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Assessing the Impact of NordLink on Day-Ahead Prices in NO2 and Germany

A Quantile Regression Approach

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Abstract

This thesis studies the new interconnector *NordLink*'s effect on electricity prices in the Norwegian price area NO2 and in Germany. When examining the cable's price effect, we assess how the price volatility has developed, whether price convergence between the areas has occurred, and if the highest price levels in Germany have been reduced. The study is conducted by estimating a quantile regression model for both areas. In the models, we control for various factors known to impact day-ahead electricity prices. The variable of interest is a dummy variable that marks the first exchange of electricity through NordLink, which allows for a before-after analysis of the cable's price effect on both areas.

Our results indicate that NordLink has had a price-reducing effect in the German market, while it has increased prices in NO2 for the given period. Hence, price convergence between the previously separated markets is seen as an effect of the cable. The results also show that NordLink has had the most significant impact on German prices at the highest parts of its distribution, confirming a peak shaving effect. Moreover, the results show decreasing price volatility in Germany and partial evidence for volatility exacerbation in NO2.

Further, the thesis argues that through NordLink, gas and EUAs' effect on electricity prices in NO2 has been strengthened. Additionally, we find renewables' downward pressure on electricity prices to be strengthened in both areas after the opening of NordLink. In Germany, the price-reducing effect from NordLink is only found in conjunction with renewables.

Keywords – Electricity Markets, Market Integration, Electricity Prices, Interconnector, NordLink, NO2, Germany, Quantile Regression

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List of Abbreviations

ATC	Available transfer capacity
CET	Central European time
CO2	Carbon dioxide
CSC	Current source converters
CWE	Central Western Europe
DSO	Distribution System Operator
EU	European Union
EUA	European Union Allowance
EUPHEMIA	Pan-European Hybrid Electricity Market Integration Algorithm
FBMC	Flow-based market coupling
FTP	File transfer protocol
GHG	Greenhouse gas
GME	Italian power exchange)
GW	Gigawatt
HEnEX	Hellenic Energy Exchange
HVDC	High voltage direct current
ITVC	Interim Tight Volume Coupling
kV	Kilovolt
kWh	Kilowatt hour
log	Logarithmic
MCP	Market clearing price
MW	Megawatt
MWh	Megawatt hour
NEMO	Nominated Electricity Market Operators
nex	Net positions
NO2	Norwegian price area NO2 ("Sørlandet")
NSL	North Sea Link
NTC	Net-transfer capacity
NVE	Norwegian Water Resources and Energy Directorate
OLS	Ordinary least square
OMIE	Spanish and Portuguese power exchange
OPCOM	Romanian power exchange
OTE	Czech power exchange
PCR	Price coupling of regions
PTDF	Power transfer distribution factor
PV	Photovoltaics (Power)
RAM	Remaining available margin
RSI	Residual supply index
SDAC	Single Day-Ahead Coupling
TGE	Polish power exchange
TRM	Transmission reliability margin
TSO	Transmission System Operator
TTC	Total transfer capapcity
TWh	Terawatt-hour
VSC	Voltage source converters

1 Introduction

Electricity markets in Europe have been subject to substantial developments in the last decades. Since the beginning of the markets' deregulation process in the early 1990s, a shift toward greener energy production and market integration has been the most significant changes (Fulli et al., 2019). The European Commission has, as early as 1988, and particularly since 1996, been striving to achieve the European single market for electricity (Pollitt, 2019). Following their assessment of the prevailing competitive conditions and causes for the perceived market malfunction in 2005, the commission emphasized that improving interconnection capacity was necessary to develop the competition and integration of electricity markets (The European Commission, 2007). Norway and Germany have introduced new transmission lines following this report, improving their interconnection capacity. The newly opened North Sea Link (2021) and NordLink (2020) are the most substantial market changes in Norway (Statnett, 2020a). Germany has, in addition to NordLink, projects regarding transmission lines to Sweden, Denmark, the UK, and Austria, either up for consideration or under construction[1].

NordLink, which has been operational for over a year at the time of writing, is the thesis' focus. According to the Norwegian TSO Statnett, the cable is expected to benefit market participants in both Norway and Germany (Statnett, nd). These benefits arise particularly due to the complementary characteristics of the two markets, with their different access to energy domestically. Interconnecting complementary markets are exemplified by Mauritzen (2013) in the case of Denmark and Norway, highlighting the benefits of the ability to store excess wind power in water reservoirs through interconnectors. As electricity markets are likely to continue their development with further interconnectors, assessing NordLink's effect on electricity prices is important and relevant.

Electricity prices in Norway soaring to record-high levels in 2021 is another reason for assessing the cable's price effects. These price levels have received considerable publicity in the media and have been a hot topic of debate, where NordLink and North Sea Link have been argued to be among the main price drivers by the public. Døskeland et al. (2022) do, on the other hand, claim that although the new cables have increased prices to

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[1] See: https://tyndp2020-project-platform.azurewebsites.net/projectsheets/transmission

some extent, the main reasons for these price levels are high prices on fossil fuels and CO_2, and low water inflow. Our empirical analysis of electricity prices after NordLink opened for exchange will contribute to this debate. Additionally, the thesis will help create a better understanding of market integration's effect on day-ahead prices. Lastly, to the best of our knowledge, no other studies have empirically analyzed the price effects of transmission cables using quantile regression in either Norway or Germany.

To analyze NordLink's price effect in NO2 and Germany, we fit a quantile regression model to data from before and after NordLink was made available for the market. In the model, we use a dummy variable to capture the cable's effect while controlling for other factors that have an explanatory effect on electricity prices. This method is similar to a study performed by Sapio (2019) on the Italian SAPEI cable, an interconnector between Sardinia and mainland Italy. Similar to Sapio's research, we aim to investigate NordLink's impact on price levels, volatility, and peak prices in NO2 and Germany. The analysis of these price aspects forms the thesis' research question:

"How has the introduction of NordLink affected day-ahead electricity price levels and price volatility in NO2 and Germany?"

A new transmission cable is expected to reduce energy costs, improve the security of supply, and reduce reserve requirements (Sapio, 2019; Panapakidis, 2021). As a result, market integration is expected to cause price convergence. However, this effect is questioned by Gianfreda et al. (2016), arguing that the characteristics of intermittent energy sources are forces working against price convergence, mainly due to the increasing share of intermittent energy in electricity markets today. Valeri (2009) proved in a study on electricity markets in Ireland and Great Britain that welfare effects from interconnection are most significant in the market with the initially highest prices. Our results confirm price convergence as an effect of NordLink, as price levels around the median increase for NO2 while decreasing for Germany.

Furthermore, market integration through NordLink improves the allocation of resources, as it allows for the export of renewables from areas where those resources are excessively concentrated. This is supported by Sapio (2019), who argues that transmission lines are expected to mitigate volatility in both areas. This contradicts our results, as volatility is reduced in Germany but not in NO2. As Germany has higher and more volatile prices due to their larger share of intermittent energies, these results are sensible. Our results also provide partial evidence for volatility exacerbation in NO2.

Sapio (2019) describes increased competition and thereby a reduced possibility of exercising market power as another effect of transmission cables that could reduce the highest price levels. This effect is mainly caused by the increased risk of being undercut by competitors from other market areas. However, when there is no scarcity of electricity, and both demand and prices are low, this effect is not likely to be detected (Sapio, 2019). The highest price levels in Germany being reduced following the opening of NordLink are proven in our analysis. In NO2, this effect is not seen, nor was it expected.

In summary, we find evidence of price convergence between NO2 and Germany, as well as German peak prices being reduced. Additionally, price volatility in Germany is reduced, and partial evidence for increased volatility in NO2 is found. When controlling for mechanisms, we see that gas and EUAs' price effects are strengthened in NO2 after NordLink's implementation. Lastly, we find that renewables' downward pressure is strengthened in both areas after the opening of the cable. NordLink's negative effect on prices in Germany was only found in conjunction with wind- and PV production.

The rest of the thesis proceeds as follows. Chapter 2 describes the characteristics of both countries, their common calculation of electricity prices, and the interconnecting of electricity markets. Chapter 3 presents an overview of the data used to model electricity prices in NO2 and Germany, including descriptions of price data and the reasoning for each included control variable. Chapter 4 describes the basics of a quantile regression model, our model specifications, and the expected results from NordLink. Chapter 5 presents the results from the quantile regressions, where results are interpreted and underlying causes discussed. Lastly, Chapter 6 consists of concluding remarks, summarizes the thesis' main findings, and presents the possibilities for future research.

2 Description of Electricity Markets

Until the 1990s, electricity markets in Europe were organized as vertically integrated monopolies with little cross-border exchange. As the deregulation processes of different countries' markets began, competition in both production and retail was introduced. The difficulties of utilizing excess Norwegian hydropower domestically in the 1980s drove the interest in exporting electricity to other markets, improving the level of cross-border trade. As such changes required robust market institutions and contracts, the Nordic region became increasingly integrated with several interconnectors allowing for the physical flow of electricity between areas (Bolton, 2022). The idea of interconnecting areas further expanded to the rest of Europe, where the interconnecting capacity has continuously increased up until today. Hence, electricity markets that were previously isolated now have electricity flow frequently across borders.

Today, the electricity markets for Norway and Germany are interconnected through the Price Coupling of Regions (PCR) and NordLink. PCR is the project of developing a common price coupling solution that calculates electricity prices across Europe with respect to the capacity of the relevant grids. The price calculation is performed by the algorithm PCR EUPHEMIA. Before PCR, the Interim Tight Volume Coupling (ITVC) connected Norway (Nordic region) and Germany (CWE region), launched in 2010. Before ITVC, the two countries' markets were not directly connected. NordLink is a subsea transmission cable that opened for trial in December 2020. The cable physically enables electricity trade between Norway and Germany and is the first direct connection between the two countries. The amount of electricity flowing through the cable is decided by EUPHEMIA's calculations, based on submitted capacities.

Prior to EUPHEMIA being progressively used from February 2014, various algorithms were used locally by the involved power exchanges. These algorithms included, for example, COSMOS, SESAM, SIOM, and UPPO, which focused on the products and features of the corresponding power exchange. Then, these power exchanges calculated prices and were the only operators enabling electricity trade in their respective regions (NEMO Committee, 2020). After implementing EUPHEMIA, these exchanges serve as platforms for trading electricity with competition between them. This is seen in the Nordic region and Germany, as market participants can now exchange electricity at both Nord Pool and EPEX SPOT, with EUPHEMIA calculating the prices. However, Nord Pool is still the most used market exchange in the Nordic region and EPEX SPOT in CWE. These exchanges will be described in further detail later in this chapter.

Creating an internal European electricity market offers the opportunity to combine different countries' resources, allowing for an optimization of the overall welfare. However, national differences will continue to persist in the production of electricity and platforms used for trade. Further in this chapter, we will look at the differences in characteristics between Norway and Germany from a historical perspective, their production types, most used power exchanges, and price areas. Additionally, we will further explain the algorithm PCR EUPHEMIA and how price differences between areas occur. Finally, we will present theories in connection with market coupling and relate them to NordLink before giving an overview of both countries' plans to further improve their interconnection capacity.

2.1 The Norwegian Market

Up until 1991, the Norwegian electricity market was divided into several local electricity markets. In these markets, local power plants were monopolists and delivered electricity to the nearby areas. However, on January 1st, 1991, the Energy Act was implemented, deregulating the market. A vital point of the act was to divide the energy sector into two parts. The first part includes the distribution and transmission of electricity, organized as monopolies. The second part is electricity production and trade, which should now be exposed to market competition (NVE, 2016). The deregulation meant that the state no longer had complete control of the power market, as free competition was introduced. The liberalization was believed to ensure higher efficiency, lower prices, more even prices between different types of consumers, and a higher return on investment (Bye and Hope, 2007).

Today, the Norwegian electricity grid consists of three levels: the transmission grid, the regional grid, and the distribution grid. The transmission grid connects producers with consumers in a nationwide system and controls interconnectors to other countries' electricity markets. Statnett operates the transmission grid. The regional grid's purpose is to connect the transmission grid with the distribution grid. The distribution grid consists of several local electricity grids that typically supply smaller end-users with power (Norwegian Ministry of Petroleum and Energy, 2019).

In 2021, the total energy consumption in Norway was 138 TWh. According to NVE, consumption is expected to increase by 36 TWh by 2040, totaling 174 TWh. A significant driver for the increased consumption is the electrification of oil platforms, industry, and transportation (NVE, 2021). Changes in Norwegian production and improved interconnection capacity are expected to cover this increased consumption.

Production Types: Norway

One unique feature of the Norwegian power supply system is the large share of hydropower. The Norwegian hydropower system provides high levels of storage capacity, contributing to approximately 50% of Europe's total reservoir storage capacity (Norwegian Ministry of Petroleum and Energy, 2021a). An overview of the production types found in Norway and their respective shares can be seen in Table 2.1. From the information provided in Table 2.1, it is clear that hydropower accounts for most of Norway's energy supply, implying that the resource base for production is highly dependent on precipitation (Norwegian Ministry of Petroleum and Energy, 2021a). The Norwegian Ministry of Petroleum and Energy points out that more than 75% of the system's capacity is flexible, meaning that production can be increased or decreased when it is needed, at a low cost. Flexible capacity is essential in balancing production and consumption, especially with increasing shares of intermittent production, such as PV and wind. Towards 2040, NVE expects an 11 TWh increase in hydropower production. This increase stems from expanding existing hydropower plants, new hydropower plants, turbine upgrades, and increased inflow (NVE, 2021).

Production type	**Share**
Hydropower	91.82%
Wind Power	6.43%
Thermal Power	1.75%

Table 2.1: Energy Mix in Norway. Data from 2020. Source: Statistisk Sentralbyrå (2022).

The operation of Norway's first wind farm began in 2002, with an installed capacity of 40 MW. In recent years, investments in wind power have increased substantially, with a capacity of 1405 MW installed in 2020. At the beginning of 2021, the number of wind farms had grown to 53, totaling 3977 MW of installed capacity (Norwegian Ministry of Petroleum and Energy, 2021a). The increased capacity makes wind power the second-largest energy source in Norway, as seen in Table 2.1. Regarding future developments of wind power, the licensing of on-shore wind power was stopped in April 2019, while the licensing of off-shore wind power is yet to begin. Thus, a relatively small increase in wind power production is expected towards 2030 (NVE, 2021).

Thermal power accounted for 1.75% of Norwegian production capacity in 2020, with a total installed capacity of approximately 700 MW from the 30 thermal power plants. These thermal power plants in Norway are often located in industrial installations, where they use the generated electricity themselves. Thus, the electricity generation from thermal power depends on the industry's electricity needs. The energy sources used in the thermal plants vary between gas, coal, oil, surplus heat, and municipal- and industrial waste (Norwegian Ministry of Petroleum and Energy, 2021a).

At the beginning of 2021, PV power in Norway had a total installed capacity of 160 MW. However, the capacity for PV production is expected to significantly increase, with an expected production of 7 TWh in 2040 (NVE, 2021). The anticipated increase in PV production is mainly caused by decreasing costs but is also positively affected by plans for ground-mounted systems (Norwegian Ministry of Petroleum and Energy, 2021a).

2.2 The German Market

Before the German electricity market became fully liberalized in 1998, the market consisted of eight vertically integrated utilities with area monopolies. As the liberalization began, several mergers and acquisitions took place, resulting in the number of vertically integrated utilities being reduced to four: RWE, E.ON, Vattenfall, and EnBw Energi. At one point, these companies jointly owned around 80% of the generation capacity and owned transmission grids in their area and half of the end-user contracts. Due to the liberalization process moving slower than desired, the EU and the German government chose to implement several policy changes. These changes included the implementation of three

Energy Packages and the Energy Industry Act, aimed at creating a more competitive environment in the electricity market. As a result of these policy changes, the four utilities sold a majority stake of their transmission share to third parties (Agora Energiwende, 2019; Do, 2015).

Today, the German electricity market is liberalized in supply and retail but is still dominated by four major generator companies and four transmission companies. These companies are not vertically integrated but operate as independent market participants. Today, the German market is considered competitive, although there is some degree of market power (Agora Energiwende, 2019; Do, 2015).

The German transmission system is divided into four control areas, where each control area has a responsible TSO. Following the third EU Energy Package and Energy Industry Act of 2011, three out of the initial four TSOs were sold to third parties, resulting in today's TSOs being: TransnetBW, Ampirion GmbH, Tennet TSO GmbH, and 50Hertz Transmission GmbH. Each TSO's control area is shown in Figure 2.1 (Agora Energiwende, 2019; Bundesnetzagentur, nd).

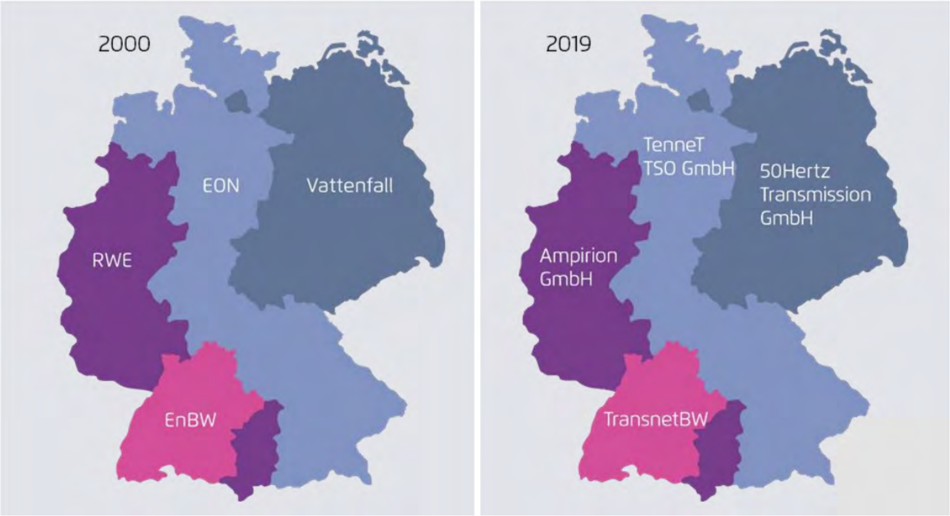

Figure 2.1: Development of control areas in the German electricity market and their respective TSOs (Agora Energiwende, 2019).

TSOs' responsibility is stipulated in German law, as they should ensure the safety and stability of the network through operations, maintenance, and infrastructure expansions in line with new requirements. To avoid possible fluctuations in system frequency that can create instability, TSOs use balancing services equivalent to the balancing power market in Norway (Bundesnetzagentur, nd).

The German electricity network is divided into several voltage levels. Out of these levels, transmission systems are the highest, as they cross the whole country with a minimum of 220 kV. These lines transport electricity from the major generators to the downstream distribution systems delivering electricity to consumers (Bundesnetzagentur, nd). DSOs operate these distribution grids. The DSO's primary responsibility is to maintain and monitor the grids (Agora Energiwende, 2019).

According to AG Energiebilanzen (2022), net electricity consumption amounted to a total of 555.3 TWh in 2020, a decrease from 575.2 TWh in 2019. AG Energiebilanzen (2021) cites the economic repercussions of the Covid-19 crisis as the main reason for the experienced decline in consumption. With regards to the future development of consumption, various German institutions provide different estimates[2]. However, the German Association of Energy and Water Industries estimates that German consumption will increase to around 700 TWh in 2030. The increase is associated with more electricity used in transportation, heating, and industry. Additionally, increasing digitalization will affect electricity consumption positively (Bundesverband der Energie- und Wasserwirtschaft, 2021).

Production Types: Germany

Compared to Norway's production types, Table 2.2 illustrates how German electricity production is more diversified, including a higher number of electricity sources and a more CO_2-intensive production. German production is, however, becoming increasingly renewable, which is exemplified by the fact that electricity produced from renewable sources exceeded production from fossil fuels for the first time in 2020 (AG Energiebilanzen, 2021).

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[2] https://www.dw.com/en/how-much-power-will-germany-need-for-its-energy-revolution/a-58116209

Production type	**Share**
Wind Power	22.92%
Photovoltaic Power	8.8%
Other renewables	12.18%
Natural Gas	16.2%
Lignite	16.1%
Hard Coal	11.3%
Nuclear Energy	7.6%
Mineral Oil Products	0.8%
Other	4.5%

Table 2.2: Energy Mix in Germany. Data from 2020. Source: AG Energiebilanzen (2021).

As a part of transitioning its economy to become carbon-neutral, Germany introduced a series of policies called the *Energiewende*, aimed at reducing emissions from greenhouse gases while phasing out nuclear energy (Clean Energy Wire, nd). These policies included plans for actions such as phasing out nuclear power by 2022 and the use of coal by 2038. The Energiewende has received praise for its ambitious goals for CO_2-reductions and criticism for its financial burden on the national economy. This financial burden is shown by the project's high direct costs, €500 billion as of 2017, and the high electricity prices for households and industries. Unnerstall (2017) argues that Energiewende demonstrates the more expensive way of transitioning to renewable energies in the electricity sector.

In their Climate Action Plan, Germany has set out goals for reducing GHG emissions by 55% in 2030, 70% in 2040, and 80-95% in 2050, compared to emission levels in 1990. Simultaneously as GHG emissions are reduced, the share of renewable electricity generation should increase to 50% by 2030, 65% by 2040, and 80% by 2050 (International Energy Agency, 2020). Exactly how much of the out-phased capacity that needs to be replaced remains unclear, as the German government works towards decreasing electricity consumption and excess capacity. Nevertheless, the International Energy Agency believes that the capacity is likely to be replaced by renewables (International Energy Agency, 2020).

As shown in Table 2.2, electricity produced from renewables accounted for 43.9% of the total electricity production in 2020, increasing by 3.2% from 2019. Out of the share for renewables, wind power accounts for 52.2% of the electricity produced. Both on-shore and off-shore wind have produced more electricity than in previous years, indicating a willingness to invest in renewable electricity production. However, this growth is likely to stop, as there are no significant increases in capacity planned (AG Energiebilanzen, 2021). As of 2020, the total installed capacity of on-shore wind was 55 100 MW and 7725 MW for off-shore wind.

PV systems' total production of 50.6 billion kWh in 2021 accounts for approximately 20% of renewables' total production, increasing 9.1% compared to 2020 (AG Energiebilanzen, 2021). This increased capacity illustrates how investments in PV production have followed investments in wind power production.

2.3 Power Exchanges

2.3.1 Nord Pool

In 1993, the first Norwegian power exchange was established as a result of the Norwegian deregulation process. With Sweden joining in 1996, the joint market exchange *Nord Pool* was formed. As Finland and Denmark joined in respectively 1998 and 2000, the creation of a fully integrated Nordic marketplace was complete. Later on, the Baltic states of Estonia, Lithuania, and Latvia have also joined the marketplace (2010-2013), making Nord Pool one of the leading power exchanges in Europe. Today, Nord Pool operates in the Nordic and Baltic regions, Germany, Poland, France, the Netherlands, Belgium, Austria, Luxembourg, and the UK (Nord Pool Group, nd). The countries using Nord Pool are connected to other European markets through the PCR.

Day-ahead Market: Elspot

The majority of volume traded at Nord Pool is settled in the day-ahead market *Elspot*. In 2021, day-ahead markets accounted for 97.4% of the volume traded at Nord Pool, with 75.03% occurring in the Nordic and Baltic regions (Nord Pool, 2022a). The day-ahead market follows a uniform price periodic double auction, as buyers and sellers submit their bids in a closed auction the day before delivery for each hour of the following day. After the publication of available capacities and interconnectors in the grid at 10:00 CET, market participants submit their orders, specifying the volumes they are willing to buy or sell at given price levels, up until the deadline at 12:00 CET (Nord Pool, ndb; Spodniak et al., 2021). After the deadline, submitted orders are matched, which constructs the aggregated supply and demand curves for a particular area (Brose and Haugsbø, 2019; Spodniak et al., 2021). The supply curve ranks generation bids according to increasing price, referred to as the Merit-Order Curve, whereas the demand curve ranks buy-bids in the opposite manner (Next Kraftwerke, nd). The intersection of the aggregated supply and demand curves provides the market equilibrium for the entire Nordic electricity market, called the system price, illustrated in Figure 2.2 (Spodniak et al., 2021). It is important to note that the system price should not be confused with the area price, as the system price is solely a reference price that does not consider capacity constraints and is not used for electricity trade. The system price and area prices are calculated for all 24 hours in the upcoming day and are announced at 12:45 CET. Area prices are calculated through the EUPHEMIA algorithm, further elaborated in Section 2.5.1.

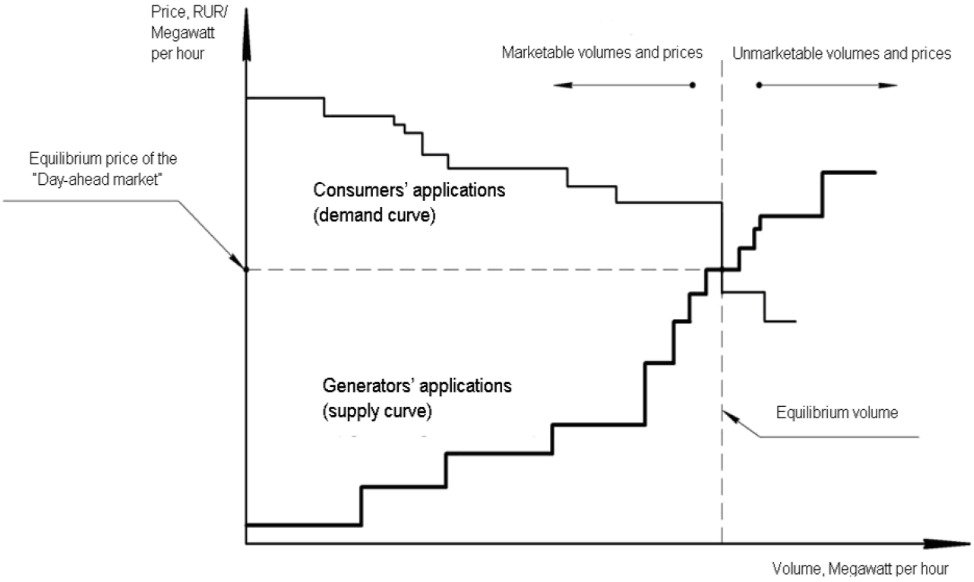

Figure 2.2: Illustration of the equilibrium price of the day-ahead market. (Mokhov and Demyanenko, 2015)

Order Types: Day-ahead Market

Market participants can submit different types of orders in the day-ahead market. Single hourly orders are most frequently used and contribute to the largest share of matching in day-ahead trading. These orders specify the price and volume given separately for each hour. Further, block orders create a dependency between hours, as it specifies an "all or nothing"-condition for all hours included in the block (Bjørndal et al., 2013; Nord Pool, 2022b). Several block bids can also be submitted in clusters, out of which only one block can be activated, called an exclusive group. Finally, one can submit flexible orders, which are bids that may be accepted in an hour, given that price conditions are met (Nord Pool, 2022b).

