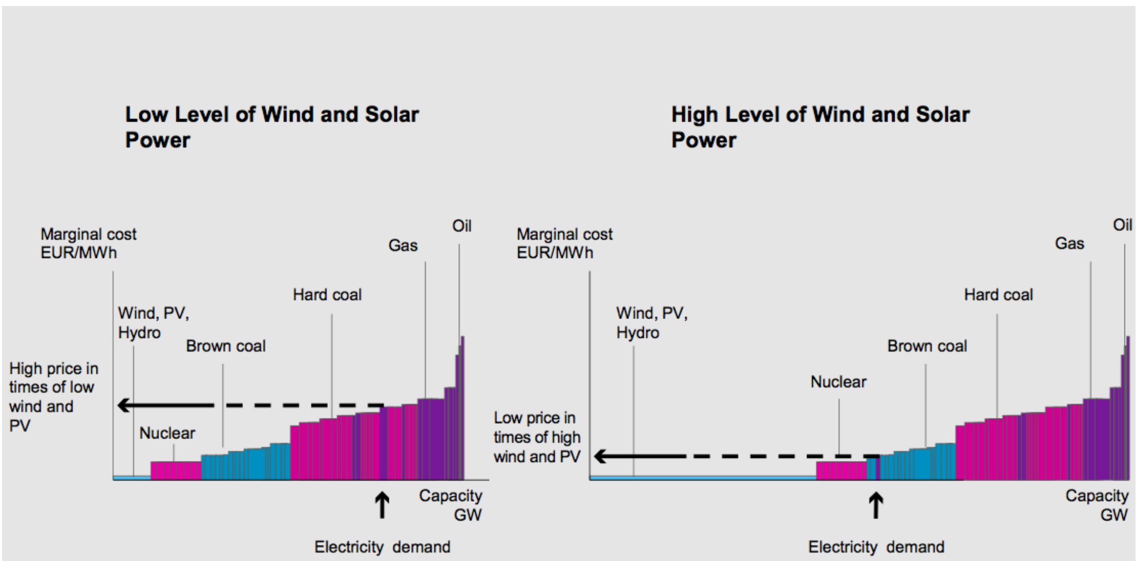


**Figure 8:** *Merit-order curves*
Source: Cleantechnica (2013)

**Table 8:** *Trade with countries outside of the Nordics*

| Year | Trade flow | Reporter | Partner | MWh | Share of trade |
|---|---|---|---|---|---|
| 2016 | Import | Denmark | World | 13,144,542 | 0.62 |
| 2016 | Export | Denmark | World | 8,087,631 | 0.38 |
| 2016 | Import | Denmark | Germany | 4,476,297 | 0.21 |
| 2016 | Export | Denmark | Germany | 2,323,248 | 0.11 |
| 2016 | Import | Finland | World | 22,111,403 | 0.88 |
| 2016 | Export | Finland | World | 3,135,564 | 0.12 |
| 2016 | Import | Finland | Estonia | 660,842 | 0.03 |
| 2016 | Export | Finland | Estonia | 3,027,056 | 0.12 |
| 2016 | Import | Finland | Russia | 5,857,593 | 0.23 |
| 2016 | Export | Finland | Russia | 456 | 0 |
| 2016 | Import | Norway | World | 3,779,404 | 0.22 |
| 2016 | Export | Norway | World | 13,612,085 | 0.78 |
| 2016 | Import | Norway | Netherlands | 184,984 | 0.01 |
| 2016 | Export | Norway | Netherlands | 2,656,705 | 0.15 |
| 2016 | Import | Norway | Russia | 44,474 | 0 |
| 2016 | Export | Norway | Russia | 15 | 0 |
| 2016 | Import | Sweden | World | 14,280,000 | 0.36 |
| 2016 | Export | Sweden | World | 25,837,000 | 0.64 |
| 2016 | Import | Sweden | Germany | 797,000 | 0.02 |
| 2016 | Export | Sweden | Germany | 1,491,000 | 0.04 |
| 2016 | Import | Sweden | Lithuania | 116,000 | 0 |
| 2016 | Export | Sweden | Lithuania | 2,378,000 | 0.06 |
| 2016 | Import | Sweden | Poland | 175,000 | 0 |
| 2016 | Export | Sweden | Poland | 2,758,000 | 0.07 |

Source: Author with data from COMTRADE (2017)

**Table 1**
Bilateral trade estimation results.

| Trade direction | | Both | | Both | | Exports | |
|---|---|---|---|---|---|---|---|
| Intercept | | 0.347 | (1.64) | $-1.681^{c}$ | (7.52) | $-0.404$ | (.970) |
| Importer load ratio | $\ln(q_j/K_j)$ | $0.701^{c}$ | (8.37) | $1.139^{c}$ | (7.34) | $0.616^{c}$ | (6.01) |
| Exporter load ratio | $\ln(q_i/K_i)$ | $-0.993^{c}$ | (11.5) | $-0.498^{c}$ | (6.00) | $-1.937^{c}$ | (10.7) |
| Multilateral resistance | $\ln(q_i^-/K_i^-)$ | | | | | $-0.053$ | (.402) |
| Transmission distance | $\ln(D_{ij})$ | $-2.410^{c}$ | (60.5) | $-2.174^{c}$ | (47.9) | $-2.626^{c}$ | (45.9) |
| Demand variability | $\ln(V_{ij})$ | $0.922^{c}$ | (17.1) | $0.342^{c}$ | (4.89) | $0.634^{c}$ | (7.17) |
| Importer hydro share | % | $-0.009^{c}$ | (10.4) | | | $-0.012^{c}$ | (7.65) |
| Importer nuclear share | % | $-0.006^{c}$ | (4.04) | | | $0.012^{c}$ | (5.97) |
| Importer renewables share | % | $-0.000^{c}$ | (6.18) | | | $0.044^{c}$ | (8.35) |
| Exporter hydro share | % | $0.013^{c}$ | (15.7) | | | $0.010^{c}$ | (8.10) |
| Exporter nuclear share | % | $-0.004^{b}$ | (2.84) | | | $-0.009^{c}$ | (4.33) |
| Exporter renewables share | % | $0.000^{c}$ | (5.64) | | | 0.000 | (.867) |
| Time trend | | $-0.015$ | (1.90) | $-0.016^{a}$ | (2.47) | $-0.006$ | (.646) |
| Observations | | 8819 | | 8819 | | 4827 | |
| Exporter & importer F.E. | | No | | Yes | | No | |
| $R^2$ | | 0.410 | | 0.494 | | 0.518 | |