Intraday Market and Balancing Services

Despite that the majority of electricity traded at Nord Pool occurs at Elspot, 2.61% is also traded in the intraday market *Elbas* (Nord Pool, 2022a). At Elbas, electricity can be traded closer to physical delivery than in Elspot. Hence, Elbas contributes to securing the necessary balance between supply and demand, which is becoming a significant challenge with increasing renewable intermittent energy production (Nord Pool, ndc). However, due to the day-ahead market being the emphasis of this thesis, the intraday market will not be explained in further detail.

The results from the day-ahead market are used as a baseline for planning the next 24-hour period, with additional changes realized in Elbas or TSO's balancing power markets. Balancing power markets regulate production or consumption to maintain balance when the market experiences disturbances within a specific hour of operation (Norwegian Ministry of Petroleum and Energy, 2021b).

2.3.2 EPEX SPOT

The European Power Exchange (EPEX SPOT) was created in 2009 by merging German EEX and French Powernext. Initially, EPEX SPOT covered the markets of Germany, Austria, France, and Switzerland. Following further expansions up until today, EPEX SPOT operates the wholesale market of power trading or offers its operations in 13 different countries: Austria, Belgium, Denmark, Germany, Finland, France, Luxembourg, the Netherlands, Norway, Poland, Sweden, the United Kingdom, and Switzerland. Like Nord Pool, EPEX SPOT offers service in the day-ahead and intraday markets, with a balancing market functioning only for TSOs (Santos et al., 2015). Most electricity traded at EPEX SPOT is exchanged in the day-ahead market. Out of the total 615 TWh traded at EPEX SPOT in 2020, 81.95% was traded in the day-ahead market and 18.05% in the intraday market (Europex, nd). The volume traded at the intraday market is noticeably higher in EPEX SPOT than the 2.61% in Nord Pool. This difference is partially explained by their different energy mix, as the stable access to hydropower in the Nordic countries needs less correction to supply and demand. Countries using EPEX SPOT are connected to other European markets through the PCR.

Day-Ahead Market at EPEX SPOT

The day-ahead market at EPEX SPOT is the same as Elspot, consisting of a blind auction taking place the day before delivery, with a deadline for submitting bids at 12:00 CET (EPEX SPOT, nda). The submission of bids is followed by the calculation of hourly prices for all areas participating in PCR, where prices are calculated with respect to each grid's constraints and capacities using the common price algorithm PCR EUPHEMIA.

At EPEX SPOT, one can submit two types of orders, identical to the single hourly orders and block orders described for Elspot in Section 2.3.1 (EPEX SPOT, nda).

2.4 Electricity Pricing and Congestion Management

As discussed earlier, the system price is an unconstrained market-clearing reference price, as it does not consider bottlenecks in the grid. Hence, it removes congestion restrictions by putting any capacity to infinity (Brose and Haugsbø, 2019; Nord Pool, ndd). Congestion can be defined as a situation where the transmission capacity of at least one transmission line is binding and therefore limiting electricity transmitted between regions (Boury, 2015). However, bottlenecks can occur in a power grid when the market-clearing implies power flows that exceed some lines' capacities in the grid. In theory, this would lead to overloaded transmission lines and, consequently, outages (Brose and Haugsbø, 2019). These outages will, however, be prevented by the responsible TSO and hence not occur in the grid.

2.4.1 Price Areas in Norway and Germany

At Nord Pool, several participating countries are divided into different areas with individual prices to manage congestion and take grid constraints partly into account. The organization of areas is based on where the presumably most prominent and long-lasting congestions are expected to occur (Bjørndal et al., 2013). In addition, the division of areas ensures that regional market conditions are reflected in the price (Nord Pool, nda). The organization of areas in each country is decided by the local TSO, where Norway has five different price areas: NO1 (Østlandet), NO2 (Sørlandet), NO3 (Midt-Norge), NO4 (Nord-Norge), and NO5 (Vestlandet), as of May 2022 (Nord Pool, nda).

Germany operates with a single bidding zone across all regions, unlike the five Norwegian bidding areas. Thus, the price does not reflect regional imbalances and the transmission network in the market dispatch (Egerer et al., 2016). The German electricity market operates with a uniform price, similar for consumers and producers in all control areas. Egerer et al. (2016) found that for Germany's current single price area, high re-dispatch levels are to be expected along with changes in generation capacities. Egerer et al. also presents the possibility of re-dispatch measures being reduced by pricing scarce transmission capacity into the electricity market. In addition, the experienced internal congestion could be improved with transmission investments, but these take years to be realized (Egerer et al., 2016). Last, Egerer et al. (2016) found that by dividing Germany into two price zones, there were slightly declining re-dispatch levels while emphasizing that one should consider distributional implications for stakeholders before changing pricing schemes.

2.4.2 The Difference in Area Prices

Through EUPHEMIA, cross-border transmission capacity is implicitly auctioned, which is part of a congestion management technique called zonal pricing (Spodniak et al., 2021). This is intended to eliminate or decrease price differences between areas, as planned cross-border energy exchange is expected to lead to price convergence. For a cross-border exchange to occur, it must be within the available capacity of the transmission network. However, zonal pricing (uniform pricing) makes this difficult, as prices are calculated regardless of constraints imposed by physical laws and network capacity (Bjørndal et al., 2018). If constraints are breached, the respective TSO must handle the imbalance after the spot market deadline, which can be costly.

If transmission capacity between two areas is limited, one area can have a surplus of power while the other has a power deficit, resulting in different prices (Brose and Haugsbø, 2019). Meanwhile, if the flow of electricity between bidding areas is within capacity limits decided by TSOs, prices will be identical. The difference in area prices, depending on the utilization of transmission capacity, is illustrated in Figure 2.3.

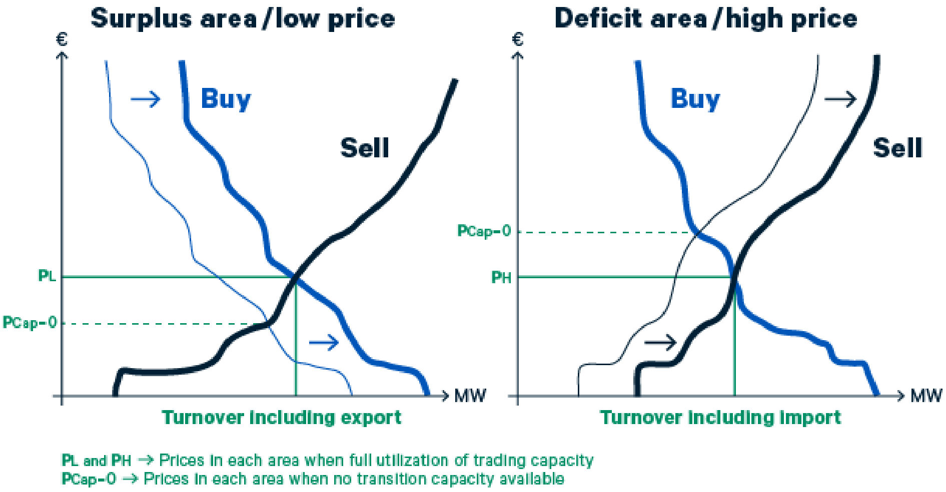

Figure 2.3: Illustration of different area prices, depending on full capacity utilization or no capacity available (Nord Pool, ndd).

Even if interconnectors are supposed to improve price stability, Gianfreda et al. (2016) argues that the increased penetration of intermittent renewable energy sources is potentially a force working against price convergence. This is due to the characteristics of wind energy enabling very low and negative prices when demand is low and supply is high. Hence, prices in two areas can be higher in area A and lower in area B, lower in area A and higher in area B, or equal in both areas (Unger et al., 2018).

2.5 Coupling of European Markets

The aggregated supply and demand curves form the equilibrium price in a presumably isolated area (Unger et al., 2018). However, different price areas and markets are interconnected through transmission lines, increasing or decreasing their net imports or exports. Hence, electricity price calculation is based not only on supply and demand but also on capacities and constraints in each grid. These inputs are matched, and prices are computed through EUPHEMIA.

2.5.1 Price Calculation: PCR EUPHEMIA

Price Coupling of Regions is a project by several European Power Exchanges to develop a single price coupling solution to calculate electricity prices across Europe. This project resulted in the algorithm EUPHEMIA. PCR was initiated by the eight power exchanges: EPEX SPOT, GME, HEnEX, Nord Pool, OMIE, OPCOM, OTE, and TGE, covering 25 countries in Europe. The project is crucial to achieving the EU's goal of a harmonized electricity market (EPEX SPOT, ndb).

In coupled markets, the supply and demand of electricity are no longer restricted to a given geographical area. Market coupling allows for electricity transactions between different areas or countries and is only restricted by grid constraints. These cross-border transactions are made possible through EUPHEMIA.

EUPHEMIA is a single price coupling algorithm that calculates prices and energy allocation across Europe to maximize the overall welfare. The use of a common price algorithm also increases the transparency of price- and flow computation (NEMO Committee, 2020). It computes a market-clearing price for each trading period in each bidding area and a net position. The calculation requires input on each grid's bids, offers, capacities, and constraints, which the involved NEMOs and TSOs submit. Each area's price is constructed when matching all these inputs through the algorithm. The net position is calculated as the difference between the matched supply and demand quantities (NEMO Committee, 2020).

EUPHEMIA has been in use since 2014, and calculations are based on three main principles (Nord Pool, nde):

1. The algorithm gives a fair and transparent determination of day-ahead electricity prices and a net position of bidding areas across Europe. It seeks to optimize overall welfare and increase transparency.
2. The process is based on decentralized sharing of data, which provides resilience and robustness to the operation.
3. Enabling the exchange of anonymized orders and network constraints among the different power exchanges to calculate bidding zone prices and other reference prices

and net positions of all included bidding areas.

Exchange of electricity between areas can be performed by using an Available Transfer Capacity (ATC) model, a flow-based model, or a combination of the two (hybrid model). Countries in CWE already operate with a flow-based market coupling (FBMC) method, while Norway plans to introduce FBMC in early 2023 (Statnett, 2021). A flow-based model allows for more precise modeling of the physical flows in the network compared to ATC. Two components give the flow-based constraints: Remaining Available Margin (RAM), which is the MW available for exchanges, and Power Transfer Distribution Factor (PTDF). PTDF is a ratio indicating how much MWh is used by the net positions (nex) resulting from the exchanges (NEMO Committee, 2020). The network constraint imposed by the flow-based model is expressed as:

$$PTDF * nex \leq RAM$$

The Nordic countries use a Net Transfer Capacity (NTC) method for capacity calculation (EnergiNet et al., 2014). NTC values may be derived from ATC values by adding long-term nominations (KU Leuven Energy Institute, 2015). Therefore, ATC and NTC are calculated by TSOs based on their assumptions about future market developments. Hence, they are decided ex-ante market clearing and need to be underestimated to avoid overloads (Van den Bergh et al., 2016). NTC can not prevent physical power from entering the network, but it can reduce it by restricting commercial trading by submitting a low NTC value. The value of NTC will, in many cases, be lower than the nominal capacity of the grid (Bjørndal et al., 2018; Van den Bergh et al., 2016). NTC is given as the difference between two components: Total Transfer Capacity (TTC), which is the maximum transmission when taking operational security standards applicable into account, and the Transmission Reliability Margin (TRM). TRM is a security margin concerning uncertainties in physical flows, emergency exchanges regarding unbalanced situations, and data inaccuracies (European Network of Transmission System Operators, 2008). The NTC network constraint is expressed as:

$$NTC = TTC - TRM$$

2.5.2 Single Day-Ahead Coupling

Norway and Germany are both a part of SDAC, an initiative between NEMOs and TSOs intended to create a single pan-European cross zonal day-ahead electricity market. A single day-ahead electricity market is believed to improve the overall efficiency of trading by creating more effective competition, increasing liquidity, and utilizing generation resources more efficiently across Europe (ENTSO-E, nd). As of the beginning of 2022, the countries highlighted in Figure 2.4 are operational members of SDAC. Further, the Croatian-Hungarian border is expected to be included in the SDAC coupling after the flow-based project is implemented (ENTSO-E, nd).

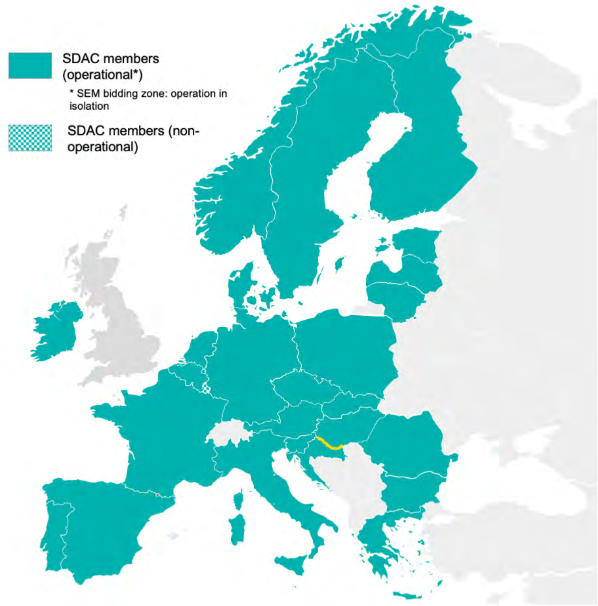

Figure 2.4: Overview of SDAC members as of May 2022, according to ENTSO-E (nd).

The discussion regarding the integration of European electricity markets has been a topic of high relevance for a long time, especially in the EU. The attention towards the topic has resulted in research and actions that facilitate the movement towards an internal market.

2.6 Development Towards A Single European Market

To reach the EU's target of 55% net emissions reductions by 2030, paving the way for climate neutrality by 2050, creating a single, interconnected electricity market is viewed as a significant contributor (European Environment Agency, 2021; Schönheit et al., 2021). The creation of a single market builds upon the concept of market coupling, which Schönheit et al. (2021) defines as *"the merging of individual, national markets to render possible the trade of electricity across a large geographical area"*. These electricity exchanges are facilitated by interconnectors between market zones and internal transmission networks (Schönheit et al., 2021). Interconnectors are defined by Turvey (2006) as transmission cables that connect two separate markets or pricing areas.

Historically, coupling electricity markets through interconnectors has primarily been performed to ensure the security of supply. In more recent years, market coupling has been mainly motivated by overcoming two major challenges. The first challenge concerns Europe's transition towards an internal electricity market. Creating an internal market is motivated by its believed enhanced competition, trade, and overall welfare. Still, a shortage of interconnections between the different markets is an obstacle to these intended effects (Jacottet, 2012). Hence, increasing interconnection capacity is essential in achieving an internal market.

The second challenge stems from the vast expansion of renewable electricity sources. Due to the nature of renewables, the production of renewable energy has to be sited where the resource is. Market coupling has proven to be an essential mechanism for suppressing the potential price impacts of expanding renewable energy production (Jacottet, 2012). In coupled markets, national surpluses and deficits are mitigated, thus providing more resilience against disturbances in supply and demand. Further, variations in renewable production, such as seasonal variations or day-to-day variations, can be counteracted between areas (EPEX SPOT, nda).

Overall, the EU and the European Parliament argue that market coupling can maintain high levels of security of supply through reliance on electricity generation from adjacent countries and integrating electricity generation from renewable energy sources. Hence, an internal market aims to achieve efficiency gains, competitive prices, and improve service standards while contributing to the security of supply and sustainability. Overall, these effects are expected to enhance social welfare in Europe (The European Parliament & Council of European Union, 2019).

With the establishment of the Energy Union in 2015 and other measures such as grid developments, the EU is trying to secure a free flow of energy through Europe. Thus, facilitating the movement towards a fully integrated internal energy market (The European Commission, 2015).

2.6.1 Interconnection Capacity: Transmission Lines

Interconnecting markets allows for improved resource utilization and will impact the market-clearing in both markets. Following this reasoning, Statnett argues that the newly opened cables NSL and NordLink allow for both better utilization of the involved countries' available energy and the facilitation of increased production of renewables (Statnett, 2020b). NSL and NordLink were launched for their trial period in October 2021 and December 2020. This thesis focuses on NordLink, due to data availability.

2.6.2 NordLink: Connecting Norway and Germany

NordLink is a subsea interconnector, providing the first direct connection between the Norwegian and German power markets. The cable is situated between NO2 in Norway and Schleswig-Holstein in Germany, making up 623 kilometers with a maximum capacity of 1400 MW (Statnett, 2020b). NordLink is a state-owned transmission line, owned and financed by Statnett, Tennet TSO GmbH, and the German state-owned bank KfW IPEX-Bank, in an equally shared partnership between Norway and Germany (KfW IPEX-Bank, nd; Statnett, nd).

NordLink is a HVDC transmission cable. Bahrman and Johnson (2007) states that HVDC technology is widely recognized as being advantageous for several applications, including long submarine cable crossings. In HVDC transmission systems, two different converter technologies are used. These are conventional line-communicated CSCs and self-communicated VSCs, also known as HVDC light (Bahrman and Johnson, 2007). NordLink uses the VSC technology (Callavik et al., 2015). Callavik et al. (2015) emphasizes three reasons to use the VSC-HVDC technology when connecting Norway and Germany. First, VSCs can connect two non-synchronized grids, thereby linking the frequencies of the separated Nordic and continental grids. Second, HVDC connections allow for long-distance electricity transmission with minimal losses. Third, converters support the AC network at the Norwegian and German points of common coupling (Callavik et al., 2015).

As highlighted in Table 2.1, a large share of the Norwegian power mix consists of the flexible source of hydropower. Germany also has an increased production capacity of intermittent energy sources, wind and PV. The countries' different access to renewable energy production is a motivational factor for market coupling, seeking optimal utilization of their resources. In periods with low levels of wind and sun in Germany, their need for energy increases, thus increasing their electricity prices compared to NO2. Statnett argues that in such a situation, Norwegian producers can improve the value of their power by exporting hydropower (Statnett, 2020b). On the other hand, in periods with high levels of wind and sun in Germany, excess electricity can be exported to Norway for either consumption or pumped storage (TenneT, nd).

Overall, national TSOs Tennet and Statnett describe NordLink as a connection between two complementary systems. The coupling is believed to facilitate increased use of renewable energy while improving value creation for power producers in both markets, as the utilization of excess power is improved (Statnett, nd; TenneT, nd).

2.6.3 Future Developments & Plans

Norway

A planed project for increasing interconnection capacity in Norway is NorthConnect, a proposed HVDC cable with a capacity of 1400 MW connecting Norway and Scotland. The cable is intended to transmit hydropower to Scotland while transmitting wind power to Norway (NorthConnect, nd). The concession application for NorthConnect is currently for review at The Norwegian Water Resources and Energy Directorate. However, as of April 2022, a concession will not be granted for the project, according to the Norwegian Minister of Finance (NTB, 2021).

Germany

Germany and Sweden are planning a new interconnector called Hansa Powerbridge, which will have a capacity of 700 MW. Hansa Powerbridge will, similarly to NordLink, use HVDC-SVC technology and is planned to start construction in 2024 if a concession is granted (Svenska Kraftnät, nd). Further, there are plans to increase the capacity between Germany and Denmark with a new interconnector between Klixbüll and Endrup. The cable is planned to begin construction in 2023 and will be both underground and overhead (TenneT and Energinet, nd). Another project is NeuConnect, a planned subsea interconnector between Germany and Great Britain with a planned capacity of 1400 MW. NeuConnect is planned to be completed in the mid-2020s (NeuConnect, nd). Lastly, Germany is planning to increase its cross-border transmission capacity with Austria by constructing a new 380 kV line (APG, nd). In addition to these highlighted projects, there are other prospects in the planning phase or under consideration [3]

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[3] See: https://tyndp2020-project-platform.azurewebsites.net/projectsheets/transmission

3 Data

Our data sample of hourly day-ahead prices consists of observations starting at the first trading hour of January 6th, 2015, for NO2. For Germany, the data sample starts at the latest trading hour at January 11th, 2015. Price data for both areas have the last observation at the last trading hour of September 30th, 2021. Observations beyond this date are not included in the analysis. This is mainly due to the opening of the NSL on October 1st, 2021, which changed the Norwegian electricity market in terms of 1400 MW becoming incrementally available for cross-border exchange.

Due to data availability, prices prior to January 2015 were also excluded from the data sets. As there have been no other major structural changes to either country's market structure between January 2015 and September 2021, observations from this period are considered representative of both markets. However, Austria exiting the German-Austrian price area on October 1st, 2018, is a market change that should be noted. The Austrian exit was due to a decision made by the Agency of Cooperation of Energy Regulators, where a congestion management procedure replaced the free trade of electricity at the countries' border (Austrian Power Grid, nd). Scientists predicted the split to affect prices in both areas slightly, but the effect was not expected to be significant. This is partly due to 4.9 GW of the commercial capacity between the countries being allocated in long-term cross-border auctions, which was a part of the countries' agreement regarding the change (Argus Media, 2018; Oroschakoff, 2018). Overall, the collected observations are considered adequate in illustrating price behavior in both NO2 and Germany.

3.1 Descriptive Statistics of Day-Ahead Prices

Data on day-ahead spot prices for NO2 in Norway have been collected from Nord Pool's FTP server. Day-ahead spot prices for the German price area, traded at EPEX Spot, have been extracted from Entso-e's Transparency Platform, a cooperative association created by countries' TSOs. Price data is observed hourly and is measured in EUR/MWh.

As aggregating our hourly price data to daily observations does not return more informative data, observations are kept on an hourly basis. Figure A1.1, A1.2, A1.3, and A1.4 in

Appendix A1, illustrates the differences in price distribution after the inception of NordLink, supporting the decision to keep hourly observations.

Electricity spot prices possess several characteristics. Geman and Roncoroni (2006) points out that they are mean-reverting, also across different markets. Another characteristic is small random movements around the average trend, representing the market's imbalance of supply and demand. Furthermore, a third characteristic is so-called price spikes (Geman and Roncoroni, 2006). Escribano et al. (2011) also points out characteristics such as seasonality, high volatility, and volatility clustering.

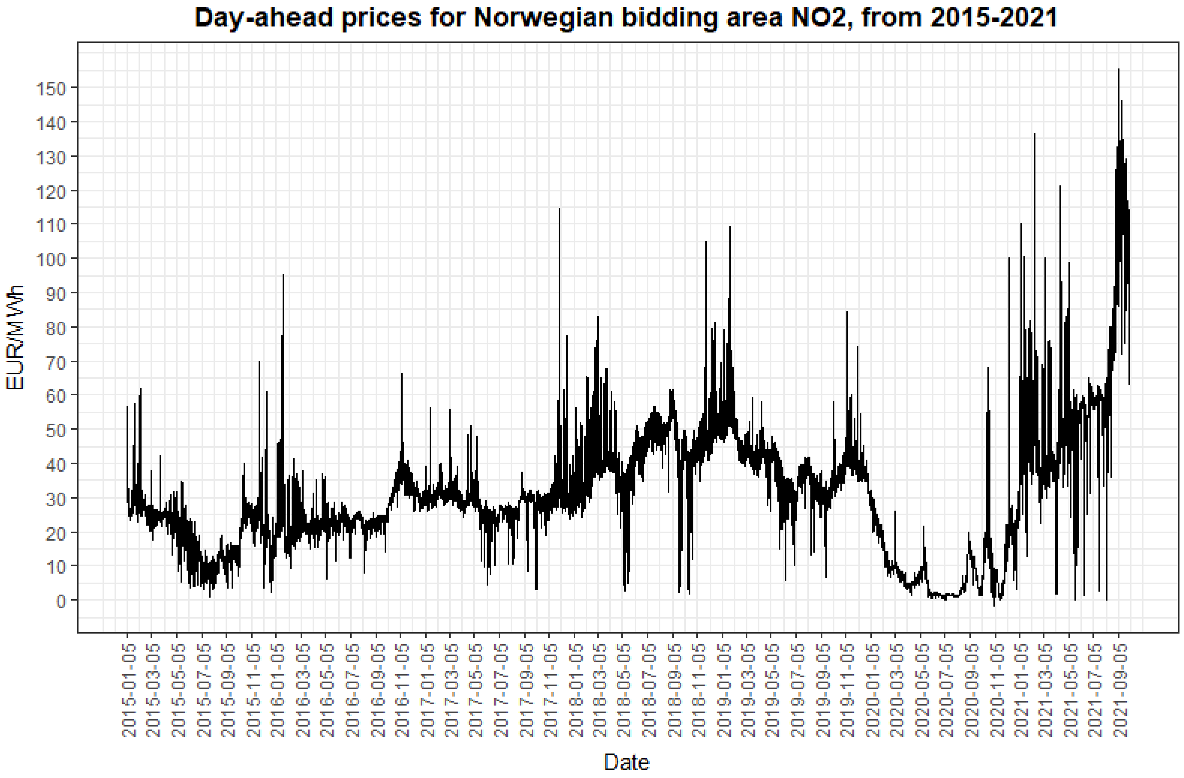


Figure 3.1: NO2 day-ahead prices for each hour of the day from 05.01.2015 - 30.09.2021.