Note: Statistical significance at the 95%, 99%, and 99.9% confidence levels are indicated by superscripts $^{a}$, $^{b}$, $^{c}$, respectively. Standard scores (unsigned z-values) are shown in parentheses.

**Figure 9:** *Main regression results from Antweiler (2016a)*
Source: Antweiler (2016*a*)

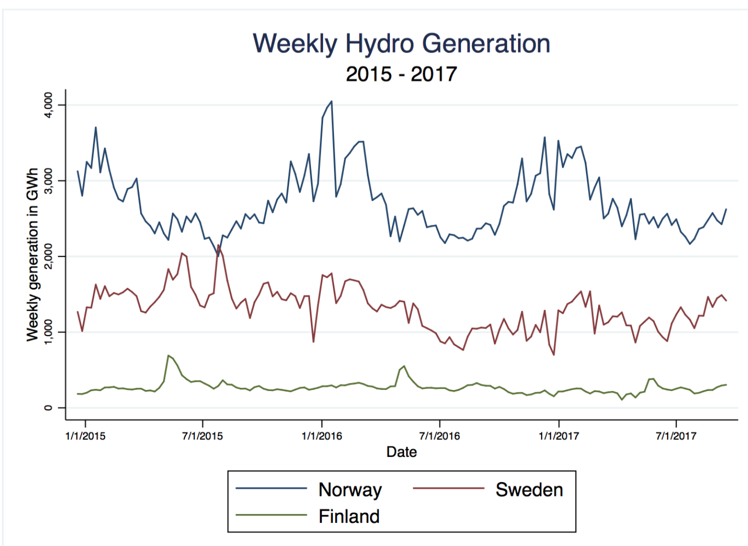


**Figure 10:** *Weekly hydro generation*
Source: Author with data fromNord Pool Group (2017*e*)

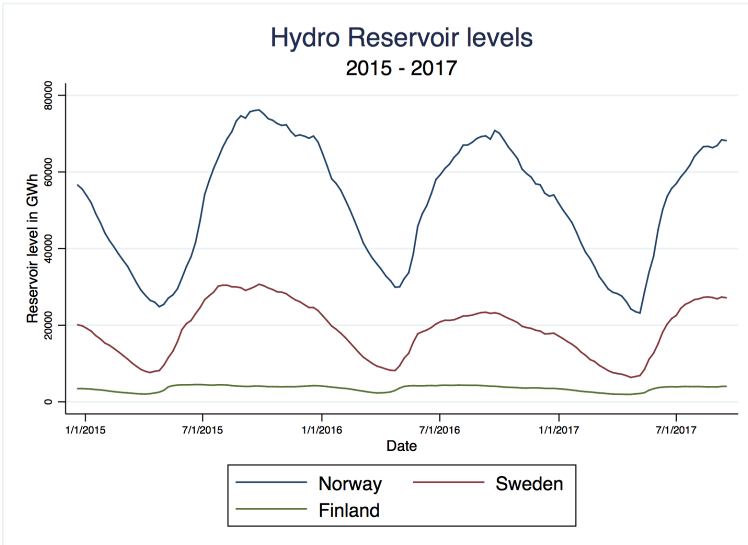


**Figure 11:** *Weekly hydro levels*
Source: Author with data fromNord Pool Group (2017*e*)

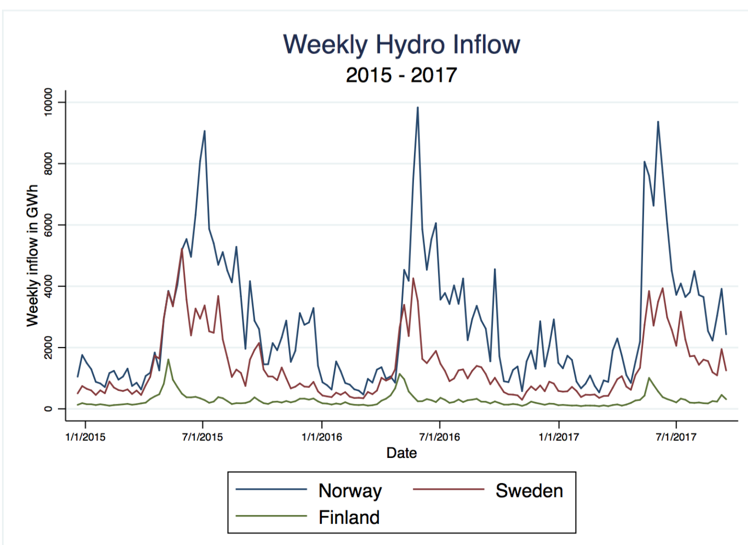


**Figure 12:** *Weekly hydro inflow*
Source: Author with data fromNord Pool Group (2017*e*)

**Table 9:** *Monthly demand and supply per bidding area*

| | Demand | | | | Supply | | | |
|---|---|---|---|---|---|---|---|---|
| Bidding area | Minimum | Maximum | Median | Average | Minimum | Maximum | Median | Average |
| DK1 | 1390 | 1965 | 1598 | 1647 | 960 | 2911 | 1663 | 1695 |
| DK2 | 938 | 1371 | 1084 | 1110 | 299 | 1248 | 761 | 732 |
| NO1 | 1810 | 4775 | 2958 | 3015 | 1022 | 3480 | 1665 | 1925 |
| NO2 | 2209 | 3883 | 2836 | 2875 | 2124 | 6098 | 4429 | 4196 |
| NO3 | 1453 | 2521 | 1882 | 1898 | 749 | 2332 | 1421 | 1419 |
| NO4 | 1108 | 2009 | 1560 | 1543 | 1504 | 2918 | 1973 | 2025 |
| NO5 | 945 | 2060 | 1398 | 1401 | 970 | 4155 | 2360 | 2362 |
| SE1 | 625 | 1182 | 835 | 838 | 1115 | 2495 | 1765 | 1791 |
| SE2 | 909 | 1978 | 1330 | 1351 | 1963 | 4633 | 3576 | 3464 |
| SE3 | 5281 | 9970 | 7218 | 7219 | 4350 | 9041 | 7081 | 6949 |
| SE4 | 1521 | 2741 | 2018 | 2028 | 295 | 1134 | 583 | 621 |
| FI | 5446 | 9177 | 6871 | 6865 | 4062 | 7093 | 5507 | 5417 |

Note: All values in GWh per month for the period: November 2011 - September 2017

Source: Author with data from Nord Pool Group (2017*e*)

**Table 10:** *Monthly production/demand*

| Bidding area | Minimum | Maximum | Median | Average | Swap |
|---|---|---|---|---|---|
| DK1 | 0.652 | 1.505 | 1.021 | 1.019 | 15 |
| DK2 | 0.301 | 0.971 | 0.677 | 0.644 | 0 |
| NO1 | 0.285 | 1.491 | 0.686 | 0.683 | 4 |
| NO2 | 0.961 | 1.745 | 1.487 | 1.446 | 2 |
| NO3 | 0.405 | 1.123 | 0.734 | 0.751 | 5 |
| NO4 | 1.032 | 1.654 | 1.330 | 1.315 | 0 |
| NO5 | 0.694 | 2.658 | 1.804 | 1.702 | 4 |
| SE1 | 1.515 | 3.073 | 2.177 | 2.164 | 0 |
| SE2 | 1.641 | 4.454 | 2.513 | 2.602 | 0 |
| SE3 | 0.755 | 1.296 | 0.954 | 0.966 | 26 |
| SE4 | 0.182 | 0.489 | 0.297 | 0.299 | 0 |
| FI | 0.692 | 0.901 | 0.789 | 0.787 | 0 |

Note: The column *Swap* shows how often a bidding area has changed from being importer to exporter or vice versa from one month to the next.

Source: Author with data from Nord Pool Group (2017*e*)

**Table 11:** *Share of total installed capacity by bidding area 2016*

| Bidding Area | Nuclear | Thermal | Hydro | Wind | Other renewable |
|---|---|---|---|---|---|
| DK1 | 0.000 | 0.507 | 0.001 | 0.405 | 0.087 |
| DK2 | 0.000 | 0.736 | 0.000 | 0.187 | 0.077 |
| FI | 0.177 | 0.452 | 0.198 | 0.069 | 0.106 |
| NO1 | 0.000 | 0.000 | 1.000 | 0.000 | 0.000 |
| NO2 | 0.000 | 0.039 | 0.937 | 0.024 | 0.000 |
| NO3 | 0.000 | 0.098 | 0.810 | 0.092 | 0.000 |
| NO4 | 0.000 | 0.052 | 0.901 | 0.048 | 0.000 |
| NO5 | 0.000 | 0.043 | 0.957 | 0.000 | 0.000 |
| SE1 | 0.000 | 0.044 | 0.872 | 0.085 | 0.000 |
| SE2 | 0.000 | 0.054 | 0.757 | 0.189 | 0.000 |
| SE3 | 0.517 | 0.240 | 0.138 | 0.106 | 0.000 |
| SE4 | 0.000 | 0.578 | 0.078 | 0.343 | 0.000 |
| All bidding areas | 0.124 | 0.250 | 0.471 | 0.127 | 0.029 |

Source: Author with data from ENTSOE (2017*b*) and Svensk Energi (2016)

**Table 12:** *Overview over bidding area pairs in the Nordics*

| Bidding Area | Distance | Min export | Max export | Mean export | Median export | SD |
|---|---|---|---|---|---|---|
| DK2-DK1 | 157 | 0 | 83 | 11 | 6 | 13 |
| DK1-DK2 | 157 | 86 | 394 | 251 | 260 | 76 |
| DK1-NO2 | 412 | 3 | 500 | 141 | 116 | 121 |
| NO2-DK1 | 412 | 38 | 814 | 429 | 438 | 186 |
| NO2-NO1 | 303 | 1 | 1875 | 769 | 777 | 511 |
| NO1-NO2 | 303 | 0 | 861 | 74 | 6 | 161 |
| NO3-NO1 | 390 | 0 | 177 | 31 | 14 | 39 |
| NO1-NO3 | 390 | 1 | 288 | 98 | 83 | 79 |
| NO5-NO1 | 306 | 9 | 2001 | 883 | 996 | 563 |
| NO1-NO5 | 306 | 0 | 126 | 8 | 0 | 20 |
| NO5-NO2 | 158 | 0 | 435 | 121 | 77 | 116 |
| NO2-NO5 | 158 | 0 | 311 | 36 | 20 | 56 |
| NO4-NO3 | 788 | 109 | 599 | 318 | 307 | 118 |
| NO3-NO4 | 788 | 0 | 3 | 0 | 0 | 1 |
| NO5-NO3 | 430 | 0 | 101 | 10 | 0 | 24 |
| NO3-NO5 | 430 | 0 | 139 | 13 | 0 | 31 |
| SE2-NO3 | 488 | 5 | 536 | 164 | 140 | 123 |
| NO3-SE2 | 488 | 0 | 245 | 68 | 47 | 63 |
| SE1-NO4 | 467 | 0 | 171 | 33 | 14 | 40 |
| NO4-SE1 | 467 | 10 | 387 | 175 | 167 | 90 |
| SE2-SE1 | 195 | 2 | 530 | 99 | 61 | 109 |
| SE1-SE2 | 195 | 68 | 1168 | 582 | 580 | 247 |
| NO4-SE2 | 634 | 0 | 134 | 40 | 35 | 29 |
| SE2-NO4 | 634 | 0 | 81 | 23 | 19 | 19 |
| SE3-SE2 | 525 | 0 | 345 | 43 | 10 | 71 |
| SE2-SE3 | 525 | 948 | 3787 | 2501 | 2467 | 723 |
| DK1-SE3 | 590 | 1 | 441 | 156 | 149 | 108 |
| SE3-DK1 | 590 | 0 | 424 | 118 | 79 | 105 |
| NO1-SE3 | 417 | 6 | 1108 | 552 | 539 | 248 |
| SE3-NO1 | 417 | 0 | 728 | 135 | 86 | 154 |
| SE4-SE3 | 518 | 0 | 112 | 6 | 1 | 14 |
| SE3-SE4 | 518 | 1110 | 2936 | 2011 | 2028 | 456 |
| DK2-SE4 | 29 | 0 | 378 | 115 | 96 | 89 |
| SE4-DK2 | 29 | 84 | 747 | 338 | 299 | 175 |
| SE1-FI | 617 | 321 | 922 | 662 | 669 | 141 |
| FI-SE1 | 617 | 0 | 57 | 9 | 3 | 12 |
| SE3-FI | 395 | 55 | 906 | 624 | 666 | 208 |
| FI-SE3 | 395 | 0 | 293 | 17 | 0 | 50 |
| NO4-FI | 1091 | 0 | 46 | 11 | 6 | 12 |
| FI-NO4 | 1091 | 0 | 31 | 6 | 3 | 8 |

Note: Distance in km, export in GWh/Month

Source: Author with data from Nord Pool Group (2017*e*)

**Table 13:** *Monthly electricity demand correlation*

| | DK1 | DK2 | NO1 | NO2 | NO3 | NO4 | NO5 | SE1 | SE2 | SE3 | SE4 | FI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DK1 | 1 | | | | | | | | | | | |
| DK2 | 0.947* | 1 | | | | | | | | | | |
| NO1 | 0.880 | 0.938 | 1 | | | | | | | | | |
| NO2 | 0.851* | 0.902 | 0.980* | 1 | | | | | | | | |
| NO3 | 0.596 | 0.697 | 0.814* | 0.855 | 1 | | | | | | | |
| NO4 | 0.818 | 0.874 | 0.933 | 0.959 | 0.874* | 1 | | | | | | |
| NO5 | 0.838 | 0.840 | 0.896* | 0.924* | 0.672* | 0.901 | 1 | | | | | |
| SE1 | 0.766 | 0.799 | 0.786 | 0.705 | 0.508 | 0.728* | 0.692 | 1 | | | | |
| SE2 | 0.767 | 0.833 | 0.896 | 0.939 | 0.847* | 0.902* | 0.851 | 0.506* | 1 | | | |
| SE3 | 0.878* | 0.933 | 0.993* | 0.981 | 0.824 | 0.944 | 0.899 | 0.798 | 0.899* | 1 | | |
| SE4 | 0.875 | 0.935* | 0.987 | 0.970 | 0.812 | 0.936 | 0.886 | 0.818 | 0.887 | 0.994* | 1 | |
| FI | 0.865 | 0.918 | 0.959 | 0.965 | 0.848 | 0.951* | 0.886 | 0.753* | 0.917 | 0.971* | 0.966 | 1 |

Note: The * indicates actual trading pairs. Monthly data from November 2011 to September 2017

Source: Author with data from Nord Pool Group (2017*e*)

**Table 14:** *Daily summary statistics*

| | N | Mean | SD | Min | Max |
|---|---|---|---|---|---|
| Export/ Joint capacity | 86440 | .0852811 | (.1743373) | 0 | 1.810161 |
| Load ratio | 86440 | .6484002 | (.1805668) | .0630914 | 1 |
| Distance | 86440 | 445.5 | (232.7382) | 29 | 1091 |
| Demand variability | 86440 | .2175841 | (.2578352) | .0154297 | 1.178547 |
| Hydro share | 86440 | .5981927 | (.3950971) | 0 | 1 |
| Nuclear share | 86440 | .0772452 | (.1720031) | 0 | .5252735 |
| Renewables share | 86440 | .1134723 | (.1227024) | 0 | .492293 |
| Time | 86440 | 1081 | (623.8305) | 1 | 2161 |
| $N$ | 86440 | | | | |