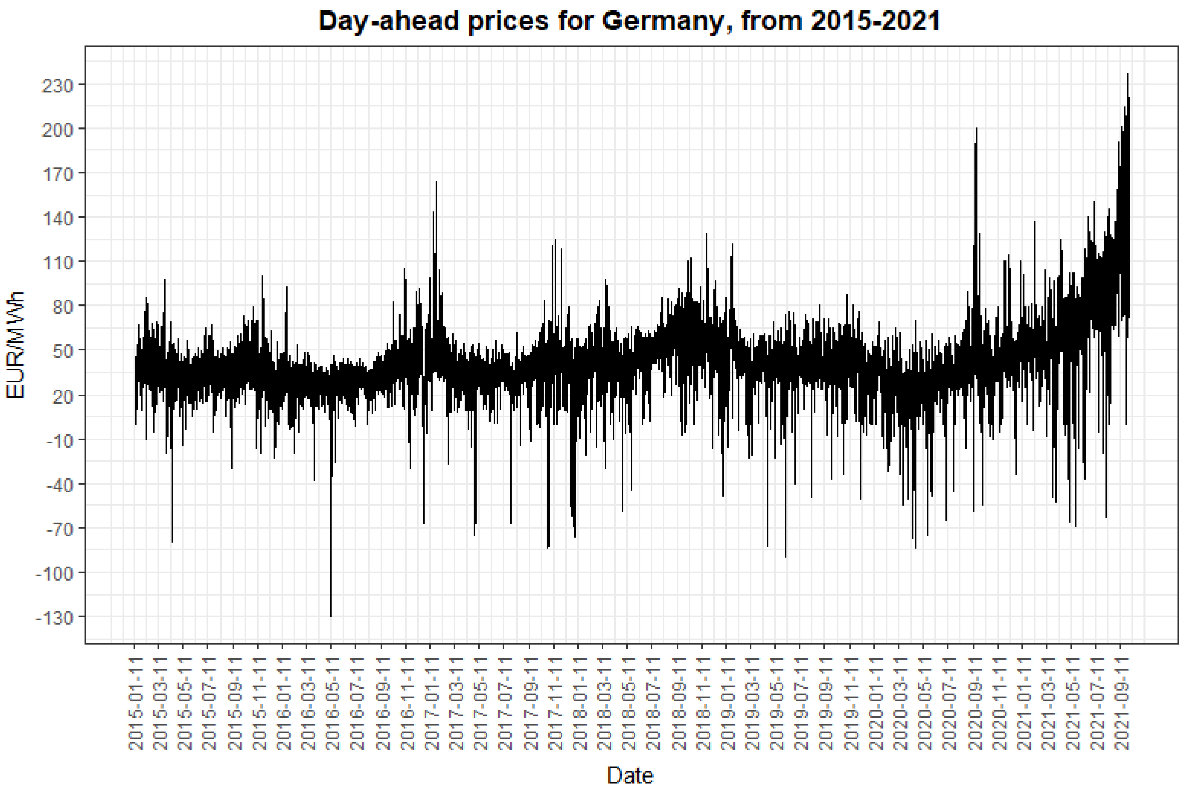
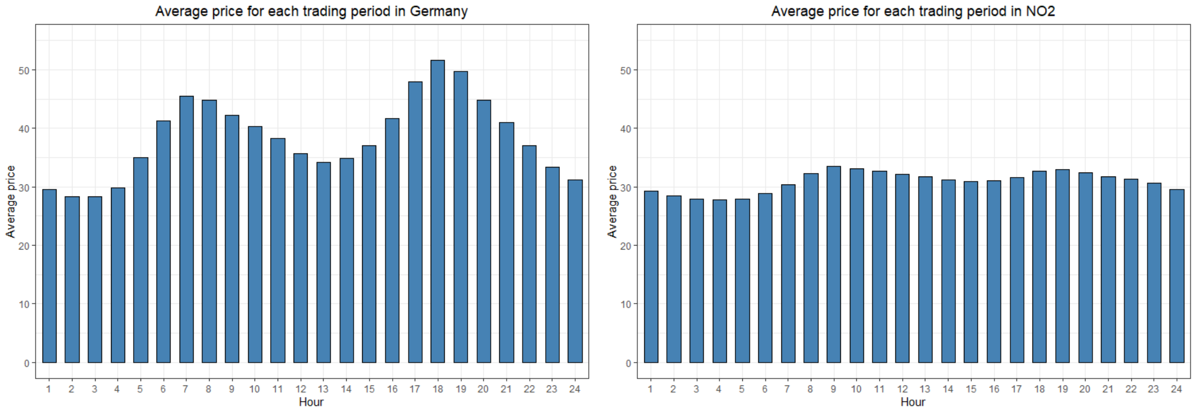
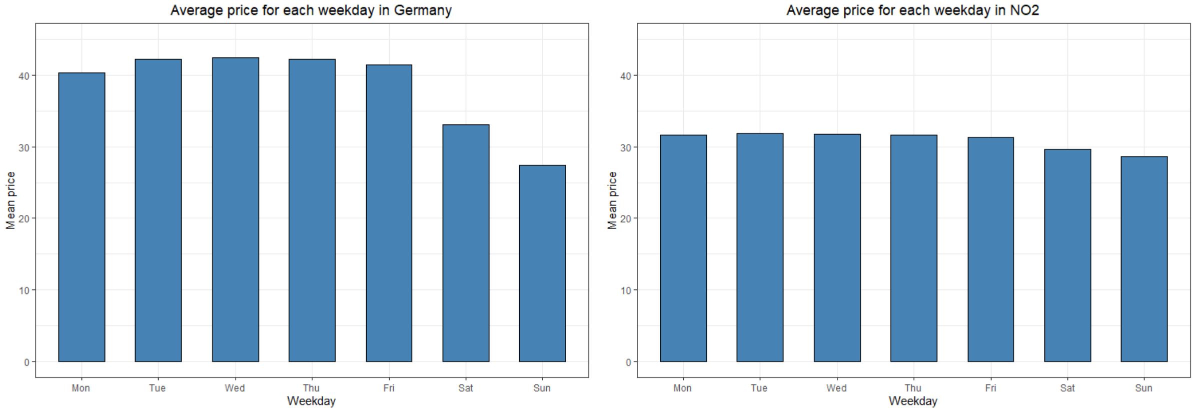


Figure 3.2: German day-ahead prices for each hour of the day from 11.01.2015 - 30.09.2021.

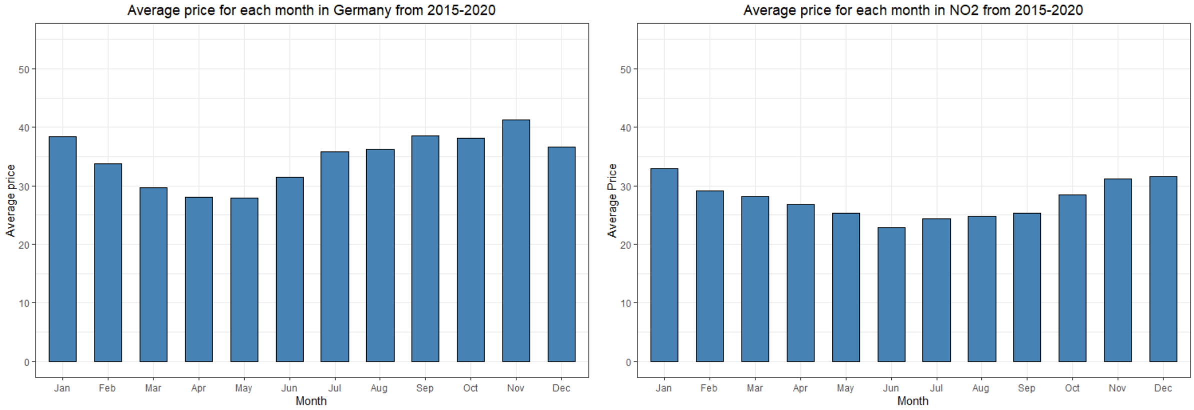
Figure 3.1 and Figure 3.2 show the day-ahead spot price series for NO2 and Germany. These figures indicate that both price areas exhibit occasional positive- and negative price spikes in addition to high volatility and volatility clustering, supporting the results from Geman and Roncoroni (2006). Mean reversion is more clearly seen in the German prices. Further, we notice seasonality in the price data, shown in Figure 3.3. These subfigures show that prices exhibit seasonality throughout the year, as warmer months have lower average prices. There are also lower price levels during weekends and differences throughout the hours of the day.



(a) Hour (Germany) **(b)** Hour (NO2)



(c) Weekday (Germany) **(d)** Weekday (NO2)



(e) Month (Germany) **(f)** Month (NO2)

Figure 3.3: Average day-ahead prices for each trading hour, weekday, and month, in NO2 and Germany from 2015 to 2021.

Table 3.1 presents the descriptive statistics of day-ahead prices for NO2 and Germany, consisting of 117 907 price observations in total. Noticeably, Germany has had the highest mean price of €38.48/MWh, compared to €30.93/MWh in NO2. Both markets' median price is smaller than their mean, indicating a higher chance of observing prices in their lower tail. This is supported by the positive skewness of both markets, implying a higher probability of observing prices at the lower end of the distribution. The price range in Germany is observed to be larger than in NO2, as both the registered maximum price of €237.01/MWh and minimum price of - €130.09/MWh is, respectively, higher and lower than the observed maximum of €155.36/MWh and minimum of -€1.73/MWh in NO2. Hence, the German market has both thicker and longer tails. Standard deviation is high for both markets, with Germany's value being 4.49 higher than Norway's value of 17.75. The high standard deviation substantiates the volatile characteristics of electricity prices in both markets. Germany having higher variation can be explained by its energy mix having larger shares of intermittent energy sources and its dependency on carbon-intensive energy sources, contributing to a higher market clearing point. A more extensive price range and higher variance imply that the German market is more likely to experience more extreme prices than NO2.

	NO2	**Germany**
Minimum	-1.73	-130.09
Maximum	155.36	237.01
Mean	30.93	38.48
Median	29.03	35.79
Standard deviation	17.75	22.24
Skewness	1.21	1.31
Kurtosis	6.87	10.76
Jarque-Bera	51237.04	164538.65
N	59010	58897

Table 3.1: Descriptive statistics of day-ahead prices.

Both markets' sizeable standard deviation, high positive excess kurtosis, and a high score on the Jarque-Bera test confirm that electricity prices' distributions are highly non-normal.

From Table 3.2 it is noted that the German market experiences negative prices more frequently than NO2. In general, negative prices occur when very low demand meets high supply. Fanone et al. (2013) argues that the limited flexibility of power plants can cause these situations. This is observed in Paraschiv et al. (2014), where high wind infeed is claimed to be a leading cause of negative prices during night hours in Germany. It is reasonable to assume that the inflexibility of wind power is a significant contributor to the negative prices observed in our data.

Hour	**Germany**	**NO2**	**Hour**	**Germany**	**NO2**
0	75	0	12	94	0
1	85	0	13	93	0
2	85	1	14	62	0
3	73	1	15	25	0
4	53	1	16	7	0
5	54	2	17	1	0
6	38	0	18	2	0
7	28	0	19	8	0
8	37	0	20	13	0
9	43	0	21	7	0
10	54	0	22	33	0
11	81	0	23	60	0

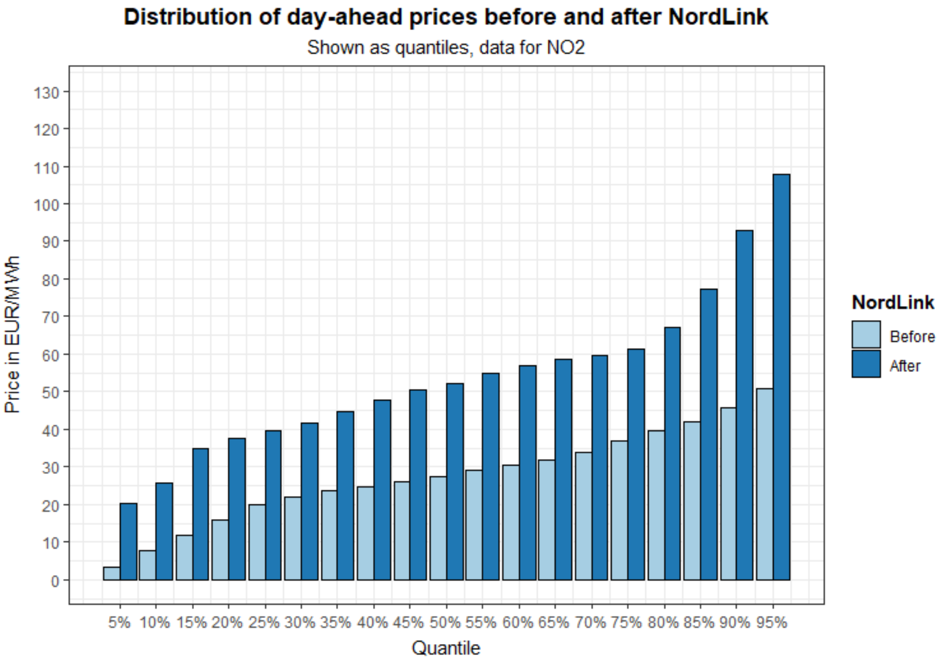
Table 3.2: The number of negative price observations in each trading period, data for bidding area NO2 and Germany.

As shown in Table 3.3, the empirical quantiles at the 5% - 95% level for the price series confirm large variations, as prices increase consistently across quantiles. There is also a substantial size difference between the 5% and 95% quantile, indicating a large variance between the highest and lowest parts of the distribution. The variance and different price levels across the distribution support the choice of quantile regression as a suitable method for modeling electricity prices. This is further supported by the findings in Figure 3.4a and 3.4b, presenting day-ahead prices in NO2 and Germany before- and after the implementation of NordLink. The figures illustrate a substantial increase in price levels across quantiles and a difference in the relative increase for each quantile. For example, the relative increase in prices for NO2 is most substantial in the lowest quantile.

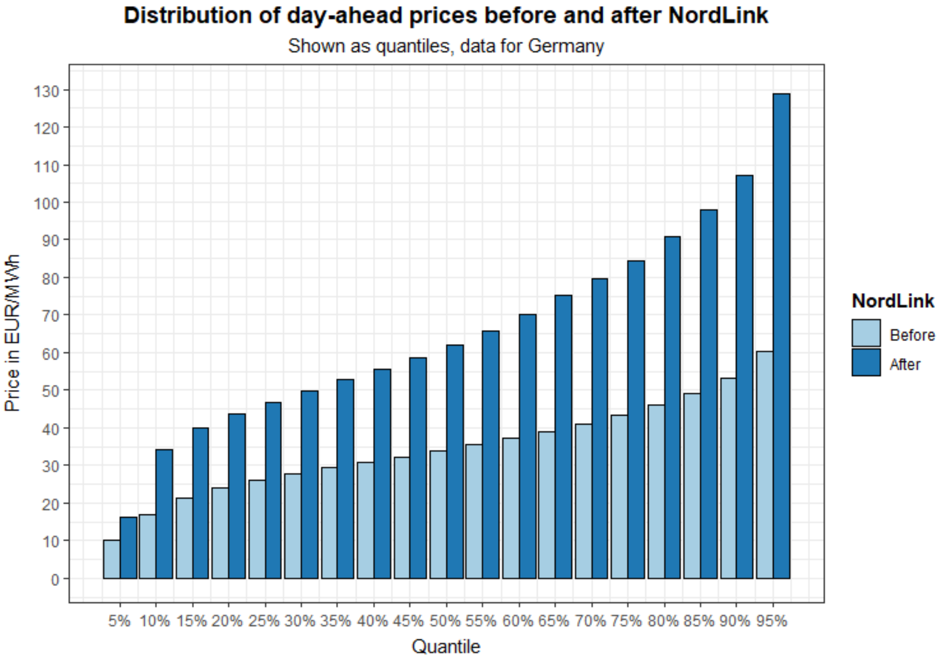
Quantile	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
NO2	3.98	8.88	13.02	18.00	21.23	23.07	24.41	25.91	27.38	29.05
Germany	10.17	17.75	22.00	24.73	26.90	28.77	30.34	32.07	33.97	35.79

Quantile	55%	60%	65%	70%	75%	80%	85%	90%	95%
NO2	30.57	32.20	35.03	37.90	40.27	42.95	47.14	51.55	58.50
Germany	37.62	39.64	41.91	44.34	47.02	50.20	54.80	61.92	76.64

Table 3.3: Empirical quantiles of day-ahead prices for NO2 and Germany for the complete data set.



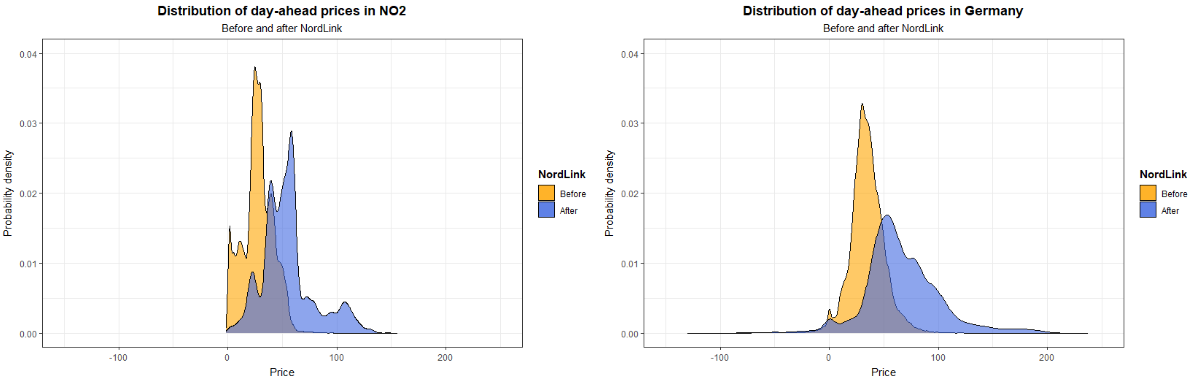
(a) NO2



(b) Germany

Figure 3.4: Distribution of day-ahead prices in NO2 and Germany, before and after NordLink opened.

The relevance of assessing NordLink's impact on electricity prices is further supported by Figure 3.5, which shows the probability density of different prices in NO2 and Germany before and after NordLink. Both figures show clear differences in the probability for different price levels before and after NordLink was introduced. These differences suggest a larger probability of observing higher prices in both areas after NordLink. Our thesis aims to analyze whether the price difference is due to NordLink or other factors in our model.



(a) NO2 **(b)** Germany

Figure 3.5: Distribution of day-ahead prices in NO2 and Germany, before and after NordLink opened.

3.2 NordLink Power Cable

A dummy variable for the inception of NordLink is used to capture its effect on day-ahead prices in NO2 and Germany. The dummy is given the value of 0 for every observation prior to December 9th, 2020, and a value of 1 for every observation after, reflecting the availability of the cable. December 9th, 2020, is preferred as a starting point as it is the first day of physical electricity flow through the cable (Statnett, 2020a). However, it should be noted that the cable opened with a capacity constraint of 700 MW, which was further increased to 1400 MW during December 2020 (Statnett, nd). Due to almost the entire trial period, between December 9th, 2020, and March 31st, 2021, having the cable's maximum capacity available, all observations are included for the dummy.

3.3 Control Variables

Day-ahead electricity prices are affected by several fundamental factors. The included fundamental variables and their impact is introduced and discussed in this section. The results for the control variables are presented and interpreted in the Appendix Section A2.

The included control variables do not exhibit problems with collinearity, with pairwise correlations shown in Figures A1.5 and A1.6 in Appendix A1.

Table 3.4 shows an overview of data granularity and the sources from which the data is gathered.

Variable	Hourly	Daily	Weekly	Data source
Day-ahead electricity price, EUR/MWh	x			Nord Pool, ENTSO-E
Demand forecast, MW	x			ENTSO-E
Import capacity, MW	x			Nord Pool, ENTSO-E
Export capacity, MW	x			Nord Pool, ENTSO-E
Wind production, MW	x			ENTSO-E
Solar production, MW	x			ENTSO-E
Reservoir level, GWh			x	Nord Pool
Electricity certificate price, EUR		x		Macrobond
Lagged spot price, EUR/MWh	x			Nord Pool, ENTSO-E
Price volatility, EUR/MWh	x			Nord Pool, ENTSO-E
Coal price, EUR/1000t		x		Bloomberg, Ticker: API21MON OECM Index
Gas price, EUR/MWh		x		Bloomberg, Ticker: EGTHDAHD OECM Index
Oil price, EUR/bbl		x		Bloomberg, Ticker: CO1 Comdty
EUA price, EUR/1000t CO_2		x		Bloomberg, Ticker: DBRST3PA Index

Table 3.4: Overview of data granularity and data source for the variables included in the models.

The variables for reservoir levels, electricity certificates, coal-, gas-, oil-, and EUA prices have the same values when estimating the models for both NO2 and Germany.

Adaptive behavior

Market participants are influenced by historical prices and risk signals, affecting their price expectations and risk aversion (Paraschiv et al., 2014). Therefore, a variable with prices from the previous day is included, as they are likely to have an explanatory effect on electricity prices. Further, Bunn et al. (2016) argues that adaptive behavior is shown through market participants reinforcing previously successful offers, resulting in high prices being followed by high prices.

In line with Bunn et al. (2016) and Paraschiv et al. (2014), we expect lagged spot prices to have a positive effect on today's prices across quantiles. Following Bunn et al. (2016), we also expect to see this effect being greater at higher quantiles, as these periods are known to be less competitive, thereby making gaming more possible and plausible.

Price volatility

In an attempt to capture effects regarding price uncertainty that is not already ingrained in the other fundamental factors, we include a price volatility term. As described in Karakatsani and Bunn (2010), price volatility is an indicator of price instability and risk, which might influence the market participants' risk aversion. Hence, it is likely important to explain today's electricity price.

As a proxy for price volatility, we compute the standard deviation of the hourly spot prices in a seven-day moving window. Following the results from Bunn et al. (2016), we expect price volatility to negatively depend on the spot prices for lower quantiles and positively depend on the spot prices for higher quantiles. Bunn et al. (2016) explains that in times of low prices, an increase in volatility tends to drive prices even lower, and in times of higher prices, an increase in volatility tends to drive prices even higher. In short, Bunn et al. (2016) finds price volatility to have an amplifying effect on both low and high prices.

Demand forecast

Electricity demand is close to inelastic in the short run. However, it will vary with the consumption patterns of consumers like industry and households. Demand has a basic level which it rarely goes below in addition to it following a periodic pattern (Cretì, 2019, p. 84). It also tends to follow different time trends, shown in Cretì (2019, p.84), where demand follows a weekly pattern with lower levels during the weekends.

We have access to day-ahead demand forecasts for each given hour for both markets, which are included in the models. Since we are using day-ahead prices, demand is demonstrated through day-ahead forecasts rather than actual demand data. Using forecasts is viewed as the most sensible approach, as this is the information available for market participants, which inevitably sets the market-clearing price. Similar to Bunn et al. (2016), we expect demand to have a positive effect on hourly day-ahead prices while increasing nonlinearly towards the higher quantiles. This expectation is based on the assumption of a convex supply function in available capacity, leading to demand having higher effects at higher prices (Bunn et al., 2016). It should be noted that there is associated missing data for NO2, these observations are therefore not included in the data set.

Transmission capacities - Import and Export

As described in Section 2.4, transmission capacity is included when calculating area prices. Transmission cables are intended to eliminate or decrease price differences, as electricity is exchanged between areas with a deficit or surplus. Hence, imports and exports are expected to have different effects on electricity prices and will be included as two separate variables. Since information on cross-border capacities is available for participants in the day-ahead market, these capacities are used in the models. Actual cross-border flow is also likely to be affected by trades in the intraday market, making it less suitable when investigating day-ahead prices. We expect import capacity to positively affect prices across quantiles and export capacity to negatively affect prices across quantiles.

Renewable energies

From Tables 2.1 and 2.2, it is clear that renewable energy sources make up a significant part of the overall electricity production in both markets. Wind power and PV power are the two prominent renewable electricity sources in Germany, while hydropower and wind power are most prominent in Norway.

Wind power & Photovoltaic power

A common finding from literature is that renewables such as wind- and PV power crowd out fossil-fueled units, exercising a downward pressure on electricity prices (Cludius et al., 2014; Ketterer, 2014; Paraschiv et al., 2014; Sapio, 2019). This effect is mainly caused by their low operational costs and that they must run when there is access to either wind- or PV power.

Since the thesis focus on day-ahead prices, we see it as appropriate to use day-ahead generation forecasts instead of actual generation. The use of forecasts is due to the difference in actual generation compared to the results in the day-ahead market, as a consequence of trading in the intraday- or the balancing market. As both wind- and PV power should exercise a downward pressure on prices, we expect their coefficients to be negative across quantiles for both markets.

Water Reservoir Levels

Contrary to intermittent energy sources such as wind and PV, hydropower is a dispatchable energy source. Dispatchability allows producers to optimize the value of their stored water depending on the current prices and future expectations. It is also an energy source with very low operational costs, making it one of the first energy sources in the merit order unless the current water value increases its marginal costs extensively. Water reservoir levels are expected to change the competitive environment in the electricity market, depending on whether it is high or low.

Hydropower producers would want to sell when reservoir levels are high to prevent low water value and invaluable spillovers. Huisman et al. (2014) argues how this increased drive to sell hydropower puts more pressure on the competition, consequently lowering prices where the power is consumed. High reservoir levels can also increase Norwegian electricity prices if certain market conditions are present. Døskeland et al. (2022) argue that this was the case during a lot of 2021, as high reservoir levels and high European electricity prices encouraged hydro producers to produce- and export substantial amounts of hydropower despite the low water inflow. In contradiction, low reservoir levels would make hydropower producers more reserved about their actions, making their competitive behavior more strategic. Hydro producers will then carefully pick the moments to produce based on when the water value is high (Huisman et al., 2014). It should be noted that hydro reservoir levels have been linearly interpolated from weekly- to daily data. Results of the interpolation can be seen in Figure A1.7 in the Appendix.

Fossil Fuel Prices

As seen in Section 2.2, production stemming from fossil fuels represent a significant amount of the total electricity production in Germany. Contrary, fossil fuels are not a considerable part of Norwegian electricity production, as shown in Section 2.1. However, fossil fuel prices affect the opportunity cost of water and thus the water values. Hence, fossil fuel prices are included as control variables. Notably, oil is not a significant source of electricity production in either Germany or Norway. Nonetheless, oil prices are included as a control variable due to their considerable impact on the transportation costs of imported coal (Paraschiv et al., 2014).

Following Bunn et al. (2016), we expect fuel prices to have a positive effect on day-ahead prices. It should be noted that the markets for fossil fuels are closed during weekends. The corresponding missing data is filled with the last observed price. Meaning that the price observation for Friday is also used for Saturday and Sunday as it represents the latest available information for market participants.

EUA Prices

The market for EUAs is an international effort to shift investments to renewable energy by making carbon-intensive production more expensive. The overall volume of greenhouse gases that can be emitted is limited by a cap in the EU Emissions Trading System. Within this cap, companies can receive or buy allowances that can be traded as needed. The cap decreases every year, which ensures that emissions fall (European Commission, nd). Each allowance gives the owner the right to emit 1 tonne of CO_2 or the equivalent amount of other greenhouse gases (European Commission, nd).

As stated in Paraschiv et al. (2014), carbon-intensive electricity generation such as coal- and gas-fired power plants are influenced by the price of EUAs as it increases costs of production. Fuel switching can be observed during a phase of high EUA prices. Fuel switch is a change in the merit-order curve, where plants emitting less CO_2 in production obtain lower marginal production cost than more CO_2-intensive plants (Paraschiv et al., 2014). Overall, the price for EUAs will impact electricity prices through its effect on fossil fuels. Similar to Bunn et al. (2016), we expect the electricity prices to depend positively on EUAs. The market for EUAs is also closed during weekends. Using the same rationale as for fuel prices, we fill in missing data with the latest price observation.

Electricity Certificates

Electricity certificates are a scheme to support renewable energy production in Norway and Sweden. A certified plant will receive one electricity certificate per produced MWh, which the producers can trade. Retailers are obliged to cover the electricity they sell to consumers with a certain share of electricity certificates, which makes up the demand for the certificates (NVE, 2022). The renewable electricity producers will then have two revenue streams; one from selling the electricity and another from selling electricity certificates. The additional revenue will make production more profitable. The price of electricity certificates reflects the cost differential between renewably based- and thermally based production. This cost differential is the subsidy (price) needed to ensure the desired deployment of renewable energy, meaning that an increase in electricity certificate price implies a lower electricity price (Jensen and Skytte, 2002). This system ensures that the marginal costs of production are covered.

Due to the price computation of electricity certificates, we expect it to affect electricity prices negatively. Similar to the markets for fuel prices and EUAs, the market for electricity certificates is closed during weekends. In addition, the data is only updated when the certificate price changes. Thus, there are associated missing data. Using the same rationale as for fuel prices and EUAs, we fill in missing data with the latest price observation.

Time Variables

The model includes dummy variables for hours, months, weekends, and holidays to control for time's effect on electricity prices. Time can affect prices by impacting supply, which is highly relevant in the case of Norway and its production of hydropower. Hydropower capacity is determined by installed capacity and water inflow, implying that hydropower supply relies on water inflow, which varies substantially during the year, and from year to year. Inflow is usually highest in the spring and autumn while lower during summer and winter (Norwegian Ministry of Petroleum and Energy, 2021a). Hence, variations in both supply and demand will naturally affect the electricity price.

As seen in Figure 3.3, the given hour of the day is expected to exhibit different price levels. Therefore, we include dummies for each hour of the day, with 00:00-01:00 serving as the baseline. Additionally, demand follows a pattern on an intra-day scale. It is lowest during the night, increases during the day, declines slightly during mid-afternoon, and increases again during the early evening before falling again during nighttime (Cretì, 2019, p. 84). As a result, we expect hour dummies where demand is higher to affect prices positively and vice versa.

To control for different months, we include dummies for February to December, while January serves as the base period. Further, we include a dummy variable for weekends, which takes the value of 1 if the day is either a Saturday or Sunday. Lastly, we want to control for public holidays' effect on electricity prices. For this purpose, we include a variable that equals 1 if the date is a national holiday in the respective country. Table A1.1 in the Appendix, summarizes which holidays are included in the dummy variable. We expect both weekends and holidays to have a negative effect on prices because of their lower levels of demand. With reference to Figure 3.3, we expect the winter months to experience higher electricity prices than periods with warmer temperatures, such as summer and spring.

In addition to the included dummies, we construct a variable that aims to capture the general time trend throughout our sample. Including a time trend in the regression allows us to capture the exogenous increase in electricity prices that the included independent variables do not explain, making it sensible to control for in the model. The variable is constructed as an ordered set of natural numbers that increases with each day of our data sample. Consequently, $Timetrend = 1$ for the first day in our data samples and increase by 1 for each day.

4 Methodology

4.1 Quantile Regression

Quantile regression was first introduced by Koenker and Bassett Jr (1978) and is a method that seeks to estimate the conditional relationship between the dependent variable and the independent variables for different quantiles. This differs from standard OLS regression, which models the relationship between the independent variables and the conditional mean of the dependent variable. Quantile regression models a linear regression line independently for each quantile, which allows for studying any given position of the distribution. This feature enables a more complete understanding of how the dependent variable's distribution is affected by the independent variables, including information about shape change (Hao et al., 2007, p.4). Thus, it allows for a more comprehensive understanding of the independent variables' effect on the dependent variable. As seen in Table 3.3, electricity prices in our sample vary significantly across the distribution, further supporting the use of quantile regression. In addition, Table 3.1 reveals minimum and maximum prices substantially distant from the median and mean values, implying outliers in the data. Quantile regression estimates are robust against outliers due to it minimizing the weighted sum of absolute residuals, further supporting the use of the method (Hao et al., 2007, p.41). Finally, the quantile regression model makes no assumptions regarding the distribution, which is particularly useful in the case of electricity prices due to its high skewness and excess kurtosis.

The aim of our study and the characteristics of our data is similar to most of the conditions presented in Waldmann (2018), argued to be the situations most suited for using quantile regression. This includes the analysis of given positions in the distribution, the number of outliers, and the unknown type of distribution. Hence, quantile regression is a suitable method for answering the research question. The general quantile regression model can be expressed as:

$$Q^q(P_{h,d}|X_{h,d}) = \alpha^q + \boldsymbol{\beta}^q \boldsymbol{X}_{h,d} + \epsilon^q_{h,d} \tag{4.1}$$

where Q^q is the conditional q-quantile function of the day-ahead price $P_{h,d}$, as $0 < q < 1$ indicate the different quantiles q. α^q is a constant term at quantile q, and $\boldsymbol{\beta}^q$ is a vector of estimated coefficients for the predictors $\boldsymbol{X}_{h,d}$ associated with the quantile q. The error term is $\epsilon^q_{h,d}$, where the subscript h denotes the trading hour, and d denotes the day.

As described in Waldmann (2018), a potential disadvantage of using quantile regression is the difficulties of estimating coefficients due to them being unavailable in closed form. As a result of these difficulties, various methods exist for estimating quantile regression coefficients, but there is little consensus on which method is superior. We have applied a linear optimization algorithm, which Koenker and Portnoy presented in 1997 (Waldmann, 2018). This method computes the estimated constant α^q and the estimated vector of coefficients $\boldsymbol{\beta}^q$ by solving the minimization problem for a given quantile q:

$$\underset{\alpha^q \boldsymbol{\beta}^q}{min} \sum_{d=1}^{D} (q - 1_{P_{h,d} \leq \alpha^q + \boldsymbol{\beta}^q \boldsymbol{X}_{h,d}})(P_{h,d} - (\alpha^q + \boldsymbol{\beta}^q \boldsymbol{X}_{h,d})) \tag{4.2}$$

where

$$1_{P_{h,d} \leq \alpha^q + \boldsymbol{\beta}^q \boldsymbol{X}_{h,d}} = \begin{cases} 1, & \text{if } P_{h,d} \leq \alpha^q + \boldsymbol{\beta}^q \boldsymbol{X}_{h,d} \\ 0, & \text{otherwise} \end{cases} \tag{4.3}$$

Function 4.3 equals 1 when the residual is negative and 0 when the residual is positive. A residual is the difference between the actual observed electricity price and the fitted value from our model, $P_{h,d} - \hat{P}_{h,d}$. The minimization problem seeks to estimate coefficients that minimize the weighted sum of absolute residuals. Underpredictions, where the residuals are positive, have a weight of q. Overpredictions, where the residuals are negative, have a weight of $|q - 1|$. Hence, the model minimizes the weighted absolute distances from the observed values to the fitted values of the model (Hao et al., 2007, p.37). Hao et al. further explains that the proportion of data points lying below the fitted line $\hat{\alpha}^q + \hat{\boldsymbol{\beta}}^q X_{h,d} + \hat{\epsilon}^q_{h,d}$ equals q and the proportion of data points lying above the fitted line equals $1 - q$. An overall example could be the estimation of coefficients for the 20% quantile. The estimation would give observations below the line a weight of 80%, while observations above are given a weight of 20%. Consequently, 80% of the observations will have negative residuals, while the remaining 20% will have positive residuals.

We fit two regression models with the control variables presented in Section 3.3, one for Germany and another for NO2. The two areas are differentiated by the subscript i, where the model is expressed as follows:

$$Q^q(P_{h,d,i}) = \alpha_i^q + \beta_{C,i}^q NordLink_d + \gamma_{h,d,i}^q + \phi_{h,i,d-1}^q + \Omega_{h,i,d}^q + \epsilon_{h,d,i}^q \tag{4.4}$$

where control variables consist of

$$\begin{aligned} \gamma_{h,d,i}^q &= \beta_{1,i}^q ImportCap_{h,d,i} + \beta_{2,i}^q ExportCap_{h,d,i} \\ &+ \beta_{3,i}^q Demand_{h,d,i} + \beta_{4,i}^q WindProd_{h,d,i} \\ &+ \beta_{5,i}^q PVProd_{h,d,i} + \beta_{6,i}^q Volatility_{h,d,i} \\ &+ \beta_{7,i}^q ResLevel_d \end{aligned} \tag{4.5}$$

and,

$$\begin{aligned} \phi_{h,d-1,i}^q &= \beta_{8,i}^q CoalPrice_{d-1} + \beta_{9,i}^q GasPrice_{d-1} \\ &+ \beta_{10,i}^q OilPrice_{d-1} + \beta_{11,i}^q EUAPrice_{d-1} \\ &+ \beta_{12,i}^q ElCertificate_{d-1} + \beta_{13,i}^q LagPrice_{h,d-1,i} \end{aligned} \tag{4.6}$$

and fixed effects consist of

$$\begin{aligned} \Omega_{h,d,i}^q &= \beta_{14,i}^q MonthDummy_d + \beta_{15,i}^q WeekendDummy_{d,i} \\ &+ \beta_{16,i}^q HolidayDummy_d + \beta_{17,i}^q HourDummy_h \\ &+ \beta_{18,i}^q TimeTrend_d \end{aligned} \tag{4.7}$$

We let q vary between the 5% and 95% quantile, separating the quantiles at 5% intervals. The spot price for each day in the day-ahead market $P_{h,d}$ is the dependent variable on $\boldsymbol{X}_{h,d}$, which is the 19-dimensional vector of explanatory variables, with the first observation equalling $d = 1$. In the baseline model expressed in Equation 4.4, explanatory variables $\boldsymbol{X}_{h,d}$ are divided into the cable dummy $NordLink$, control variables $\gamma_{h,d,i}^q$ and $\phi_{h,d-1,i}^q$, and fixed effects $\Omega_{h,i,d}^q$, with each variables' corresponding coefficient. NordLink's coefficient is represented through $\beta_{C,i}^q$, control variables' coefficients as $\beta_{1-13,i}^q$, and fixed effects as $\beta_{14-18,i}^q$. In addition to the model terms specified above, interaction terms between the NordLink dummy and other control variables will be introduced at a later stage.

Standard errors are obtained by bootstrapping. The bootstrap is a resampling method used to estimate statistics such as standard errors by sampling a data set with replacement (James et al., 2013). The method is advantageous since it makes no assumptions about the distribution of the response variable or the error term. The bootstrap approach for obtaining standard errors is therefore preferred over other asymptotic approaches since they often rely on strong parametric assumptions, such as independently and identically distributed errors, that are unlikely to hold (Hao et al., 2007, p.47).

4.1.1 Timing of Variables

When modeling day-ahead electricity prices, it is crucial to handle the time aspect of the information correctly. We want our model to reflect the information available to the market participants when submitting their bids in the day-ahead auction. Therefore, the price of fossil fuels, EUAs, and electricity certificates, are lagged by one day. For example, this would imply that day-ahead prices on January 10th are regressed on the corresponding values for fuel prices, EUAs, and electricity certificates for January 9th.

4.1.2 Transformation of Price Data

Studies such as Bunn et al. (2016) apply log transformation to obtain a series with more stable variances. On the other hand, Paraschiv et al. (2014) and Karakatsani and Bunn (2010) argue that a log transformation could imply multiplicative error- and exponential causal effects, in addition to not being ideal for all interpretations. Further, log transformation can only be applied to positive numbers, whereas our price data contains negative values. Our thesis aims to investigate NordLink's effect on aspects such as price volatility and peak-shaving. Hence, we are interested in analyzing extreme prices that would be largely mitigated through log transformation as it would include the transformation of negative prices (Do et al., 2019). As this thesis relies on coefficients' sign and shape to answer our hypotheses, transforming data to compare variables' coefficients on a log level is not considered necessary. To maintain all available information in the data and due to interpretability purposes, log transformation is not applied in the thesis.

Lastly, Do et al. (2019) argues that log transformation is justified if extreme prices exceed the average price in the order of several magnitudes. As shown in Section 3.1, this is not the case for either NO2 or Germany, supporting the decision of using price data directly rather than their logarithmic form.

4.2 Expected Results: NordLink

The expected effects from NordLink on Equation 4.4, are summarized in Table 4.1 and 4.2, where $\beta^q_{C,i}$ is NordLink's coefficient estimate.

Effect	**Result**
Price convergence	$\beta^{0.5}_{C,i} > 0$
Volatility exacerbation	$\beta^q_{C,i}$ increasing across quantiles

Table 4.1: Hypotheses for NO2 and their corresponding expected results.

Effect	**Result**
Price convergence	$\beta^{0.5}_{C,i} < 0$
Volatility reduction	$\beta^q_{C,i}$ decreasing across quantiles
Peak shaving	$\beta^q_{C,i} < 0$ for q large

Table 4.2: Hypotheses for Germany and their corresponding expected results.

Price Convergence

One of the expected effects of NordLink is price convergence, as the integration of markets should converge prices in the two areas. NordLink is therefore presumed to perform a downward pressure on prices in the German market, as their historical electricity prices are higher than Norway's. As a result of Norway's lower prices and possible excess hydropower, we expect the majority of electricity through NordLink to be exported from NO2 to Germany. These expected results create the hypothesis regarding price convergence, shown through the sign of the cable-dummy coefficient. We expect NordLink's coefficient to be negative around the median of the price distribution in Germany and be positive around the median of distribution in NO2.

Volatility Developments

As market integration should improve the allocation of resources, Sapio (2019) argues that a transmission line should mitigate volatility in both markets. However, due to Germany's high and volatile prices caused by their large share of intermittent energy sources, we do not expect volatility mitigation in NO2. Hence, volatility reduction from NordLink is expected in Germany through a decreasing pattern across quantiles for the cable's coefficient estimates, indicating a convergence between the lowest- and highest price levels in the distribution. This convergence would imply a smaller variance in the price distribution, indicating reduced volatility. In discord with Sapio (2019), who finds a shift in the sign of the coefficients, we could potentially see coefficient estimates being consistently negative across quantiles. Negative values across quantiles will be the case if German prices at the distribution's tails are also reduced.

Contrary, we could also see a volatility increase in NO2, in line with the argumentation in de Menezes and Houllier (2015). de Menezes and Houllier highlights that interconnecting European electricity markets imply a trade-off between lower average prices and export of volatility from markets that are larger and likely more dependent on intermittent electricity sources.

Peak Shaving

Market integration will increase competition in both NO2 and Germany, which reduces the possibility of exercising market power when there is a scarcity of electricity. As transmission cables move electricity towards the area with the highest prices, we would expect NordLink to negatively affect the highest prices, where demand is usually high. Due to the intermittent energy sources in Germany, we believe it is unlikely for them to counteract high prices in NO2. On the other hand, we expect the exchange of dispatchable hydropower from Norway to have a peak shaving effect on German electricity prices. As a result, we expect price levels in the higher quantiles in Germany to decrease following the implementation of NordLink. We do not expect to see this effect from NordLink in the results for NO2.

5 Results & Discussion

In the following chapter, the results of the NordLink cable dummy are presented. These results make up the main part of this thesis and will be interpreted with a focus on the hypotheses described in Section 4.2. Further, mechanisms that are possible underlying causes for these results will be analyzed and discussed. Results of control variables can be found in Appendix A2. In addition to estimates from quantile regression, estimates from OLS regression and their confidence interval are reported as the solid- and dotted red lines.

5.1 NordLink Results: NO2

5.1.1 Naive Model Specification

Initially, we estimate a naive model that only includes the cable dummy as an explanatory variable. This will provide us with a strictly before-after assessment regarding the first market exchange through NordLink on December 9th, 2020.

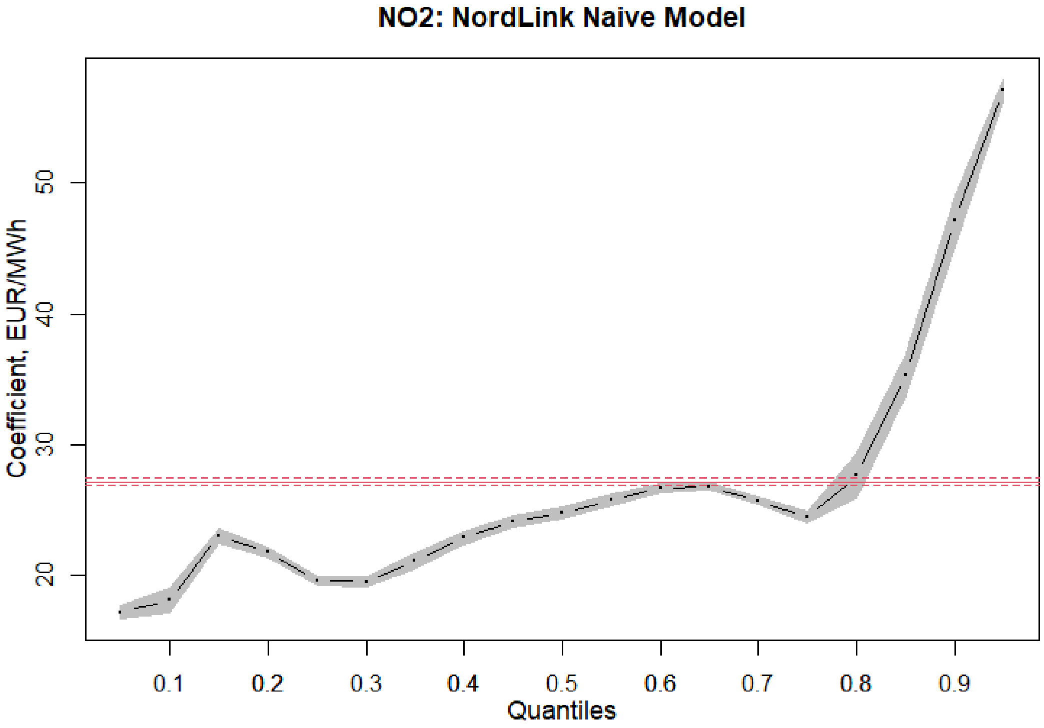


Figure 5.1: Quantile regression estimates of the NordLink cable dummy when using a naive model.

The positive sign of coefficient estimates in Figure 5.1 suggests that prices in NO2 have increased after the inception of NordLink. Further, the estimates' values rise across quantiles, with substantially larger magnitudes in the higher quantiles. The increasing pattern suggests that the cable has had a more substantial effect on the highest price levels. All coefficient estimates are significant at a 5%-level.

Increased electricity prices following the introduction of NordLink are not surprising, but its magnitude and consequently strong effect on prices was not expected. These results are likely caused by the naive model specifications, as various other factors should be controlled for to isolate the cable's effect on prices. As shown in Figure 3.1 in Section 3.1, electricity prices have significantly increased in 2021. This increase indicates that our naive model mainly captures the general increase in electricity prices but reveals limited information about NordLink's effect on prices. Therefore, we estimate a new model that controls for all fundamental variables.

5.1.2 Controlling for Fundamental Variables

When controlling for fundamental factors, we include the variables that compose $\gamma^q_{h,d,i}$ and $\phi^q_{h,i,d-1}$ in Equation 4.4 in Chapter 4. These variables include forecasted demand, import- and export capacity, forecasted wind production, forecasted PV production, fuel prices, EUA prices, electricity certificates, price volatility, adaptive behavior, and reservoir level.

NordLink's coefficient estimates with this model specification are shown in Figure 5.2.

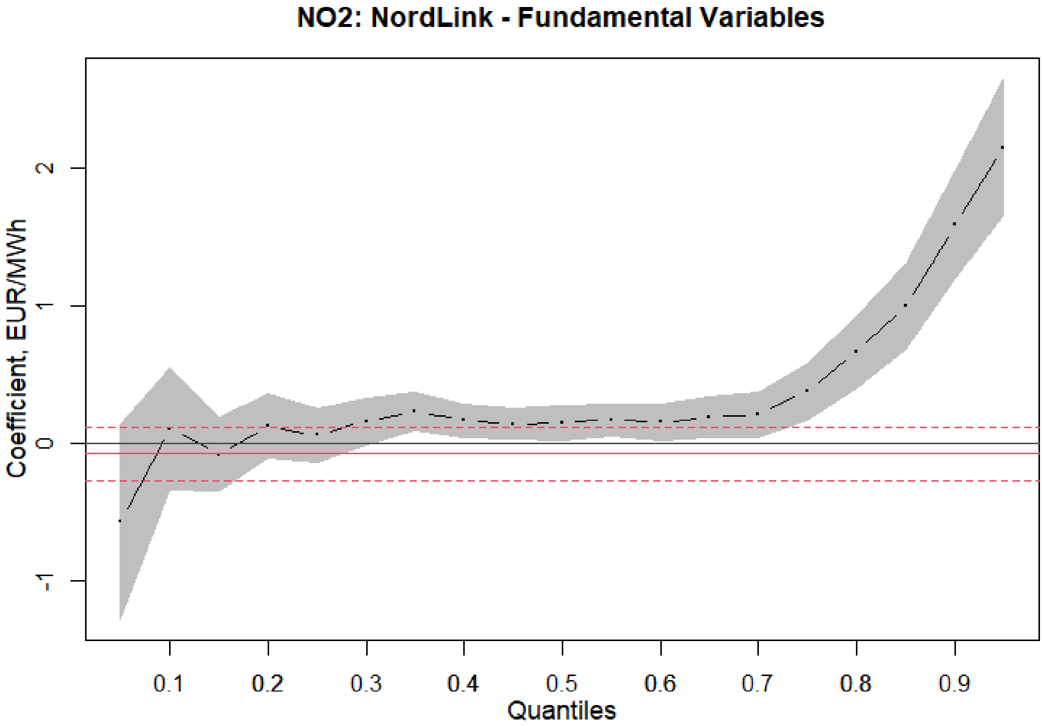


Figure 5.2: Quantile regression estimates of the NordLink cable dummy when controlling for fundamental variables.

Initially, we notice that the estimates' values have changed substantially. From having coefficient estimates with values ranging from approximately 20 to over 50 EUR/MWh, the cable dummy now has values ranging from just below 0 to slightly above 2 EUR/MWh. The reduced magnitude of coefficients implies that a substantial amount of NordLink's price effect in the naive model was caused by the control variables. Coefficient estimates are significant at a 5%-level, except in the 5% - 30%, 45% and 50% quantiles.

Coefficient estimates' pattern across quantiles has slightly changed from the naive model. Instead of steadily rising across quantiles, the estimates are now relatively stable before exponentially increasing after the 70% quantile. However, our model still does not control for fixed effects that could be captured by our cable dummy. Thus, a new model that controls for fixed effects is estimated to further isolate NordLink's effect on prices.

5.1.3 Controlling for Fixed Effects

Fixed effects consist of all variables included in $\Omega^q_{h,d,i}$, in Equation 4.4. These include individual dummies for hour, month, weekend, and national holidays, in addition to a variable capturing time trend. Figure 5.3 shows coefficient estimates for the NordLink cable dummy when controlling for both fixed effects and fundamental factors, forming our thesis' baseline results for NO2.

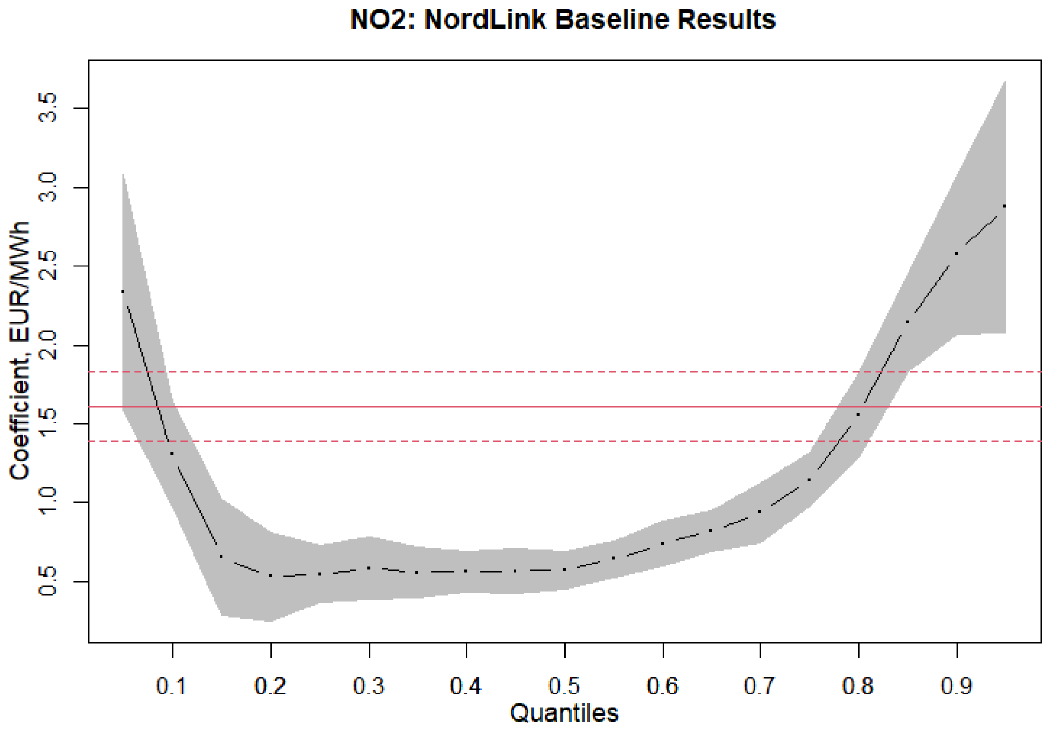


Figure 5.3: Quantile regression estimates of the NordLink cable dummy when controlling for fundamental- and fixed effect variables.

Coefficient estimates are positive across quantiles, with all estimates being significant at a 5%-level. The estimates' values follow a convex pattern, indicating that NordLink has exercised the greatest impact at the lowest and highest price levels.

NordLink has positively affected electricity prices throughout the distribution. This coincides with the hypothesis of price convergence, where we expected positive coefficient estimates around the median. As the estimate at the 50% quantile is positive and significant, we can confirm the hypothesis. This result is consistent with the intention of interconnectors, as they should eliminate or decrease price differences between areas (Meeus et al., 2009; Weber et al., 2010).

The exponential increase with corresponding high values in the higher quantiles can be explained by Norwegian electricity producers' maximizing their profits. As shown in Figure 3.1 and 3.2, historical price levels in NO2 are generally lower than in Germany. In situations with higher German prices, Norwegian producers will be inclined to export electricity to generate larger profits, increasing electricity prices in NO2 depending on the margin of excess supply. This increase would grow in magnitude along with the level of demand due to a movement upward the merit order curve, which would also help explain the exponential pattern of coefficient estimates.