**Table 15:** *Bilateral trade estimation results with daily observations*

Dependent variable: ln export over joint capacity

| | (1) | | (2) | | (3) | |
|---|---|---|---|---|---|---|
| | OLS | | F.E. | | R.E. | |
| ln importer load ratio | -0.972** | (-3.16) | -1.350*** | (-6.39) | -1.350*** | (-6.39) |
| ln exporter load ratio | 1.241*** | (4.21) | 1.599*** | (7.13) | 1.599*** | (7.13) |
| ln distance | -0.672 | (-1.97) | 0 | (.) | -0.630* | (-2.37) |
| ln demand variability | 0.415 | (1.83) | 0.365 | (1.54) | 0.364 | (1.54) |
| Importer hydro share | -3.499* | (-2.66) | | | | |
| Importer nuclear share | -1.800 | (-0.89) | | | | |
| Importer renewables share | -4.623 | (-1.71) | | | | |
| Exporter hydro share | 5.244*** | (6.62) | | | | |
| Exporter nuclear share | 6.232*** | (4.38) | | | | |
| Exporter renewables share | 9.220*** | (6.94) | | | | |
| Time | 0.0000681 | (0.83) | | | | |
| | -0.662 | (-0.56) | -2.504*** | (-4.81) | 0.661 | (0.41) |
| $N$ | 57240 | | 57240 | | 57240 | |
| $R^2$ | 0.260 | | 0.093 | | | |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