Finally, coefficient estimates increase exponentially after the 20% quantile, with the highest quantiles having the estimates of the largest magnitude. This pattern provides some evidence for volatility exacerbation as an effect of NordLink in NO2. However, the high estimates in the lowest quantiles weaken the conclusion. These estimates decrease towards the 20% quantile, contradicting the expectation of estimates increasing consistently across quantiles. Nevertheless, the results provide partial evidence for volatility exacerbation. According to de Menezes and Houllier (2015), market integration can lead to price volatility being exported from the bigger to the smaller market. In our case, volatility would be exported from Germany to NO2, as the German market is larger and consists of a greater share of intermittent energy sources. Thus, an increase in price volatility after the implementation of NordLink would be sensible.

5.2 NordLink Results: Germany

5.2.1 Naive Model Specification

Following the same process as for NO2, assessing NordLink's impact on German electricity prices is begun by estimating a naive model. The results of the naive model are seen in Figure 5.4.

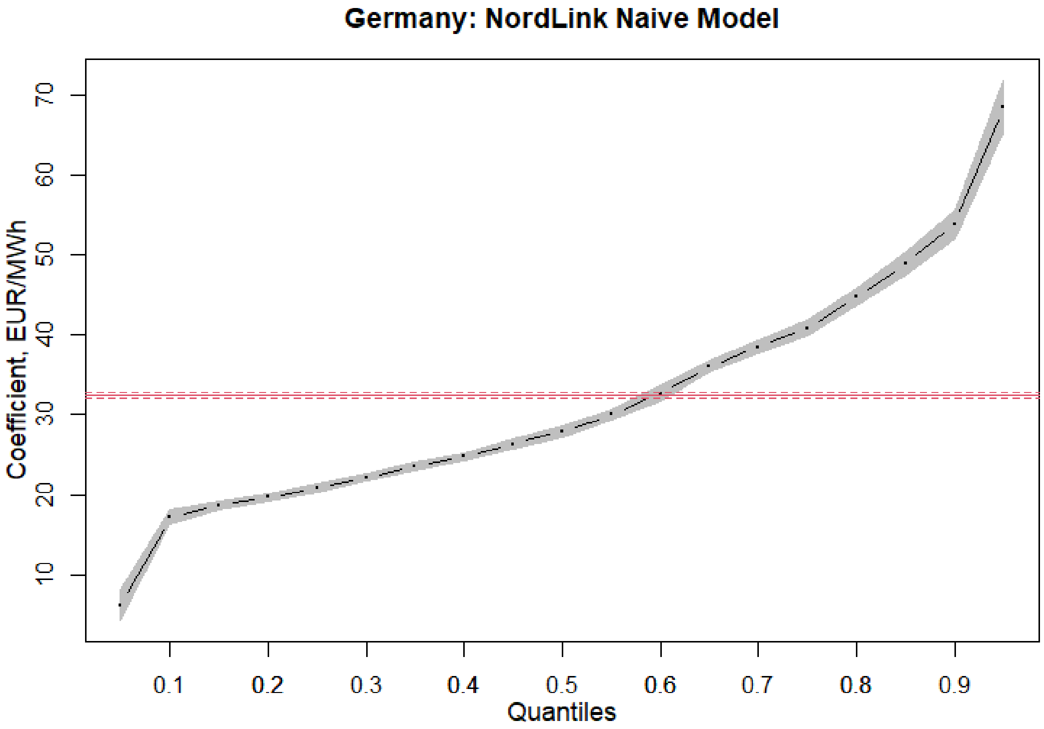


Figure 5.4: Quantile regression estimates of the NordLink cable dummy when using a naive model.

Coefficient estimates from the naive model are seen to directly oppose the hypotheses' for Germany, as they are positive and rising across quantiles. All coefficient estimates are significant on a 5%-level.

Coefficient estimates' positive sign and magnitude of values are surprising, as we expect NordLink to exercise a downward pressure on prices. Similar to the results in NO2, the naive model specification does not isolate NordLink's effect on electricity prices. A general price increase over time, in combination with the absence of other factors, explains these results. Hence, to further isolate NordLink's price effect, we control for fundamental factors.

5.2.2 Controlling for Fundamental Variables

When controlling for fundamental variables, we include the variables that compose $\gamma^{q}_{h,d,i}$ and $\phi^{q}_{h,i,d-1}$ in Equation 4.4. The model's results are seen in Figure 5.5.

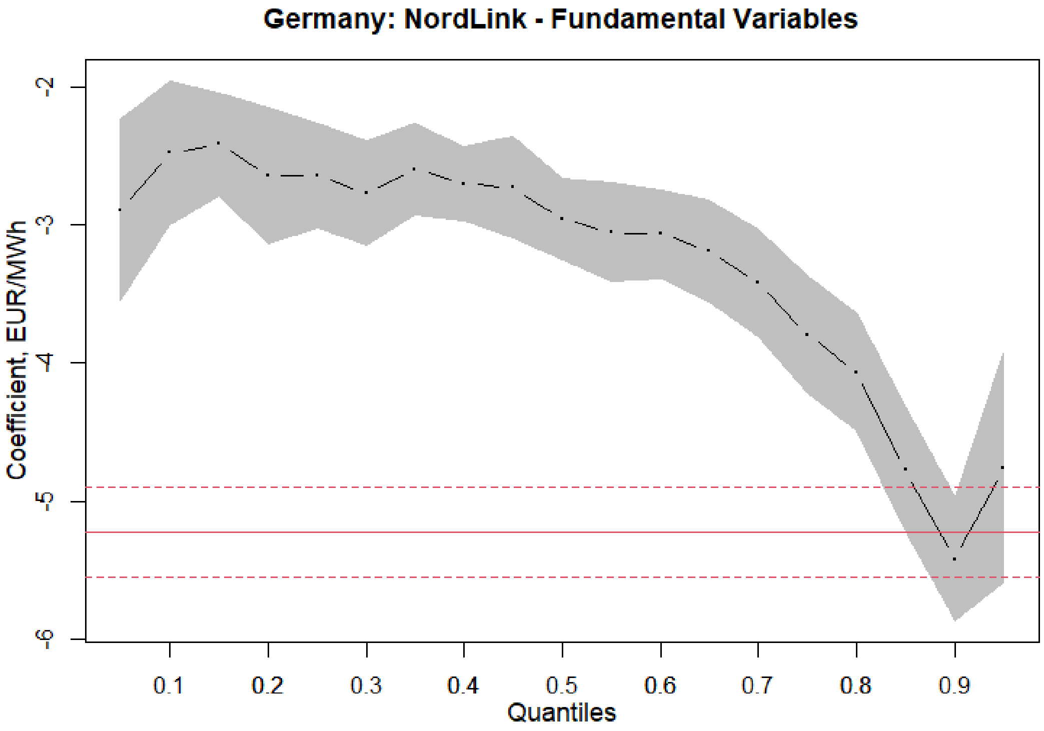


Figure 5.5: Quantile regression estimates of the NordLink cable dummy when controlling for fundamental variables.

As seen in Figure 5.5, NordLink's coefficient estimates are entirely different compared to the naive model. Coefficient estimates' signs are now negative, indicating that NordLink has exercised a downward pressure on prices. Estimates grow in magnitude when moving towards the higher quantiles, indicating a greater downward pressure at the highest price levels. All coefficient estimates are significant on a 5%-level.

However, the model does not control for fixed effects, which may lead to our cable dummy capturing effects from other time-related variables.

5.2.3 Controlling for Fixed Effects

A new model is estimated to properly isolate NordLink's effect on prices, controlling for fundamental variables $\gamma^q_{h,d,i}$ and $\phi^q_{h,i,d-1}$, and fixed effects $\Omega^q_{h,d,i}$. This forms the baseline results for Germany in our thesis. The resulting coefficient estimates are seen in Figure 5.6.

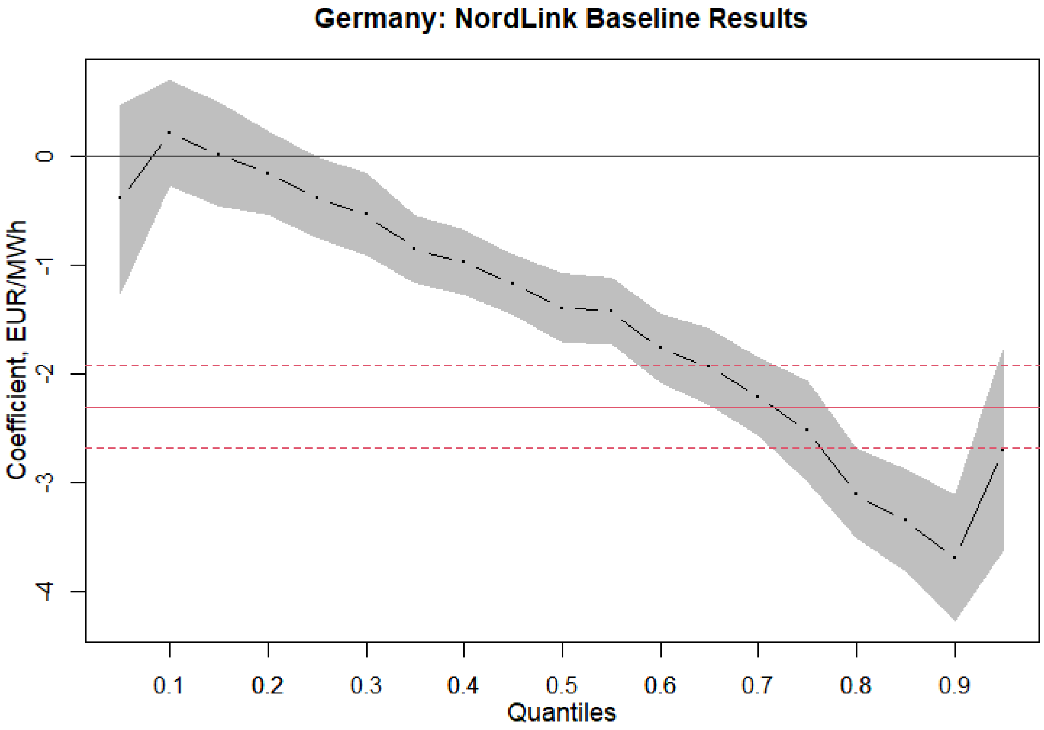


Figure 5.6: Quantile regression estimates of the NordLink cable dummy when controlling for fundamental- and fixed effect variables.

NordLink's coefficient estimates follow a generally decreasing pattern of negative estimated values. The exception is the 10% and 15% quantiles which has positive estimates. However, significance is only found at the 30% quantile and up, meaning that we cannot establish an association between NordLink and German prices in the lowest quantiles, including the positive coefficient estimates. The generally decreasing pattern suggests that the cable has exercised a greater downward pressure on prices at the higher end of the distribution.

Our hypothesis of volatility reduction in Germany would see coefficient estimates decrease across quantiles. The results from Figure 5.6confirm the hypothesis, as the significant estimates decrease across quantiles while being consistently negative. This reduction in price volatility may be explained by NordLink providing the German market with greater access to Norwegian hydropower. In general, interconnectors increase the security of supply, which is expected to have volatility mitigating effects.

Negative coefficient estimates around the median in Figure 5.6, support the hypothesis of price convergence between NO2 and Germany, implying that NordLink has negatively affected German electricity prices. In addition, estimates in Germany being negative across all significant quantiles suggest that not only prices around the median have decreased, but also prices in other parts of the distribution.

Peak shaving was another expected effect from NordLink, as increased competition from market integration should reduce the possibility of exercising market power. In other words, we expected a price reduction at peak price levels in Germany as an effect of being able to import electricity from NO2. The hypothesis of peak shaving is confirmed by the results in Figure 5.6, as estimates are both negative and relatively large in the higher quantiles. The reduced possibility of exercising market power can contribute to explaining the cable's negative effect in higher quantiles and why estimate values increase when moving towards the higher quantiles.

The robustness of NO2's and Germany's baseline models was tested using a smooth time-varying variable that slowly converges from 0 to 1 during NordLink's trial period, instead of the binary dummy variable. This variable controls for the learning effect that could be needed for NordLink to deliver its full effect on prices. Coefficient estimates changed slightly, but the conclusions from using a binary variable hold. For the interested reader, results from using a smooth time-varying variable can be found in Appendix A2.4.

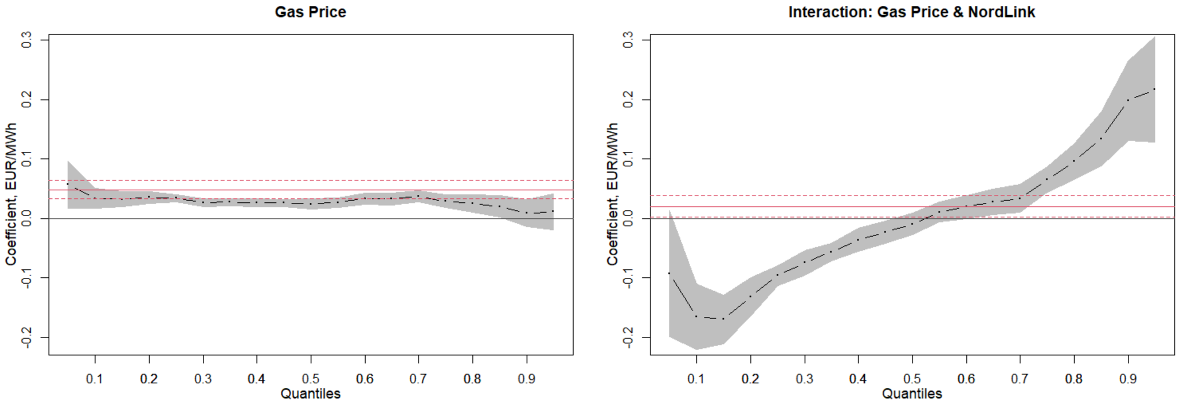
5.3 Mechanisms

This section analyzes our baseline results in further detail by investigating the possible underlying causes of price convergence, volatility changes, and peak shaving. These underlying causes can be viewed as the mechanisms that cause the experienced results from NordLink.

It is plausible that the implementation of NordLink changes some control variables' effect on electricity prices. Hence, we add interaction terms for the variables considered likely to change. In general, adding an interaction term implies that an independent variable's effect on the dependent variable is no longer unique, as it now depends on the value of some third variable. We interact gas- and EUA prices, in addition to intermittent electricity production, with the NordLink dummy. The resulting interaction terms express the variables' additional effect on prices after NordLink opened, allowing us to assess whether NordLink's price effect has come in conjunction with other explanatory variables.

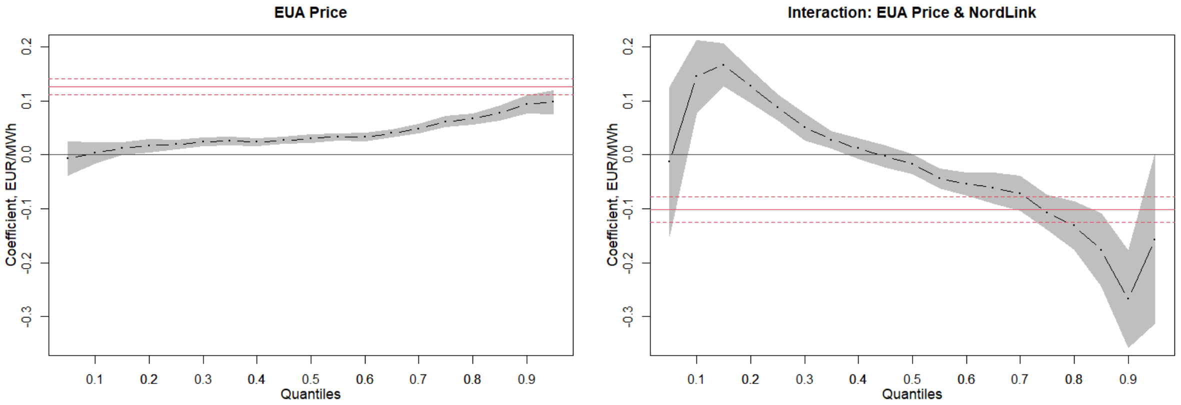
5.3.1 Increased Exposure to Gas- and EUA Prices in NO2

Gas- and EUAs are strong price drivers in European countries, including Norway, due to their effect on water values. Statnett follows this argumentation, stating that increased gas- and EUA prices have reinforcing effects on Norway's electricity prices (Døskeland et al., 2022). The introduction of NordLink is expected to strengthen gas and EUAs' effect on Norwegian electricity prices, due to increased interconnection capacity further expanding Norway's connection to European prices. Coefficient estimates for interactions between gas, EUAs, and NordLink, are shown in Figures 5.7b and 5.7d.



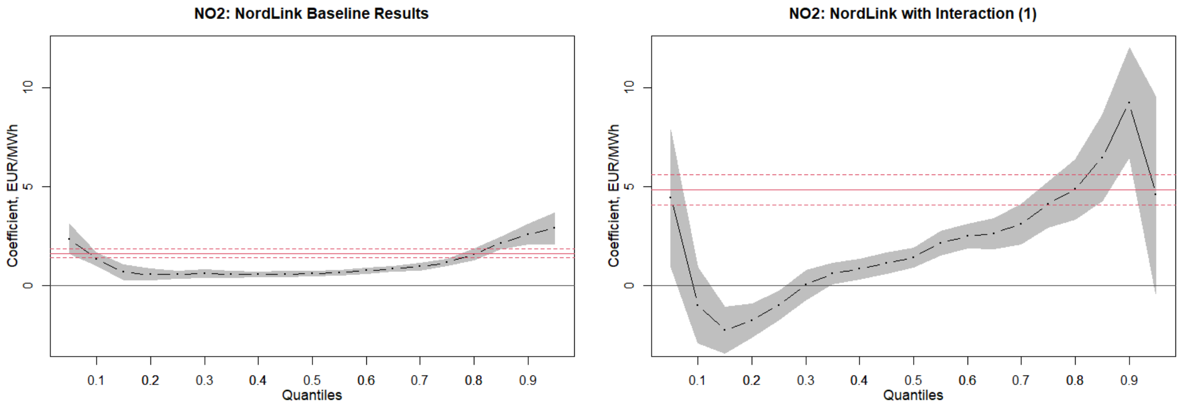
(a) Price effect of gas

(b) Additional price effect of gas



(c) Price effect of EUAs

(d) Additional price effect of EUAs



(e) NordLink baseline results **(f)** NordLink results with interactions

Figure 5.7: Interaction terms between fossil fuels and NordLink cable dummy in NO2. *Note: Y-axis for NordLink's baseline results in NO2 (shown in Section 5.1) are adjusted for comparability to NordLink's results when including interactions for gas and EUA.*

Figure 5.7a shows the coefficient estimates of the non-interacted term of gas prices. All the significant estimates have positive values, indicating that gas prices have positively affected prices in NO2. These results are expected and sensible, as higher gas prices will likely increase both European electricity prices and water values. Higher prices in nearby countries will affect NO2's prices as it incentivizes electricity export even when water inflow and reservoir levels point to prices being increased. Water values are based on producers' expectations of future electricity prices and are affected by gas prices through increased opportunity costs. Reservoir levels and water inflow affects the perceived water values, which is decisive of Norwegian electricity prices. This is supported by Døskeland et al. (2022), claiming that access to and the price of gas are the most decisive factors for electricity prices in Norway. Coefficient estimates are significant at a 5%-level, except for the 90% and 95% quantiles.

The interaction term for gas prices and NordLink captures the additional effect from gas after NordLink. Coefficient estimates seen in Figure 5.7b, are positive beyond the 50% quantile, indicating that gas' positive effect on prices is strengthened for the higher price levels after NordLink was opened. The negative coefficients in quantiles below the median suggest that the positive effect from gas has been weakened for these price levels after NordLink opened. Estimates for the interaction term are significant at a 5%-level, except at the 50%, 55%, and 60% quantiles.

Figure 5.7c shows coefficient estimates for the non-interacted term of EUA prices. Most estimates are positive and significant at a 5%-level, except for the 5% - 15% quantiles. All significant estimates have positive values that grow in magnitude across quantiles, implying that EUA prices have positively affected electricity prices in NO2, with the greatest impact in the higher price levels. As EUAs are an additional cost for producing energy that emits CO_2, this effect should be seen in relation to the costs of energy sources such as fossil fuels.

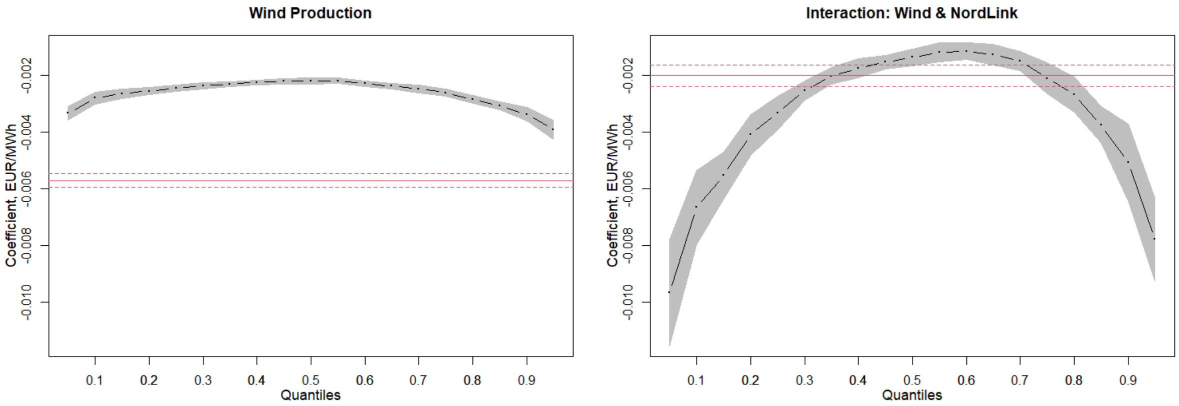
Figure 5.7d shows coefficient estimates for the interacted term between EUA prices and NordLink. Estimates' values generally decrease across quantiles, shifting from positive to negative at the 45% quantile. These values imply that EUAs' positive effect on electricity prices has been strengthened after NordLink at the lower tail of the distribution, while the effect at the higher tail has been reduced. Coefficient estimates are significant at a 5%-level in most quantiles, except for the 5%, 40%, 45%, and 50% quantiles.

NordLink's coefficient estimates after including interactions for gas and EUAs have grown in magnitude, in addition to some estimates now having negative values. These results are seen in Figure 5.7f. Estimates are significant at a 5%-level, except for the 10%, 30%, and 35% quantiles. NordLink's coefficient estimates having mostly positive values after controlling for the additional effects from gas and EUAs, imply that the cable still has an effect on electricity prices in NO2. These results allow us to conclude that increased exposure to fossil fuel prices alone does not explain NordLink's positive effect on prices in NO2.

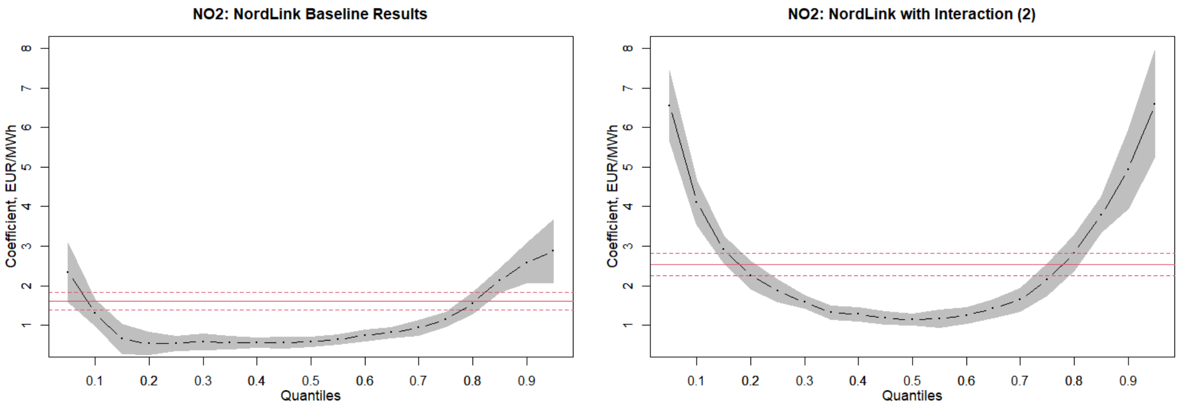
5.3.2 Renewables Downward Pressure on Electricity Prices

Interconnecting areas is expected to strengthen wind- and PV power's effect on prices, as the exposure to a larger market facilitates improved utilization of their value (Sapio, 2019; Veit et al., 2009). Further, the production capacity of intermittent energy sources such as wind and PV has increased in NO2 and Germany after the introduction of NordLink, shown in Appendix A2.5. Hence, we expect their negative effect on prices to increase after the cable.

For Germany, NordLink's negative impact on prices could appear in conjunction with renewables, whereas NordLink's positive effect on NO2's electricity prices could be moderated by wind production. The results from interacting wind production with NordLink in NO2 are shown in Figure 5.9. PV production is only included for Germany as NO2 has no PV production at the time of writing.



(a) Price effect of wind production **(b)** Additional price effect of wind production



(c) NordLink baseline results **(d)** NordLink results with interaction

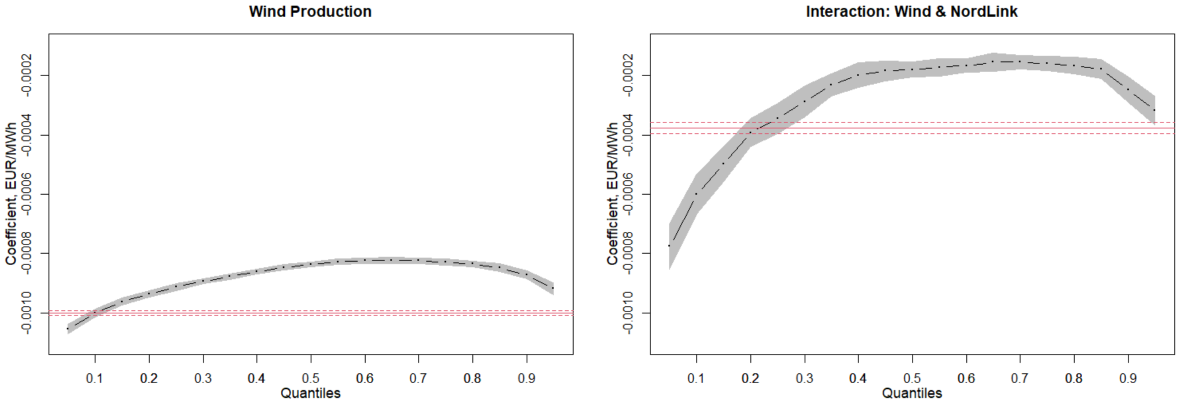
Figure 5.9: Interaction terms between wind production and NordLink in NO2.

Note: Y-axis for NordLink's baseline results in NO2 (shown in Section 5.1) are adjusted for comparability to NordLink's results when including interactions for wind production.

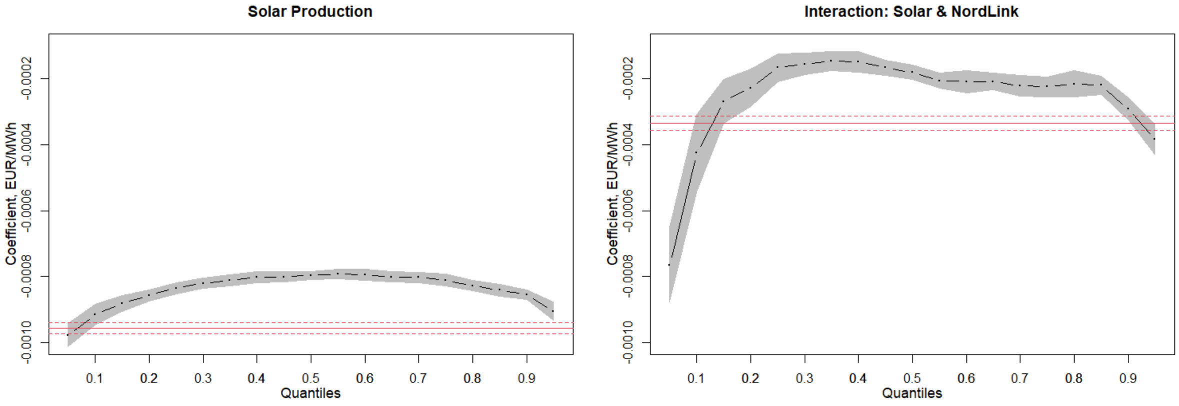
Figure 5.9a shows coefficient estimates of the non-interacted term of wind production in NO2. All estimates are negative across quantiles and follow a concave pattern. Hence, estimates are of the greatest magnitude in the lowest- and highest quantiles, indicating that wind production exercises the strongest downward pressure on prices in NO2 at the lowest and highest price levels. Coefficient estimates are significant on a 5%-level for all quantiles.

The interaction term for wind production and NordLink is shown in Figure 5.9b. The coefficient estimates follow a concave pattern and are negative across quantiles, similar to the non-interacted term. The concave and negative pattern suggests that wind production's negative effect on prices is strengthened after NordLink, with the additional effect being greatest at the higher and lower tail of the distribution. This aligns with our expectations, as NordLink facilitates an improved utilization of intermittent energy. The increase in wind production capacity during recent years could also explain some of this additional negative effects. All coefficient estimates are significant at a 5%-level.

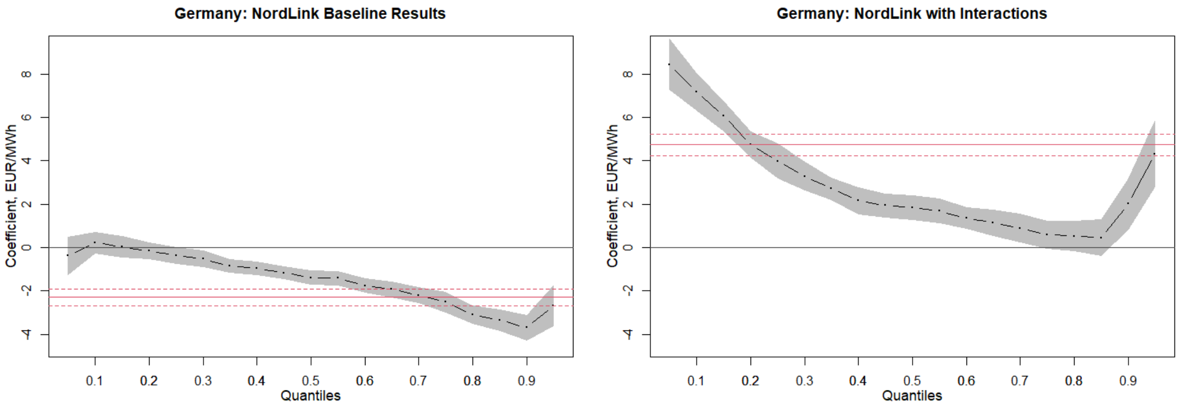
Coefficient estimates for NordLink after including the interaction for wind production are illustrated in Figure 5.9d. Estimates are positive and significant at a 5%-level across quantiles, which suggests that NordLink maintains its positive effect on electricity prices even when controlling for wind production's additional effect. These results indicate that negative price effects from wind power production have moderated NordLink's positive effect on electricity prices.



(a) Price effect of wind production **(b)** Additional price effect of wind production



(c) Price effect of PV production **(d)** Additional price effect of PV production



(e) NordLink baseline results **(f)** NordLink results with interactions

Figure 5.11: Interaction terms between intermittent electricity sources and NordLink in Germany.

Note: Y-axis for NordLink's baseline results in Germany (shown in Section 5.2) are adjusted for comparability to NordLink's results when including interactions for wind- and PV production.

Figure 5.11a shows coefficient estimates for the non-interacted term of wind production in Germany. Estimates are negative across quantiles, following an increasing pattern towards the 60% quantile. The negative values indicate that wind production negatively affects electricity prices in Germany, with the greatest effect in the lowest quantiles. All coefficient estimates are significant on a 5%-level. Coefficient estimates for the interaction term between wind production and NordLink are shown in Figure 5.9b. The estimates are negative and significant across quantiles, suggesting that wind production's downward pressure on German prices is strengthened after NordLink opened. The pattern of estimates indicates that the additional effect from wind power is greatest at the lower price levels.

Figure 5.11c shows coefficient estimates of the non-interacted term for PV production. Estimates are negative across quantiles and follow a convex pattern, indicating that PV production has the greatest effect on German prices at the distribution's tails. The negative sign of estimates suggests that PV production has negatively affected electricity prices across quantiles in Germany. All coefficient estimates are significant at a 5%-level. Coefficient estimates of the interaction term between PV production and NordLink are illustrated in Figure 5.11d. All estimates are negative and move towards zero before becoming increasingly negative beyond the 35% quantile. Coefficient estimates in the lowest quantiles are of the greatest magnitude, suggesting that PV production's strongest additional effect on German prices is seen at the lowest price levels. All coefficient estimates are significant on a 5%-level.

NordLink's coefficient estimates after including interactions with wind- and PV production is shown in Figure 5.11f. Estimates are now positive across quantiles. The shift from negative to positive estimates suggests that NordLink's price-reducing effects seen in the baseline model, are only found in conjunction with renewables. Coefficient estimates are significant on a 5%-level, except for the estimates in the 75%, 80%, and 85% quantiles.

5.4 Limitations of the Thesis

Due to various aspects, our thesis has limitations that may affect our results and their validity. We chose September 30th, 2021, as the last observation to avoid occurrences that could have a disruptive effect on Norwegian market prices. These occurrences include the introduction of the North Sea Link, record-high gas prices, and low reservoir levels. Assessing the cable over a longer period could lead to other results or strengthen the validity of our findings. This could also exhibit different physical flows through NordLink than in our data sample, which could affect results. NordLink's physical flow in our data sample can be found in Appendix A2. Further, the plans for NordLink have been known among market participants for nearly ten years. As argued by Døskeland et al. (2022), market participants have adapted according to this information through actions such as investments in production. Such changes are expected to moderate the price effect from NordLink and are not captured by our model, as their effects on prices are not directly connected to the opening of NordLink. Lastly, constructing individual variables for the capacity of each transmission line instead of aggregating the capacities for import and export, could improve the model's explanatory power. Computational costs and a parsimonious model formulation did, however, lead to capacities being aggregated.

6 Conclusion

This thesis contributes to the area of research on interconnectors in electricity markets, assessing NordLink's effects on electricity prices in Norway and Germany. With European electricity prices reaching record-high levels in 2021 and new transmission cables being implemented and planned, the importance of studying cables' price effect is indisputable. Hence, empirically analyzing NordLink's price effects could provide valuable insights for future decision-making. In Norway, our focus has solely been on prices in NO2, as it is the area where NordLink is situated. As Germany operates with uniform prices, the studied day-ahead prices are applicable for all regions. A quantile regression model based on relevant research is formed to assess price effects adequately. Based on the examined research, hypotheses are developed for both markets. These hypotheses cover price convergence, volatility developments, and peak shaving of day-ahead prices. We have also analyzed and discussed possible underlying causes when interpreting our results.

Our results show an increase in NO2's electricity prices after the implementation of NordLink, while German prices have decreased. This provides evidence of price convergence between the two areas. The results also indicate a decrease in price volatility for Germany, while we find partial evidence for volatility exacerbation in NO2. NordLink has also had a stronger negative impact on German peak prices, confirming that NordLink has reduced peak prices in Germany. By controlling for possible underlying causes of our results, gas and EUAs are found to have additional effects on electricity prices in NO2 after the opening of NordLink. However, this effect does not fully explain NordLink's positive effect on electricity prices in NO2. We also found evidence for renewables' downward pressure on prices being strengthened by NordLink's implementation in both areas. After controlling for these mechanisms, NordLink's price-reducing effect in Germany was only seen in conjunction with renewables.

Regarding further research, we believe that our findings and method are transferable to the assessment of other transmission cables. However, our conclusions would likely be most applicable to markets with similar characteristics as the two studied in this thesis. A similar study could be conducted on the newly opened North Sea Link connecting Norway and the United Kingdom. Such a study could also include NordLink, analyzing the cables' collective effect on electricity prices in NO2. This would require observations of both cables in operation for a more extended period than what is available at the time of writing. Future research could also further analyze NordLink, emphasizing its price effects on specific trading hours or use a different model specification. Such a study would have access to more data on day-ahead prices or a different electricity flow through NordLink, which could change or strengthen our findings.

The expressed goals with NordLink are to improve overall welfare and that each market can profit from the other's access to resources. Even if the aim of increasing overall welfare is indisputable, NordLink is unlikely to directly benefit consumers in both markets as prices are expected to converge, which our findings also indicate. NordLink's positive effect on day-ahead prices in NO2 and negative effect on German prices suggest that the cable's main benefiters are Norwegian producers and German consumers. NordLink's impact on prices does, however, depend on the utilization of the cable, where little precipitation and low net export or import should reduce its effect on prices. This would see price levels in NO2 near European levels. Going forward, European electricity markets becoming increasingly interconnected will increase their dependency on each other and similarity of prices.

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Appendix

A1 Data

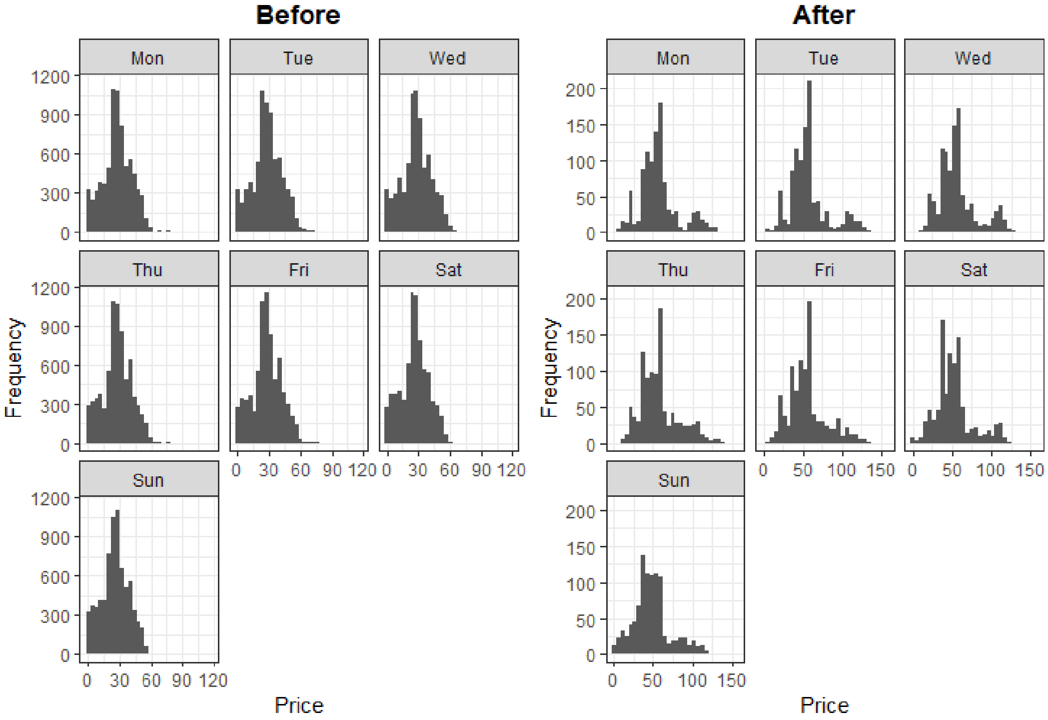


Figure A1.1: NO2 day-ahead prices for each weekday before and after NordLink opened.

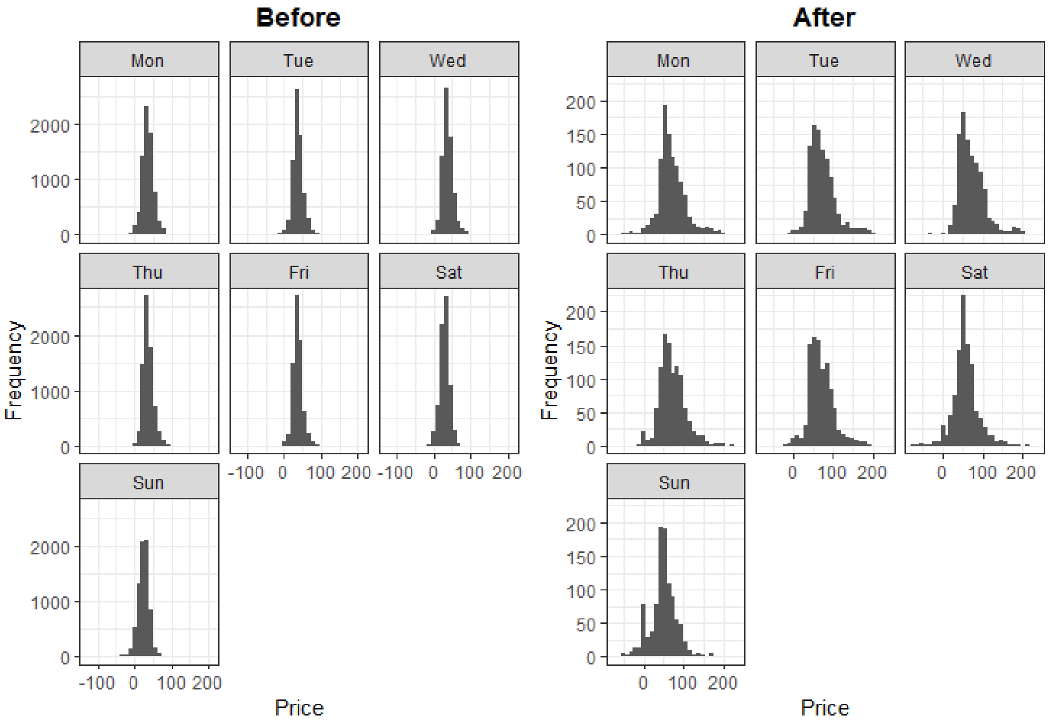


Figure A1.2: German day-ahead prices for each weekday before and after NordLink opened.

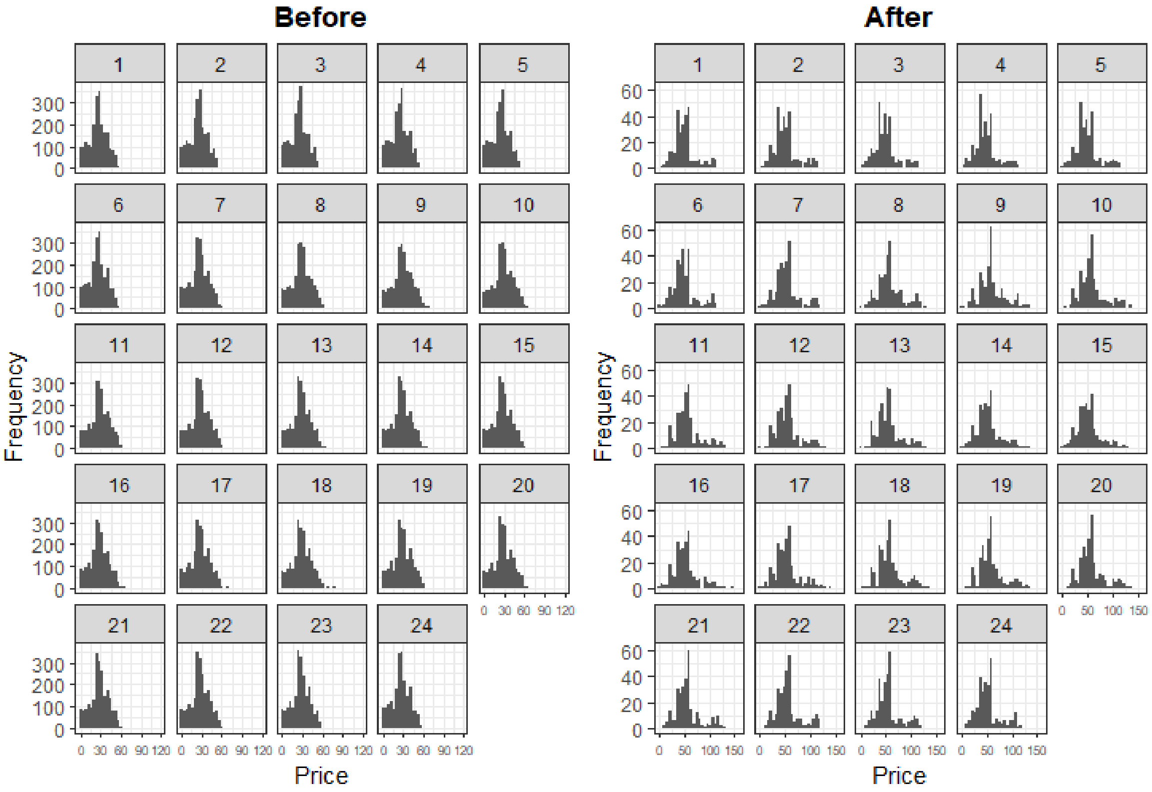


Figure A1.3: NO2 day-ahead prices for each hour before and after NordLink opened.

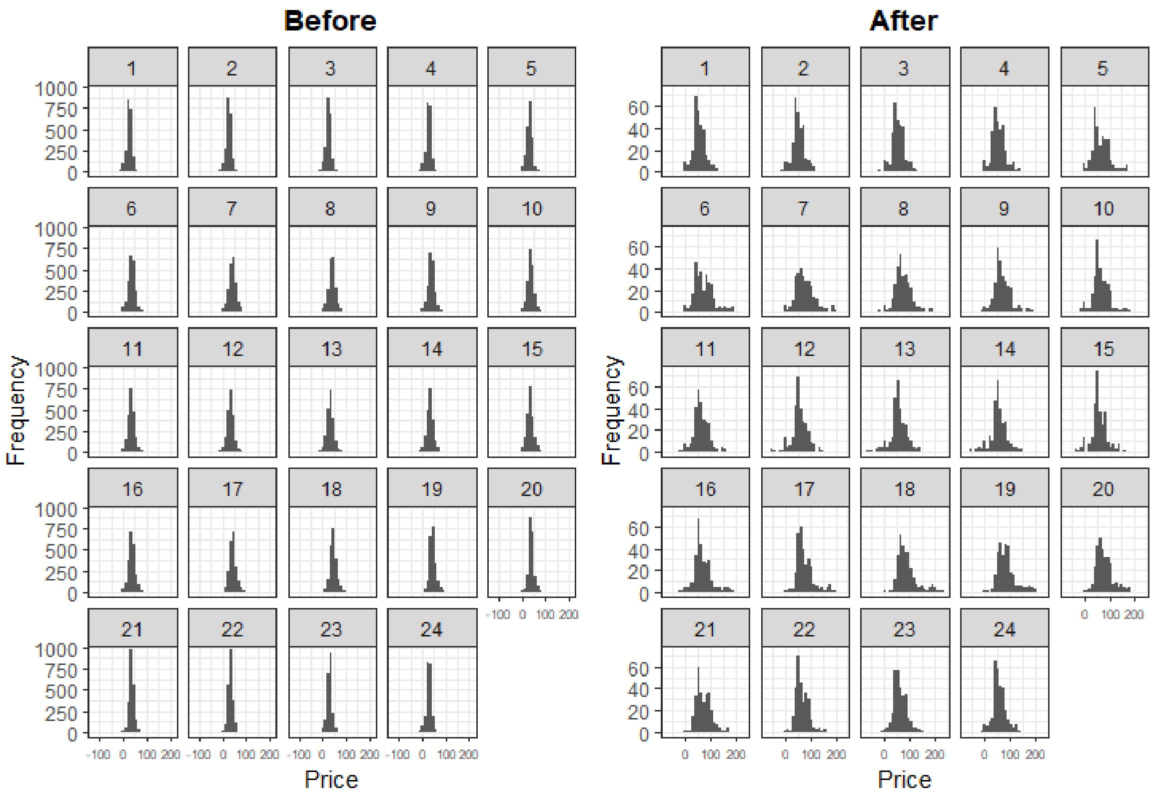
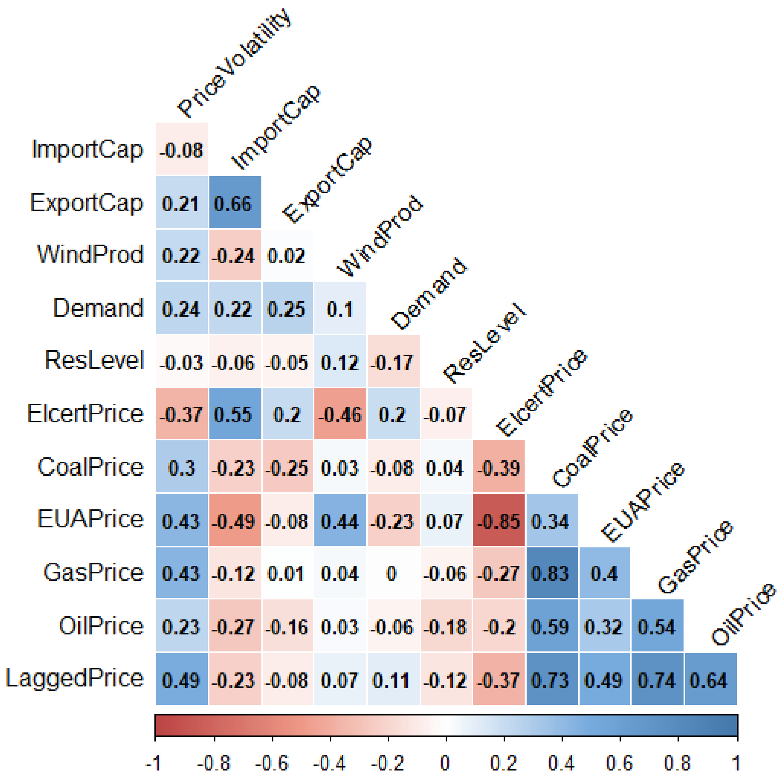
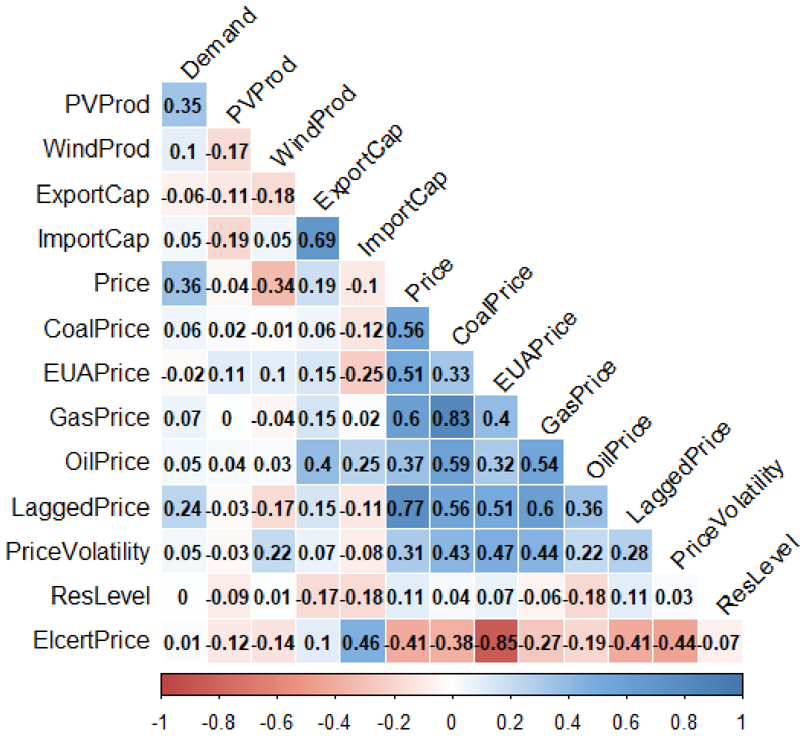


Figure A1.4: German day-ahead prices for each hour before and after NordLink opened.



	PriceVolatility	ImportCap	ExportCap	WindProd	Demand	ResLevel	ElcertPrice	CoalPrice	EUAPrice	GasPrice	OilPrice
ImportCap	-0.08										
ExportCap	0.21	0.66									
WindProd	0.22	-0.24	0.02								
Demand	0.24	0.22	0.25	0.1							
ResLevel	-0.03	-0.06	-0.05	0.12	-0.17						
ElcertPrice	-0.37	0.55	0.2	-0.46	0.2	-0.07					
CoalPrice	0.3	-0.23	-0.25	0.03	-0.08	0.04	-0.39				
EUAPrice	0.43	-0.49	-0.08	0.44	-0.23	0.07	-0.85	0.34			
GasPrice	0.43	-0.12	0.01	0.04	0	-0.06	-0.27	0.83	0.4		
OilPrice	0.23	-0.27	-0.16	0.03	-0.06	-0.18	-0.2	0.59	0.32	0.54	
LaggedPrice	0.49	-0.23	-0.08	0.07	0.11	-0.12	-0.37	0.73	0.49	0.74	0.64

Figure A1.5: Pairwise correlation between explanatory variables in NO2.