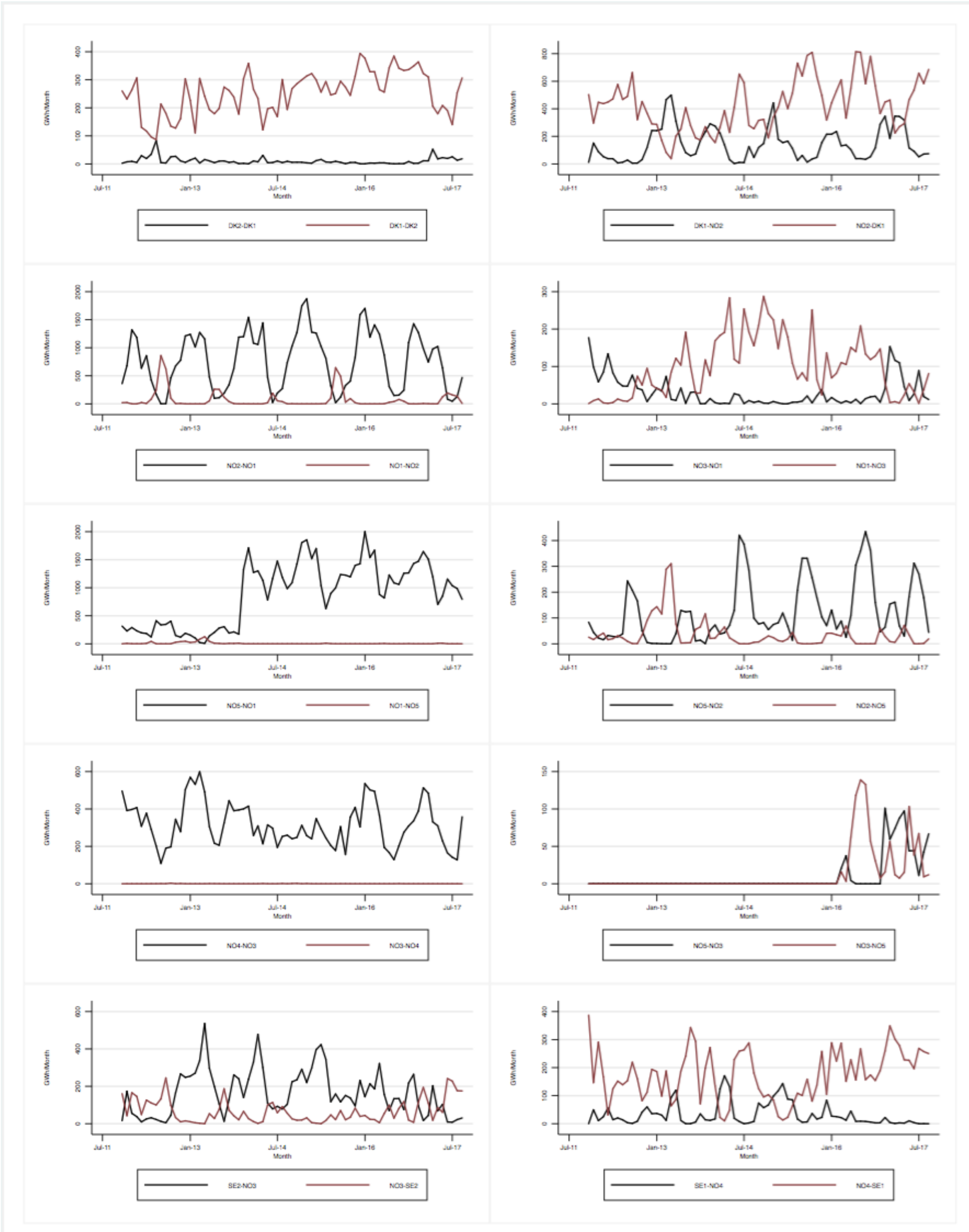


**Figure 13:** *Bilateral export 2011-2017 part I*
Source: Author with data from Nord Pool Group (2017*e*)

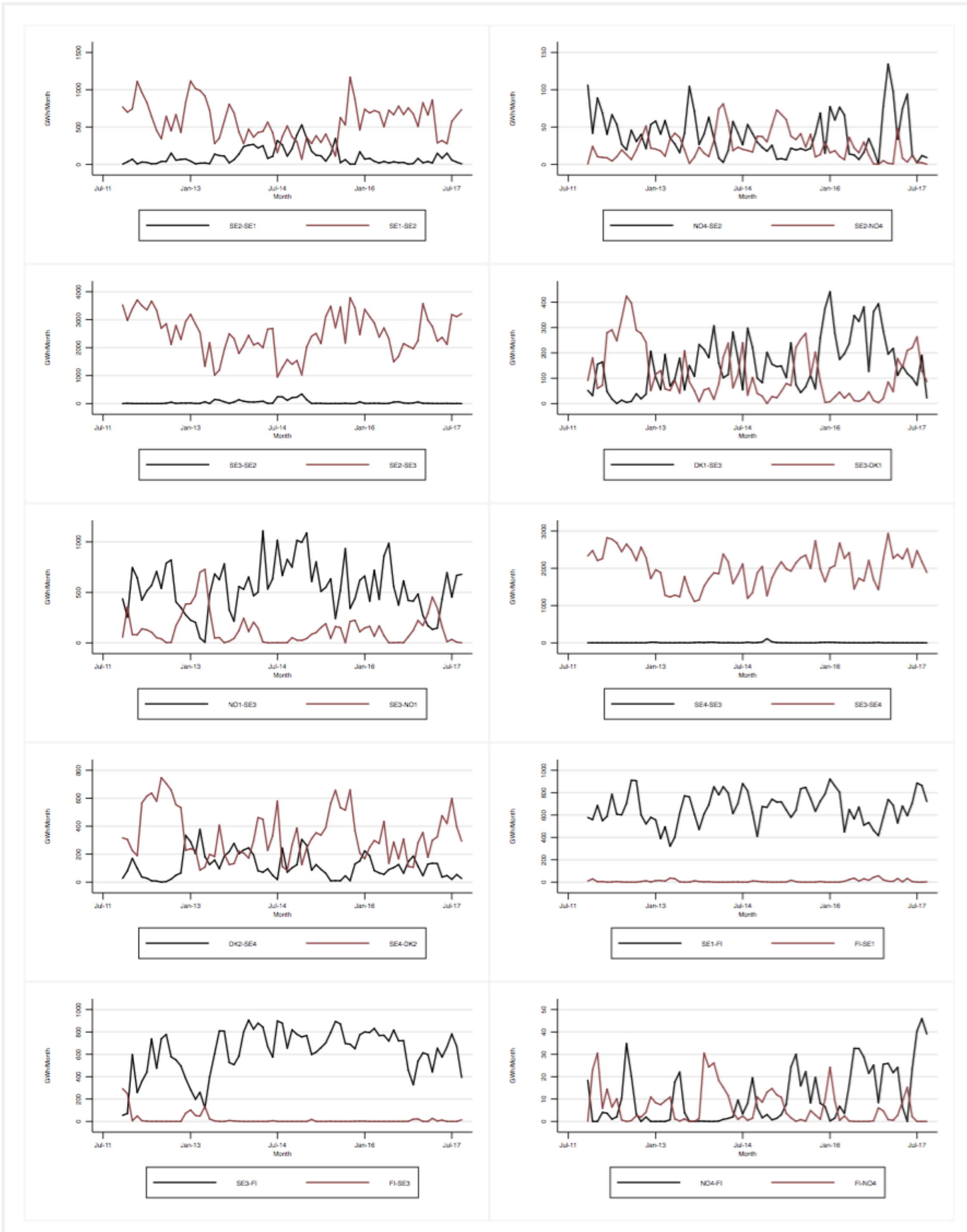


**Figure 14:** *Bilateral export 2011-2017 part II*

Source: Author with data from Nord Pool Group (2017*e*)

**Table 16:** *Daily bilateral trade estimation OLS regression with merit order-curve grouped bidding areas*

Dependent variable: ln export over joint capacity

| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) |
|---|---|---|---|---|---|---|---|---|---|
| | cons.-cons. | cons.-conv. | conv.-cons. | conv.-conv. | cons.-both | conv.-both | both-conv. | both-cons. | all |
| ln importer load ratio | -0.569 | -1.976** | -1.369* | -0.834 | -0.599 | -1.543*** | -1.322** | -0.657 | -0.972** |
| | (-1.26) | (-6.49) | (-3.51) | (-2.23) | (-1.37) | (-5.08) | (-3.18) | (-1.64) | (-3.16) |
| ln exporter load ratio | 0.960* | 1.299** | 2.680** | 0.978 | 0.941** | 1.865*** | 1.360*** | 1.113** | 1.241*** |
| | (2.71) | (5.04) | (5.46) | (2.28) | (3.10) | (4.46) | (4.37) | (3.04) | (4.21) |
| ln distance | -0.472 | -7.286*** | -0.698 | 0.440 | -0.584 | 0.156 | -0.456 | -0.700 | -0.672 |
| | (-0.67) | (-32.94) | (-1.80) | (0.74) | (-0.80) | (0.46) | (-0.80) | (-1.11) | (-1.97) |
| ln demand variability | 0.475 | 0.0443 | 0.826** | 0.559 | 0.450 | 1.420** | 0.969 | 0.595* | 0.415 |
| | (1.78) | (0.21) | (4.83) | (2.17) | (1.58) | (3.73) | (1.70) | (2.59) | (1.83) |
| Importer hydro share | 1.703 | 7.682 | 10.92 | 24.64* | -0.215 | -6.403*** | -5.326*** | 4.638 | -3.499* |