	Demand	PVProd	WindProd	ExportCap	ImportCap	Price	CoalPrice	EUAPrice	GasPrice	OilPrice	LaggedPrice	PriceVolatility	ResLevel
PVProd	0.35												
WindProd	0.1	-0.17											
ExportCap	-0.06	-0.11	-0.18										
ImportCap	0.05	-0.19	0.05	0.69									
Price	0.36	-0.04	-0.34	0.19	-0.1								
CoalPrice	0.06	0.02	-0.01	0.06	-0.12	0.56							
EUAPrice	-0.02	0.11	0.1	0.15	-0.25	0.51	0.33						
GasPrice	0.07	0	-0.04	0.15	0.02	0.6	0.83	0.4					
OilPrice	0.05	0.04	0.03	0.4	0.25	0.37	0.59	0.32	0.54				
LaggedPrice	0.24	-0.03	-0.17	0.15	-0.11	0.77	0.56	0.51	0.6	0.36			
PriceVolatility	0.05	-0.03	0.22	0.07	-0.08	0.31	0.43	0.47	0.44	0.22	0.28		
ResLevel	0	-0.09	0.01	-0.17	-0.18	0.11	0.04	0.07	-0.06	-0.18	0.11	0.03	
ElcertPrice	0.01	-0.12	-0.14	0.1	0.46	-0.41	-0.38	-0.85	-0.27	-0.19	-0.41	-0.44	-0.07

Figure A1.6: Pairwise correlation between explanatory variables in Germany.

Norway	Germany
New Year's Day	New Year's Day
Maundy Thursday	Good Friday
Easter Sunday	Easter Monday
Easter Monday	May Day
Labor day	Ascension Day
Ascension Day	Whit Monday
Constitution Day	Day of German Unity
Whit Sunday	Christmas Day
Whit Monday	Boxing Day
Christmas Day	
Boxing Day	

Table A1.1: National holidays included in holiday dummy for Norway and Germany

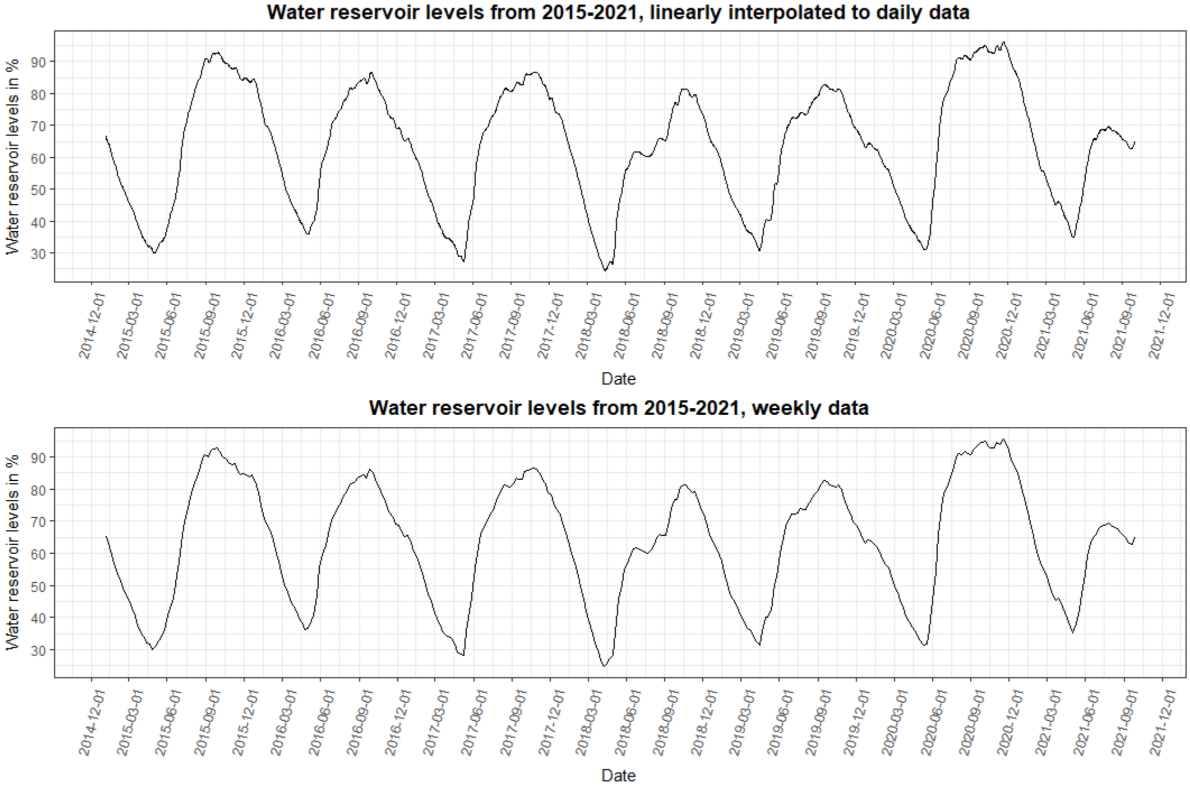


Figure A1.7: Water reservoir levels. Both original weekly data and interpolated daily data

A2 Results

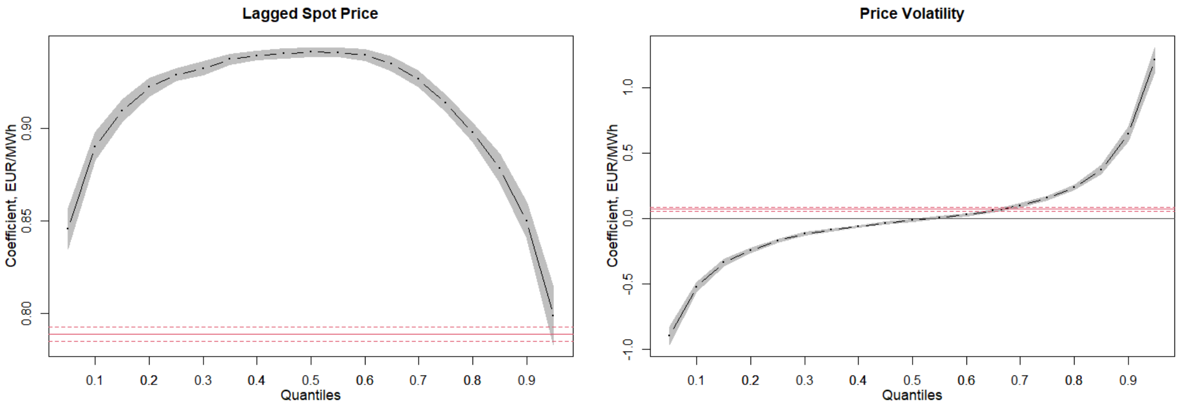
In this section, the results of explanatory variables included in the models for NO2 and Germany will be presented. The estimation results are displayed by plots, displaying each coefficient's quantile regression profile. OLS point estimates and the associated 95% bootstrapped confidence intervals are applied for comparison for each plot. Confidence intervals are illustrated through the grey area around the point estimates, and the solid red line with corresponding red dotted lines illustrate the OLS point estimates. In each plot, the x-axis represents the 19 different quantiles between 5% and 95%, while the y-axis represents the coefficient estimates for the given variable.

A2.1 NO2

	Dependent variable:								
					Price				
	5%	10%	15%	20%	25%	30%	35%	40%	45%
Import Capacity	−0.00008	0.00001	0.000002	0.0000003	−0.00001	−0.00003	−0.00003	−0.00007***	−0.00008***
	(0.00007)	(0.00005)	(0.00004)	(0.00003)	(0.00003)	(0.00003)	(0.00002)	(0.00002)	(0.00002)
Export Capacity	0.00034***	0.00021***	0.00014***	0.00010***	0.00008***	0.00010***	0.00011***	0.00014***	0.00017***
	(0.00006)	(0.00004)	(0.00003)	(0.00003)	(0.00002)	(0.00002)	(0.00001)	(0.00002)	(0.00002)
Demand Forecast	0.00018*	0.00027***	0.00034***	0.00042***	0.00042***	0.00047***	0.00051***	0.00055***	0.00063***
	(0.00011)	(0.00005)	(0.00005)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00002)
Forecasted Wind Production	−0.00458***	−0.00387***	−0.00341***	−0.00324***	−0.00304***	−0.00293***	−0.00275***	−0.00261***	−0.00251***
	(0.00030)	(0.00014)	(0.00013)	(0.00009)	(0.00008)	(0.00009)	(0.00007)	(0.00006)	(0.00006)
Reservoir Level	−0.00005***	−0.00003***	−0.00001***	−0.00001***	−0.00001**	−0.00001***	−0.00001***	−0.00001***	−0.00001***
	(0.00001)	(0.000003)	(0.000003)	(0.000003)	(0.000002)	(0.000002)	(0.000002)	(0.000001)	(0.000001)
Electricity Certificate Price	0.67355***	0.32305***	0.20340***	0.14152***	0.11606***	0.12331***	0.11874***	0.12852***	0.13463***
	(0.04896)	(0.03266)	(0.02745)	(0.02223)	(0.01379)	(0.01396)	(0.01160)	(0.01016)	(0.01144)
Adaptive Behavior	0.84569***	0.89019***	0.90948***	0.92221***	0.92899***	0.93239***	0.93726***	0.93936***	0.94044***
	(0.00467)	(0.00295)	(0.00230)	(0.00179)	(0.00162)	(0.00137)	(0.00121)	(0.00114)	(0.00117)
Price Volatility	−0.89633***	−0.52510***	−0.33865***	−0.24537***	−0.17083***	−0.11928***	−0.08816***	−0.06213***	−0.03714***
	(0.04156)	(0.02141)	(0.01712)	(0.01048)	(0.00751)	(0.00787)	(0.00606)	(0.00419)	(0.00501)
Weekend Dummy	−1.50275***	−1.19228***	−0.98421***	−0.86380***	−0.82269***	−0.75216***	−0.69202***	−0.64893***	−0.60219***
	(0.09161)	(0.06088)	(0.03757)	(0.03771)	(0.02211)	(0.02817)	(0.02273)	(0.01847)	(0.02162)
Holiday Dummy	−0.50759**	−0.32408***	−0.32206***	−0.32236***	−0.28091***	−0.26360***	−0.24142***	−0.23846***	−0.21363***
	(0.22267)	(0.10321)	(0.07478)	(0.06985)	(0.06326)	(0.05972)	(0.05315)	(0.04458)	(0.04072)
Gas Price	0.02882	−0.01056	−0.01023	−0.00587	0.00366	0.00957*	0.01585***	0.01741***	0.02002***
	(0.02288)	(0.01619)	(0.01098)	(0.00855)	(0.00750)	(0.00570)	(0.00367)	(0.00404)	(0.00485)
EUA Price	−0.03977**	0.01011	0.02560***	0.03048***	0.02376***	0.02221***	0.01947***	0.01734***	0.01814***
	(0.01948)	(0.01324)	(0.00986)	(0.00698)	(0.00584)	(0.00538)	(0.00310)	(0.00364)	(0.00357)
Coal Price	0.07729***	0.05797***	0.05150***	0.04441***	0.03743***	0.03562***	0.03174***	0.03069***	0.02967***
	(0.00827)	(0.00615)	(0.00446)	(0.00351)	(0.00255)	(0.00252)	(0.00167)	(0.00169)	(0.00184)
Oil Price	0.04672***	0.03844***	0.02770***	0.02173***	0.01951***	0.01561***	0.01337***	0.01337***	0.01303***
	(0.00764)	(0.00442)	(0.00360)	(0.00292)	(0.00239)	(0.00235)	(0.00177)	(0.00141)	(0.00156)
Time Trend	0.00514***	0.00231***	0.00136***	0.00093***	0.00086***	0.00095***	0.00097***	0.00107***	0.00110***
	(0.00049)	(0.00033)	(0.00026)	(0.00020)	(0.00015)	(0.00014)	(0.00009)	(0.00009)	(0.00010)
Cable Dummy	2.33275***	1.30899***	0.65505***	0.53235***	0.54691***	0.58597***	0.55841***	0.56302***	0.56777***
	(0.45650)	(0.20277)	(0.22483)	(0.17158)	(0.10918)	(0.12052)	(0.09976)	(0.07754)	(0.08660)

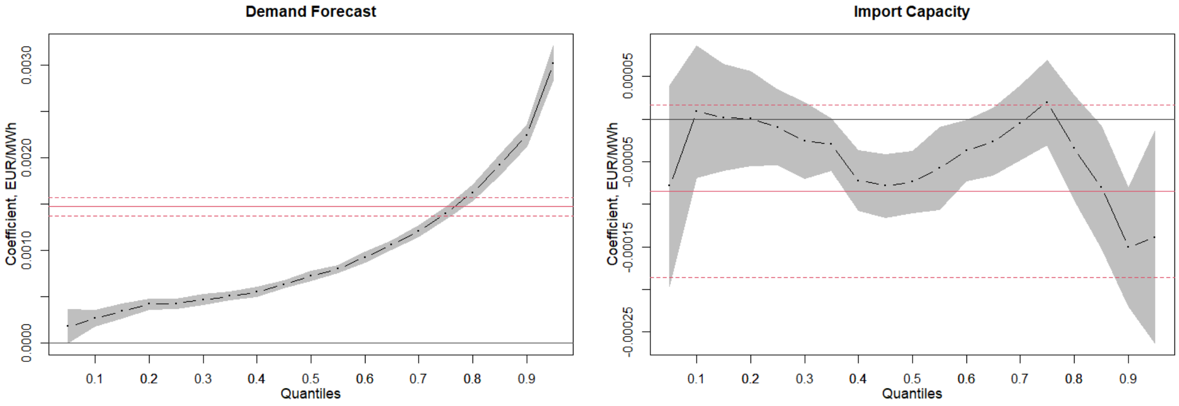
	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
Import Capacity	−0.00007***	−0.00006**	−0.00004*	−0.00003	−0.000005	0.00002	−0.00003	−0.00008*	−0.00015***	−0.00014*
	(0.00002)	(0.00003)	(0.00002)	(0.00002)	(0.00003)	(0.00003)	(0.00004)	(0.00004)	(0.00004)	(0.00008)
Export Capacity	0.00019***	0.00020***	0.00020***	0.00022***	0.00021***	0.00022***	0.00026***	0.00028***	0.00033***	0.00030***
	(0.00002)	(0.00002)	(0.00001)	(0.00002)	(0.00003)	(0.00002)	(0.00003)	(0.00004)	(0.00004)	(0.00006)
Demand Forecast	0.00072***	0.00080***	0.00093***	0.00106***	0.00121***	0.00140***	0.00162***	0.00192***	0.00224***	0.00302***
	(0.00003)	(0.00003)	(0.00003)	(0.00003)	(0.00004)	(0.00004)	(0.00005)	(0.00007)	(0.00007)	(0.00011)
Forecasted Wind Production	−0.00247***	−0.00241***	−0.00248***	−0.00261***	−0.00272***	−0.00292***	−0.00318***	−0.00349***	−0.00388***	−0.00465***
	(0.00006)	(0.00006)	(0.00005)	(0.00006)	(0.00008)	(0.00010)	(0.00009)	(0.00010)	(0.00015)	(0.00023)
Reservoir Level	−0.00001***	−0.00001***	−0.00001***	−0.00001***	−0.00002***	−0.00003***	−0.00003***	−0.00004***	−0.00005***	−0.00006***
	(0.000001)	(0.000001)	(0.000002)	(0.000002)	(0.000002)	(0.000002)	(0.000003)	(0.000003)	(0.000004)	(0.00001)
Electricity Certificate Price	0.14229***	0.15396***	0.15929***	0.16554***	0.17655***	0.19150***	0.22405***	0.27334***	0.30858***	0.38851***
	(0.00982)	(0.00999)	(0.00958)	(0.01189)	(0.01160)	(0.01344)	(0.01622)	(0.01872)	(0.02536)	(0.03852)
Adaptive Behavior	0.94124***	0.94102***	0.93963***	0.93495***	0.92657***	0.91358***	0.89778***	0.87840***	0.85008***	0.79888***
	(0.00140)	(0.00143)	(0.00181)	(0.00229)	(0.00258)	(0.00267)	(0.00316)	(0.00467)	(0.00588)	(0.00952)
Price Volatility	−0.01623***	0.00565	0.02695***	0.05638***	0.09850***	0.15366***	0.23599***	0.37142***	0.64483***	1.20760***
	(0.00532)	(0.00531)	(0.00574)	(0.00701)	(0.00869)	(0.01016)	(0.01112)	(0.02080)	(0.03414)	(0.05764)
Weekend Dummy	−0.57770***	−0.55373***	−0.53318***	−0.54178***	−0.53844***	−0.54998***	−0.58260***	−0.63691***	−0.67582***	−0.54345***
	(0.01969)	(0.01607)	(0.01480)	(0.01947)	(0.02437)	(0.02223)	(0.02616)	(0.02424)	(0.03569)	(0.04904)
Holiday Dummy	−0.20376***	−0.19300***	−0.19453***	−0.18244***	−0.12659*	−0.11721*	−0.12969*	−0.10178	−0.24502***	−0.19878**
	(0.04742)	(0.03938)	(0.04209)	(0.04700)	(0.07040)	(0.06206)	(0.07653)	(0.07080)	(0.08100)	(0.09023)
Gas Price	0.02338***	0.03105***	0.03944***	0.04402***	0.04871***	0.05191***	0.05715***	0.07248***	0.07236***	0.09249***
	(0.00436)	(0.00448)	(0.00596)	(0.00430)	(0.00550)	(0.00619)	(0.00984)	(0.01128)	(0.01567)	(0.02448)
EUA Price	0.02015***	0.01998***	0.01924***	0.02278***	0.03119***	0.04056***	0.04685***	0.04814***	0.05419***	0.08420***
	(0.00275)	(0.00317)	(0.00397)	(0.00419)	(0.00512)	(0.00569)	(0.00759)	(0.00802)	(0.01279)	(0.02198)
Coal Price	0.02905***	0.02766***	0.02521***	0.02564***	0.02712***	0.03018***	0.03559***	0.03996***	0.05124***	0.07280***
	(0.00150)	(0.00178)	(0.00201)	(0.00244)	(0.00284)	(0.00289)	(0.00394)	(0.00469)	(0.00567)	(0.00994)
Oil Price	0.01225***	0.01183***	0.01392***	0.01564***	0.01941***	0.02686***	0.03067***	0.03672***	0.04580***	0.04464***
	(0.00138)	(0.00169)	(0.00159)	(0.00199)	(0.00183)	(0.00216)	(0.00229)	(0.00333)	(0.00417)	(0.00679)
Time Trend	0.00116***	0.00129***	0.00141***	0.00150***	0.00154***	0.00161***	0.00186***	0.00229***	0.00254***	0.00297***
	(0.00008)	(0.00009)	(0.00010)	(0.00009)	(0.00011)	(0.00013)	(0.00018)	(0.00020)	(0.00028)	(0.00045)
Cable Dummy	0.57521***	0.64187***	0.74142***	0.82123***	0.93615***	1.14683***	1.55643***	2.14063***	2.57560***	2.87655***
	(0.07206)	(0.07139)	(0.08463)	(0.07846)	(0.11288)	(0.10491)	(0.16164)	(0.18537)	(0.30492)	(0.48255)
Note:										*p<0.1; **p<0.05; ***p<0.01 Constant, month-, and hour dummies omitted due to brevity.

Table A2.1: Quantile regression output for NO2.



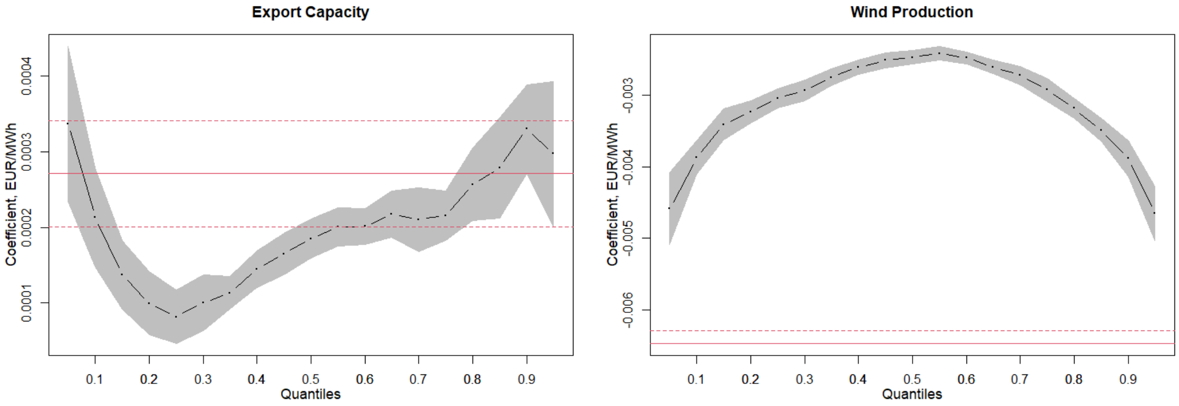
(a) Adaptive Behavior (lagged prices) NO2

(b) Price Volatility NO2



(c) Demand Forecast NO2

(d) Import Capacity NO2



(e) Export Capacity NO2

(f) Forecasted Wind Production NO2

Figure A2.1: Coefficient estimates for control variables NO2

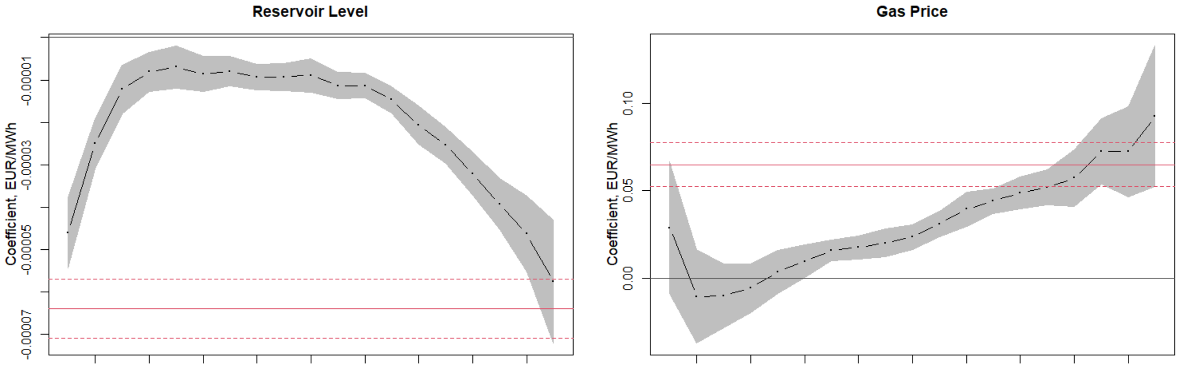
Figure A2.1a shows the coefficient estimates for lagged spot price. All estimates are positive across quantiles, providing evidence for adaptive behavior among market participants. Additionally, estimates' values imply that prices are mean-reverting.

As seen in Figure A2.1b, price volatility's estimated coefficients follow an s-shaped form across the quantiles, changing sign from negative to positive. The sign and shape of the estimates are in line with our expectations, providing evidence for price volatility amplifying both low and high prices. Bunn et al. (2016) explains that these results suggest that "*both low and high electricity prices overshoot the fundamentals when the price uncertainty is high*".

Coefficient estimates for demand forecast are positive and increasing across quantiles, seen in Figure A2.1c. This is in line with our expectations, as a shift in the inelastic demand curve when prices are high would increase prices non-linearly due to upward movement in the steeply increasing and convex merit order curve. Except the 5% quantile, all coefficient estimates for demand are significant at a 5%-level.

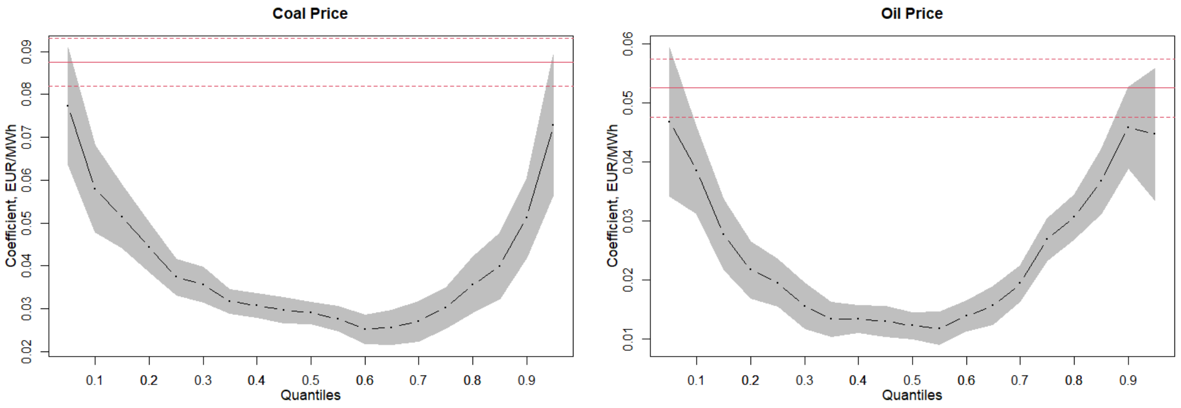
As seen in Figure A2.1d, the majority of coefficient estimates for import capacity are negative. These generally negative values confirms the expected downward pressure from import on prices. Except the estimates in quantiles 5% to 35%, and 60-85%, all estimates for import capacity are significant. Export capacity's coefficient estimates are positive across quantiles, confirming its expected positive effect on prices.

Estimates for wind production are negative across quantiles, confirming its downward pressure on electricity prices.

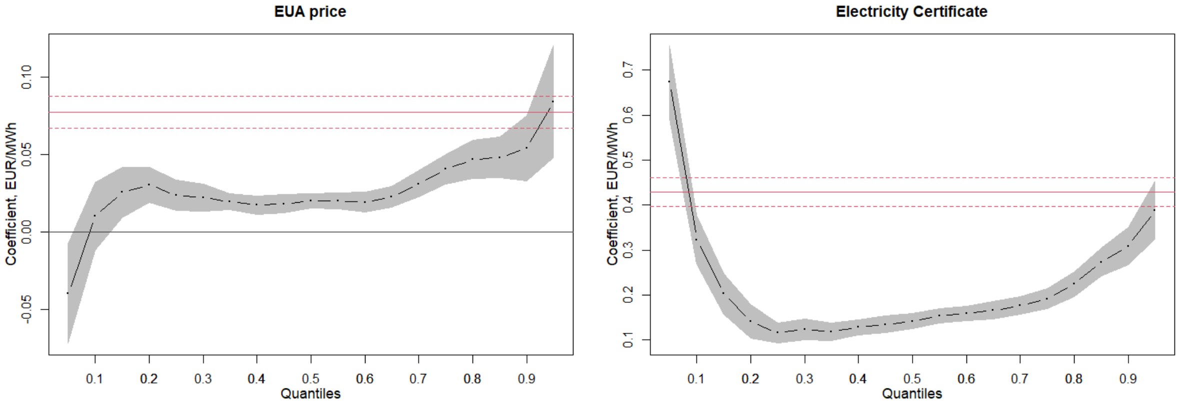


(a) Water Reservoir Level NO2

(b) Gas price NO2



(c) Coal price NO2 **(d)** Oil price NO2



(e) EUA price NO2 **(f)** Electricity Certificates NO2

Figure A2.2: Coefficient estimates for control variables NO2

Figure A2.2a shows coefficient estimates for reservoir levels being negative across all quantiles, in line with the results found in Huisman et al. (2014). This can be explained by hydro producers being more reserved about producing electricity when reservoir levels are low.