| | (0.20) | (0.35) | (2.53) | (3.10) | (-0.05) | (-5.19) | (-4.67) | (0.57) | (-2.66) |
| Importer nuclear share | 0 | -6.330 | 7.428 | -14.20** | 1.401 | -6.691** | -4.880 | 11.23 | -1.800 |
| | (.) | (-0.87) | (0.62) | (-4.92) | (0.25) | (-3.45) | (-1.49) | (1.01) | (-0.89) |
| Importer renewables share | 10.58 | -10.16 | 13.99 | -7.249* | 2.924 | -8.793** | -7.865* | 14.47 | -4.623 |
| | (0.79) | (-0.63) | (1.45) | (-3.03) | (0.33) | (-3.27) | (-2.77) | (1.16) | (-1.71) |
| Exporter hydro share | -5.394 | -18.12* | 16.75 | 28.05* | -4.737 | 7.873*** | 5.425*** | 2.633 | 5.244*** |
| | (-0.52) | (-3.20) | (1.05) | (2.76) | (-0.48) | (12.44) | (4.60) | (1.35) | (6.62) |
| Exporter nuclear share | 0 | -47.06 | 4.917 | -2.877 | -8.781 | 3.200 | 7.039* | 1.083 | 6.232*** |
| | (.) | (-1.97) | (0.85) | (-0.48) | (-0.65) | (2.14) | (2.38) | (0.37) | (4.38) |
| Exporter renewables share | -10.62 | -10.79 | 19.06 | 10.30*** | -6.428 | 11.14*** | 10.98*** | 5.103 | 9.220*** |
| | (-0.85) | (-1.62) | (1.42) | (8.08) | (-0.55) | (7.37) | (6.74) | (1.26) | (6.94) |
| Time | 0.0000407 | 0.000451** | -0.000259 | 0.000137 | 0.0000851 | 0.0000432 | 0.0000554 | -0.000164 | 0.0000681 |
| | (0.16) | (5.34) | (-1.21) | (0.61) | (0.45) | (0.26) | (0.41) | (-0.92) | (0.83) |
| | 3.497 | 62.34** | -16.69 | -5.930 | 5.385 | -1.292 | -0.126 | -5.589 | -0.662 |
| | (0.26) | (7.00) | (-1.38) | (-2.06) | (0.44) | (-1.18) | (-0.09) | (-0.64) | (-0.56) |
| $N$ | 27861 | 8030 | 6422 | 12520 | 35891 | 18942 | 20550 | 34283 | 57240 |
| $R^2$ | 0.105 | 0.641 | 0.714 | 0.569 | 0.126 | 0.569 | 0.400 | 0.242 | 0.260 |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

**Table 17:** *Monthly bilateral trade estimation OLS regression with seasonality*

Dependent variable: ln export over joint capacity

| | (1) | | (2) | | (3) | | (4) | | (5) | | (6) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time | | 4 Seasons | | Spring | | Summer | | Autumn | | Winter/Summer | |
| ln importer load ratio | -1.247** | (-3.02) | -1.322** | (-3.08) | -1.239** | (-2.98) | -1.299** | (-3.13) | -1.261** | (-3.03) | -1.311** | (-3.06) |
| ln exporter load ratio | 1.804*** | (4.58) | 1.726*** | (3.97) | 1.819*** | (4.55) | 1.751*** | (4.41) | 1.797*** | (4.60) | 1.740*** | (4.13) |
| ln distance | -1.105* | (-2.41) | -1.096* | (-2.39) | -1.100* | (-2.41) | -1.097* | (-2.40) | -1.100* | (-2.41) | -1.096* | (-2.40) |
| ln demand variability | 0.503 | (1.67) | 0.501 | (1.66) | 0.501 | (1.66) | 0.501 | (1.66) | 0.502 | (1.66) | 0.501 | (1.66) |
| Importer hydro share | -2.511 | (-1.08) | -2.538 | (-1.11) | -2.568 | (-1.12) | -2.549 | (-1.11) | -2.554 | (-1.11) | -2.545 | (-1.11) |
| Importer nuclear share | -0.748 | (-0.23) | -0.774 | (-0.25) | -0.818 | (-0.26) | -0.789 | (-0.25) | -0.798 | (-0.25) | -0.784 | (-0.25) |
| Importer renewables share | -0.235 | (-0.05) | -0.338 | (-0.07) | -0.390 | (-0.08) | -0.357 | (-0.07) | -0.357 | (-0.07) | -0.356 | (-0.07) |
| Exporter hydro share | 8.390*** | (6.58) | 8.370*** | (6.83) | 8.327*** | (6.84) | 8.358*** | (6.85) | 8.345*** | (6.81) | 8.357*** | (6.84) |
| Exporter nuclear share | 10.04*** | (4.03) | 10.02*** | (4.13) | 9.958*** | (4.12) | 10.00*** | (4.13) | 9.983*** | (4.11) | 10.00*** | (4.13) |
| Exporter renewables share | 16.40*** | (4.66) | 16.31*** | (4.84) | 16.24*** | (4.83) | 16.29*** | (4.84) | 16.28*** | (4.83) | 16.28*** | (4.85) |
| Time | -0.00170 | (-0.50) | | | | | | | | | | |
| Spring | | | -0.0348 | (-0.21) | 0.0221 | (0.32) | | | | | | |
| Summer | | | -0.127 | (-0.54) | | | -0.112 | (-0.78) | | | | |
| Autumn | | | 0.0232 | (0.29) | | | | | 0.0618 | (0.73) | | |
| Half year winter | | | | | | | | | | | 0.0847 | (0.52) |
| Constant | -2.145 | (-1.31) | -2.227 | (-1.39) | -2.115 | (-1.31) | -2.190 | (-1.36) | -2.173 | (-1.34) | -2.277 | (-1.43) |
| $N$ | 2512 | | 2512 | | 2512 | | 2512 | | 2512 | | 2512 | |
| $R^2$ | 0.337 | | 0.337 | | 0.337 | | 0.337 | | 0.337 | | 0.337 | |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Spring: April, May and June; Summer: July, August and September; Autumn: October, November and December.

Half year winter dummy: October, November, December, January, February and March

**Table 18:** *Daily bilateral trade estimation OLS regression with seasonality*

Dependent variable: ln export over joint capacity

| | (1) | | (2) | | (3) | | (4) | | (5) | | (6) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Time | | 4 Seasons | | Spring | | Summer | | Autumn | | Winter/Summer | |
| ln importer load ratio | -0.972** | (-3.16) | -1.021** | (-3.01) | -0.994** | (-3.22) | -0.964** | (-3.00) | -0.973** | (-3.13) | -1.023** | (-3.07) |
| ln exporter load ratio | 1.241*** | (4.21) | 1.171*** | (3.81) | 1.205*** | (4.05) | 1.239*** | (4.21) | 1.230*** | (4.17) | 1.177*** | (3.86) |
| ln distance | -0.672 | (-1.97) | -0.665 | (-1.95) | -0.668 | (-1.96) | -0.672 | (-1.97) | -0.671 | (-1.97) | -0.666 | (-1.95) |
| ln demand variability | 0.415 | (1.83) | 0.418 | (1.84) | 0.418 | (1.84) | 0.418 | (1.84) | 0.418 | (1.84) | 0.418 | (1.84) |
| Importer hydro share | -3.499* | (-2.66) | -3.473* | (-2.67) | -3.480* | (-2.67) | -3.489* | (-2.67) | -3.488* | (-2.67) | -3.476* | (-2.67) |
| Importer nuclear share | -1.800 | (-0.89) | -1.756 | (-0.87) | -1.776 | (-0.88) | -1.797 | (-0.89) | -1.791 | (-0.89) | -1.756 | (-0.87) |
| Importer renewables share | -4.623 | (-1.71) | -4.576 | (-1.70) | -4.572 | (-1.70) | -4.577 | (-1.70) | -4.576 | (-1.70) | -4.571 | (-1.70) |
| Exporter hydro share | 5.244*** | (6.62) | 5.283*** | (6.59) | 5.273*** | (6.62) | 5.260*** | (6.56) | 5.265*** | (6.60) | 5.292*** | (6.61) |
| Exporter nuclear share | 6.232*** | (4.38) | 6.286*** | (4.40) | 6.266*** | (4.41) | 6.245*** | (4.37) | 6.252*** | (4.39) | 6.291*** | (4.41) |
| Exporter renewables share | 9.220*** | (6.94) | 9.282*** | (6.96) | 9.284*** | (6.97) | 9.278*** | (6.94) | 9.282*** | (6.96) | 9.299*** | (6.97) |
| Time | 0.0000681 | (0.83) | | | | | | | | | | |
| Spring | | | -0.188 | (-1.58) | -0.122* | (-2.61) | | | | | | |
| Summer | | | -0.0934 | (-0.52) | | | 0.0273 | (0.24) | | | | |
| Autumn | | | -0.0837 | (-1.97) | | | | | -0.00123 | (-0.02) | | |
| Half year winter | | | | | | | | | | | 0.0997 | (0.79) |
| | -0.662 | (-0.56) | -0.647 | (-0.55) | -0.646 | (-0.55) | -0.613 | (-0.52) | -0.625 | (-0.53) | -0.787 | (-0.66) |
| $N$ | 57240 | | 57240 | | 57240 | | 57240 | | 57240 | | 57240 | |
| $R^2$ | 0.260 | | 0.260 | | 0.260 | | 0.259 | | 0.259 | | 0.260 | |

$t$ statistics in parentheses

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Spring: April, May and June; Summer: July, August and September; Autumn: October, November and December.

Half year winter dummy: October, November, December, January, February and March

**Table 19:** *Daily demand and supply divided into hourly demand and supply*

| | Demand (D) | | | | Supply (S) | | | | Differences | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Min | Max | Median | Mean | Min | Max | Median | Mean | Mean(S) - Mean(D) | Max(D) - Min(S) | Max(S) - Min(D) |
| DK1 | 1513 | 3106 | 2277 | 2254 | 537 | 4769 | 2265 | 2320 | 66 | 2570 | 3256 |
| DK2 | 1090 | 2042 | 1493 | 1519 | 146 | 2321 | 979 | 1002 | -516 | 1896 | 1230 |
| NO1 | 9654 | 22592 | 14527 | 14692 | 1021 | 5833 | 2340 | 2635 | -12057 | 21571 | -3820 |
| NO2 | 2064 | 7625 | 3993 | 4127 | 1647 | 9450 | 5683 | 5744 | 1617 | 5978 | 7386 |
| NO3 | 2690 | 5931 | 3878 | 3936 | 657 | 3428 | 1917 | 1942 | -1994 | 5274 | 738 |
| NO4 | 1654 | 3859 | 2574 | 2599 | 1360 | 4432 | 2686 | 2772 | 173 | 2499 | 2778 |
| NO5 | 1255 | 2929 | 2116 | 2112 | 1099 | 6984 | 3162 | 3233 | 1121 | 1830 | 5729 |
| SE1 | 733 | 1794 | 1130 | 1147 | 624 | 4173 | 2502 | 2452 | 1305 | 1171 | 3440 |
| SE2 | 1060 | 3261 | 1787 | 1849 | 1338 | 7313 | 4939 | 4742 | 2893 | 1923 | 6253 |
| SE3 | 6236 | 15825 | 9686 | 9883 | 4847 | 13193 | 9615 | 9513 | -370 | 10978 | 6957 |
| SE4 | 1726 | 4546 | 2694 | 2776 | 237 | 2239 | 788 | 851 | -1925 | 4309 | 514 |
| FI | 5635 | 14298 | 9251 | 9398 | 4748 | 11446 | 7432 | 7416 | -1983 | 9550 | 5810 |

All data in MWh. The values are found using daily observations which are then divided by 24. Hence, the actual minimum and maximum values are smaller and higher.

Source: Author with data from Nord Pool Group (2017*e*)