The majority of coefficient estimates for fossil fuels, seen in Figure A2.2b, A2.2c, A2.2d, and A2.2e, have positive values. This is in line with our expectations, as higher prices on fossil fuels is expected to impact Norwegian electricity prices through their effect on prices in nearby countries or the opportunity costs of hydropower.

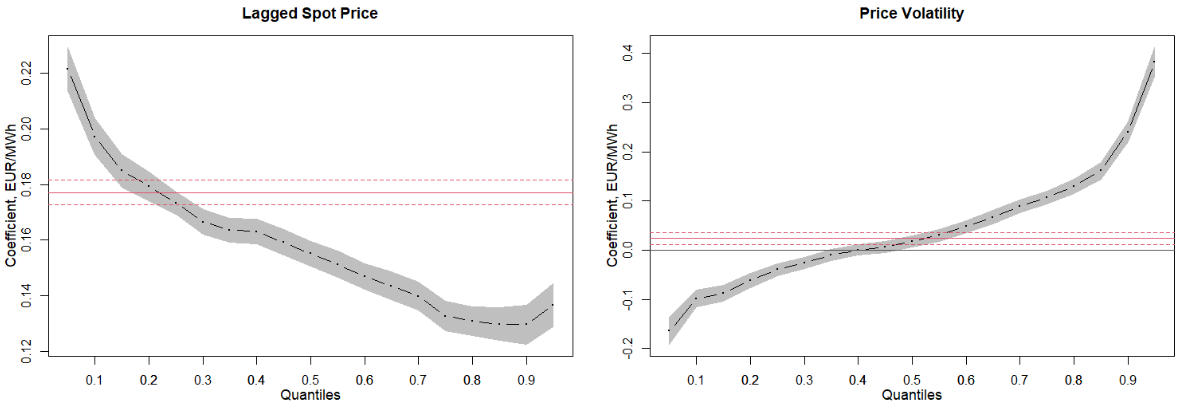
Electricity certificates' estimates, seen in Figure A2.2f, are all positive across quantiles. The positive estimates imply that electricity certificates exercise a upwards pressure on electricity prices, contradictory to our expectations.

A2.2 Germany

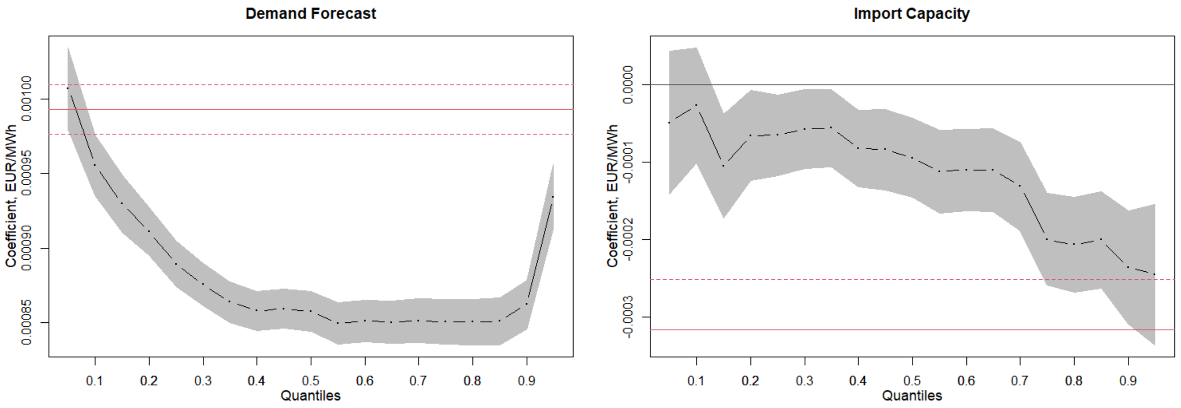
	Dependent variable:								
	Price								
	5%	10%	15%	20%	25%	30%	35%	40%	45%
Import Capacity	−0.00005	−0.00003	−0.00011**	−0.00007*	−0.00007*	−0.00006	−0.00006*	−0.00008**	−0.00008***
	(0.00007)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00004)	(0.00003)	(0.00004)	(0.00003)
Export Capacity	−0.00002	−0.00004	0.00001	−0.00004	−0.00006*	−0.00009***	−0.00011***	−0.00010***	−0.00011***
	(0.00005)	(0.00004)	(0.00004)	(0.00003)	(0.00003)	(0.00002)	(0.00003)	(0.00003)	(0.00003)
Demand Forecast	0.00101***	0.00096***	0.00093***	0.00091***	0.00089***	0.00088***	0.00086***	0.00086***	0.00086***
	(0.00002)	(0.00002)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Forecasted Wind Production	−0.00112***	−0.00104***	−0.00099***	−0.00096***	−0.00094***	−0.00092***	−0.00090***	−0.00088***	−0.00086***
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00000)	(0.00001)	(0.00001)
Forecasted PV Production	−0.00108***	−0.00096***	−0.00092***	−0.00088***	−0.00086***	−0.00085***	−0.00084***	−0.00083***	−0.00083***
	(0.00002)	(0.00002)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Coal Price	0.09758***	0.13270***	0.15166***	0.16451***	0.17561***	0.18765***	0.19204***	0.19446***	0.19975***
	(0.01084)	(0.00701)	(0.00693)	(0.00610)	(0.00678)	(0.00548)	(0.00470)	(0.00519)	(0.00530)
EUA Price	0.39716***	0.47755***	0.52387***	0.54289***	0.55467***	0.57138***	0.58299***	0.58493***	0.59475***
	(0.02585)	(0.01783)	(0.01417)	(0.01525)	(0.01400)	(0.01236)	(0.01029)	(0.01224)	(0.01129)
Gas Price	0.30373***	0.28842***	0.33714***	0.37944***	0.41103***	0.42790***	0.44913***	0.47144***	0.49338***
	(0.01773)	(0.01872)	(0.02343)	(0.02246)	(0.01951)	(0.01750)	(0.01540)	(0.01544)	(0.01821)
Oil Price	0.12187***	0.08897***	0.05928***	0.03847***	0.02386***	0.01531***	0.00866*	0.00359	−0.00024
	(0.01274)	(0.00760)	(0.00837)	(0.00603)	(0.00627)	(0.00513)	(0.00493)	(0.00455)	(0.00686)
Adaptive Behavior	0.22150***	0.19721***	0.18502***	0.17933***	0.17333***	0.16648***	0.16366***	0.16304***	0.15922***
	(0.00932)	(0.00743)	(0.00514)	(0.00451)	(0.00427)	(0.00442)	(0.00445)	(0.00385)	(0.00368)
Price Volatility	−0.16421***	−0.09859***	−0.08741***	−0.06134***	−0.03925***	−0.02560***	−0.01032	0.00048	0.00679
	(0.02238)	(0.01431)	(0.00990)	(0.00945)	(0.00716)	(0.00823)	(0.00674)	(0.00677)	(0.00688)
Electricity Certificate Price	0.10916	0.07074	0.09980**	0.20851***	0.27579***	0.34449***	0.35908***	0.38573***	0.38186***
	(0.07039)	(0.06129)	(0.04768)	(0.04658)	(0.04156)	(0.02718)	(0.02770)	(0.03222)	(0.03759)
Reservoir Level	−0.00002	−0.00001	−0.00001	−0.0000001	0.000002	0.00001	0.00001	0.000001	0.0000002
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Time Trend	0.00236***	0.00133***	0.00120***	0.00189***	0.00237***	0.00272***	0.00277***	0.00299***	0.00296***
	(0.00055)	(0.00045)	(0.00044)	(0.00045)	(0.00037)	(0.00030)	(0.00026)	(0.00030)	(0.00034)
Weekend Dummy	−0.90747***	−0.94168***	−0.89397***	−0.87288***	−0.93612***	−0.94952***	−0.97971***	−0.98977***	−0.95939***
	(0.24782)	(0.20341)	(0.16891)	(0.14589)	(0.11169)	(0.10924)	(0.10609)	(0.11370)	(0.10120)
Holiday Dummy	−16.26224***	−9.86347***	−5.15897***	−3.40130***	−2.72225***	−2.34627***	−1.79737***	−1.44057***	−1.18763***
	(2.40396)	(1.27316)	(0.93468)	(0.51675)	(0.39047)	(0.34969)	(0.32216)	(0.25999)	(0.27566)
Cable Dummy	−0.38798	0.21762	0.02071	−0.15044	−0.37865*	−0.53038**	−0.85039***	−0.96983***	−1.17385***
	(0.52243)	(0.29263)	(0.28890)	(0.23232)	(0.22386)	(0.22634)	(0.18493)	(0.18211)	(0.16541)
Note:									*p<0.1; **p<0.05; ***p<0.01 Constant, month-, and hour dummies omitted due to brevity.

	Dependent variable:									
	Price									
	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
Import Capacity	−0.00009***	−0.00011***	−0.00011***	−0.00011***	−0.00013***	−0.00020***	−0.00021***	−0.00020***	−0.00024***	−0.00025***
	(0.00003)	(0.00004)	(0.00003)	(0.00003)	(0.00004)	(0.00004)	(0.00004)	(0.00005)	(0.00004)	(0.00006)
Export Capacity	−0.00012***	−0.00012***	−0.00014***	−0.00017***	−0.00018***	−0.00020***	−0.00025***	−0.00029***	−0.00038***	−0.00042***
	(0.00003)	(0.00004)	(0.00003)	(0.00003)	(0.00003)	(0.00004)	(0.00004)	(0.00005)	(0.00005)	(0.00005)
Demand Forecast	0.00086***	0.00085***	0.00085***	0.00085***	0.00085***	0.00085***	0.00085***	0.00085***	0.00086***	0.00093***
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00002)
Forecasted Wind Production	−0.00085***	−0.00085***	−0.00084***	−0.00084***	−0.00084***	−0.00084***	−0.00085***	−0.00086***	−0.00088***	−0.00094***
	(0.00001)	(0.00000)	(0.00000)	(0.00000)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Forecasted Wind Production	−0.00082***	−0.00082***	−0.00082***	−0.00082***	−0.00082***	−0.00083***	−0.00084***	−0.00086***	−0.00087***	−0.00093***
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00002)
Coal Price	0.20470***	0.21205***	0.21951***	0.22986***	0.23668***	0.24273***	0.25307***	0.25947***	0.26283***	0.26127***
	(0.00548)	(0.00529)	(0.00656)	(0.00628)	(0.00483)	(0.00681)	(0.00757)	(0.00720)	(0.01090)	(0.01386)
EUA Price	0.61765***	0.63206***	0.66021***	0.68029***	0.70287***	0.71760***	0.73791***	0.75292***	0.74363***	0.71983***
	(0.01051)	(0.01128)	(0.01341)	(0.01267)	(0.01179)	(0.01402)	(0.01709)	(0.01498)	(0.02389)	(0.03579)
Gas Price	0.51950***	0.53520***	0.55876***	0.57750***	0.60252***	0.65441***	0.70423***	0.75535***	0.84600***	0.88274***
	(0.01129)	(0.01813)	(0.02077)	(0.01866)	(0.02113)	(0.02483)	(0.02103)	(0.02340)	(0.03032)	(0.03659)
Oil Price	−0.00899	−0.01854***	−0.03067***	−0.04010***	−0.05247***	−0.06222***	−0.07864***	−0.10189***	−0.12876***	−0.16579***
	(0.00716)	(0.00502)	(0.00679)	(0.00658)	(0.00645)	(0.00741)	(0.00913)	(0.00827)	(0.01098)	(0.01121)
Adaptive Behavior	0.15515***	0.15130***	0.14688***	0.14358***	0.13985***	0.13264***	0.13091***	0.12980***	0.12958***	0.13665***
	(0.00363)	(0.00385)	(0.00346)	(0.00366)	(0.00392)	(0.00416)	(0.00400)	(0.00408)	(0.00454)	(0.00539)
Price Volatility	0.01716**	0.03049***	0.04829***	0.06687***	0.08874***	0.10668***	0.12997***	0.16134***	0.24068***	0.38263***
	(0.00732)	(0.00718)	(0.00802)	(0.00843)	(0.00793)	(0.00698)	(0.00659)	(0.01275)	(0.01452)	(0.02223)
Electricity Certificate Price	0.38671***	0.40622***	0.42119***	0.46131***	0.51834***	0.59589***	0.67593***	0.77599***	0.97370***	1.15509***
	(0.03116)	(0.03391)	(0.03093)	(0.04015)	(0.03661)	(0.04170)	(0.04789)	(0.04185)	(0.04552)	(0.05921)
Reservoir Level	−0.000002	−0.000004	−0.00001	−0.000005	−0.00001	−0.000002	0.000001	−0.000001	−0.000004	−0.00001
	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)	(0.00001)
Time Trend	0.00282***	0.00283***	0.00271***	0.00276***	0.00293***	0.00335***	0.00383***	0.00457***	0.00626***	0.00798***
	(0.00023)	(0.00030)	(0.00031)	(0.00036)	(0.00035)	(0.00040)	(0.00037)	(0.00038)	(0.00050)	(0.00074)
Weekend Dummy	−0.96029***	−1.01106***	−0.96875***	−0.89215***	−0.87536***	−0.83087***	−0.93745***	−1.06441***	−1.11549***	−1.04890***
	(0.10875)	(0.08525)	(0.10255)	(0.09281)	(0.09239)	(0.11384)	(0.08717)	(0.10265)	(0.12965)	(0.15561)
Holiday Dummy	−1.09782***	−0.78475***	−0.39821	−0.12596	0.20350	0.37284	0.74790***	0.99576***	1.72835***	2.57507***
	(0.27957)	(0.29084)	(0.34428)	(0.25442)	(0.21826)	(0.32312)	(0.27409)	(0.26835)	(0.35779)	(0.31081)
Cable Dummy	−1.39115***	−1.41924***	−1.76266***	−1.93370***	−2.20620***	−2.52010***	−3.10303***	−3.34930***	−3.69163***	−2.70218***
	(0.19036)	(0.18313)	(0.18944)	(0.20920)	(0.21292)	(0.27998)	(0.24688)	(0.28459)	(0.34918)	(0.55817)
Note:										*p<0.1; **p<0.05; ***p<0.01 Month- and hour dummies omitted due to brevity.

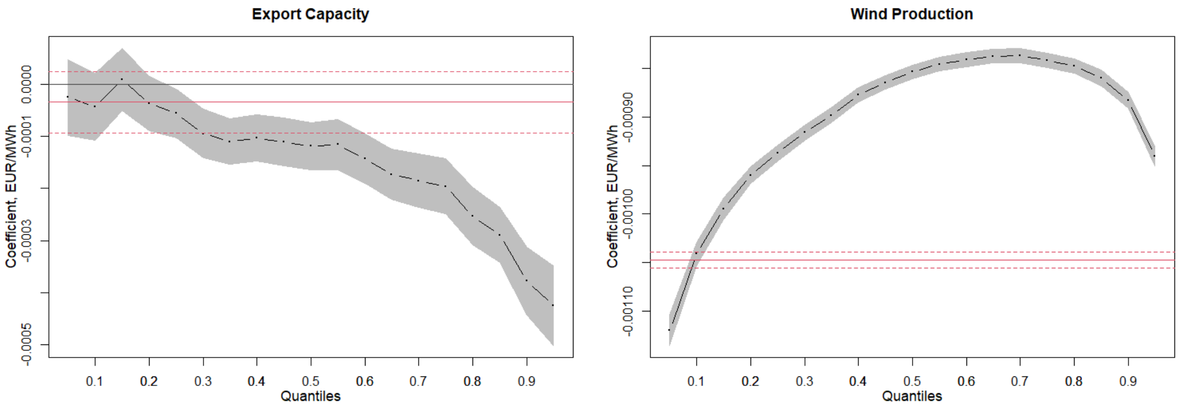
Table A2.2: Quantile regression output for Germany.



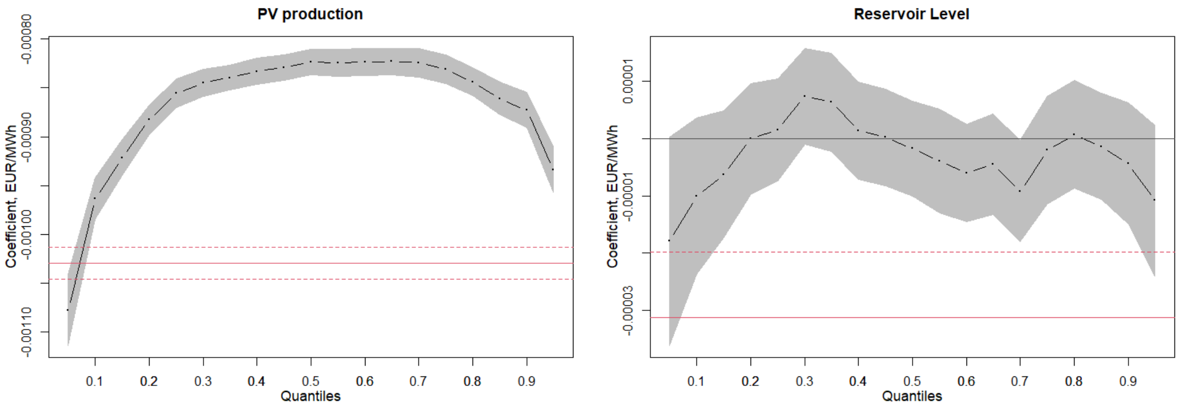
(a) Adaptive Behavior (lagged prices) Germany **(b)** Price Volatility Germany



(c) Demand Germany **(d)** Import Capacity Germany



(e) Export Capacity Germany **(f)** Forecasted Wind Production Germany



(g) PV production Germany **(h)** Water Reservoir Level Germany

Figure A2.3: Coefficient estimates for control variables for Germany

Coefficient estimates for lagged spot price are positive and decreasing across quantiles, seen in Figure A2.3a. The positive sign across quantiles confirms the presence of adaptive behavior while the reduced magnitude in the higher quantiles contradicts the expectations of adaptive behavior being more frequent when prices are high. Similarly to NO2, prices seem to be mean-reverting. Lastly, all estimates are significant at a 5%-level.

Estimated coefficients for price volatility follow an s-shaped pattern across quantiles, changing sign from negative to positive. These results confirm our expectations of price volatility amplifying low and high prices, as price uncertainty overshoots fundamentals when prices are at extreme levels. Except the 35% to 45% quantiles, all estimated coefficients are significant at a 5%-level.

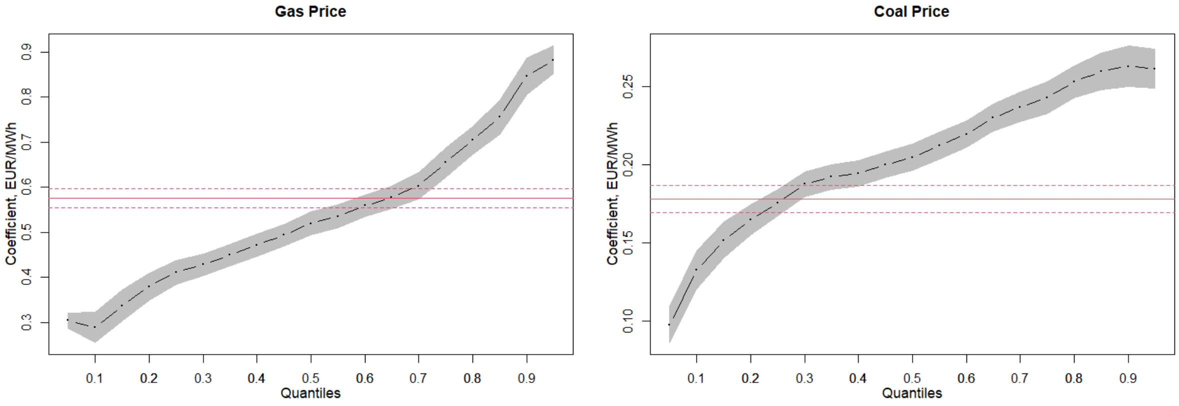
As seen in Figure A2.3c, coefficient estimates for demand forecast are positive and decreasing across quantiles, indicating that demand has a larger effect on prices at lower levels. These results does not align the findings for NO2 and Bunn et al. (2016), nor our expectations for the variable.

Import capacity's coefficient estimates are negative across all quantiles, indicating a negative effect on prices. With the exception of the quantiles 5%, 10%, 20%, 30%, and 35%, all estimates are significant at a 5%-level. Export capacity's coefficient estimates are also negative, except at the 15% quantile. This was surprising, as export was expected to positvely affect electricity prices. Estimates are significant on a 5% level, except at the 5%, 10%, 15%, and 20% quantiles.

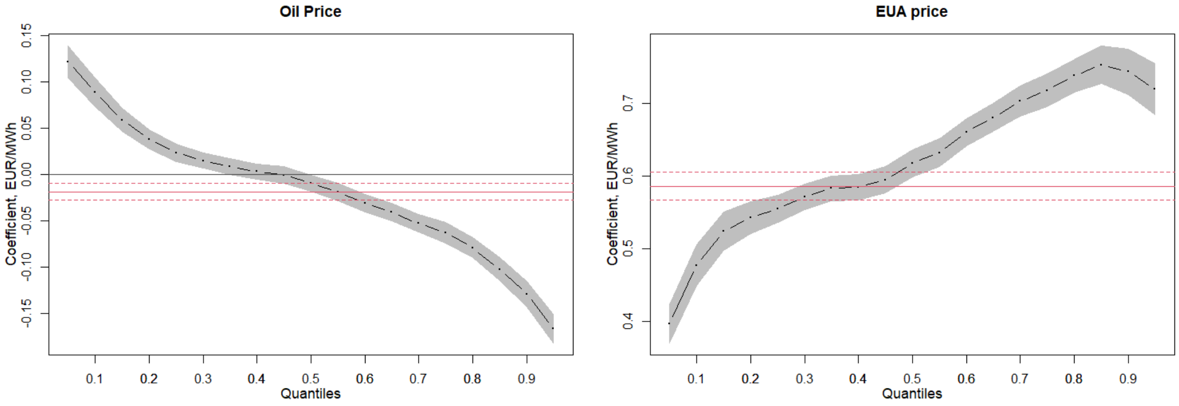
Figure A2.3f shows how the coefficient estimates for forecasted wind production are negative across all quantiles. This implies that wind production exercises a downward pressure on electricity prices, as expected.

Coefficient estimates for PV Production are negative across quantiles, seen in Figure A2.3g. These negative values implies that PV production exercise a downward pressure on prices, similarly to wind production.

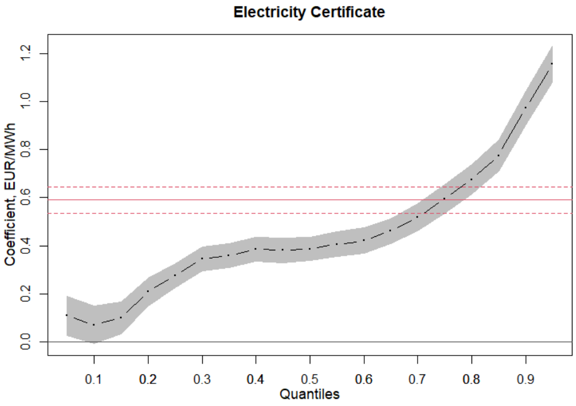
Figure A2.3h shows Norwegian water reservoir level's coefficient estimates in Germany. Estimates' values are both positive and negative, but lack significance in all quantiles. Hence, we are unable to confirm an association between reservoir levels in Norway and German electricity prices.



(a) Gas price Germany **(b)** Coal price Germany



(c) Oil price Germany **(d)** EUA price Germany



(e) Electricity Certificates Germany

Figure A2.4: Coefficient estimates for control variables in Germany

Coefficient estimates for fossil fuel prices and EUAs are shown in Figure A2.4a, A2.4b, A2.4c, and A2.4d. Estimates for gas, coal, and EUAs are strictly positive, following a rising pattern across quantiles. These characteristics implies that all three variables positively affect electricity prices, with a greater impact at the higher tail of the distribution, which is in line with our expectations.

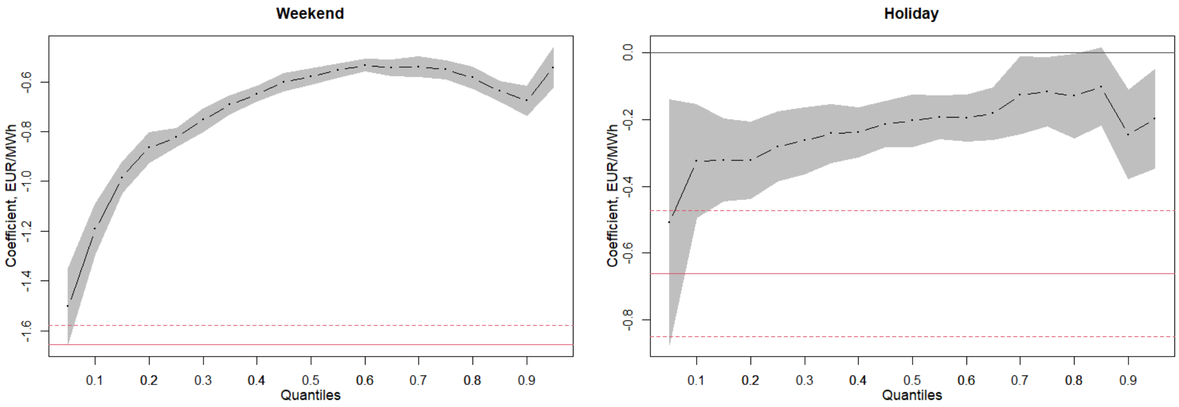
On the other hand, oil prices' estimates follow a decreasing pattern, shifting from positive- to negative values around the median. These results were surprising, as we expected oil prices to have a positive effect on electricity prices. These positive values could be caused by the high correlation between fossil fuels, seen in Figure A1.6.

Figure A2.4e shows electricity certificates' coefficient estimates for Germany, which are seen to be both positive and rising across quantiles. As the market for certificates is only available in Norway and Sweden, we did not not expect the variable to significantly affect German prices, nor be positive. These significant- and positive estimates imply an upwards pressure on electricity prices, contradictory to our expectations.

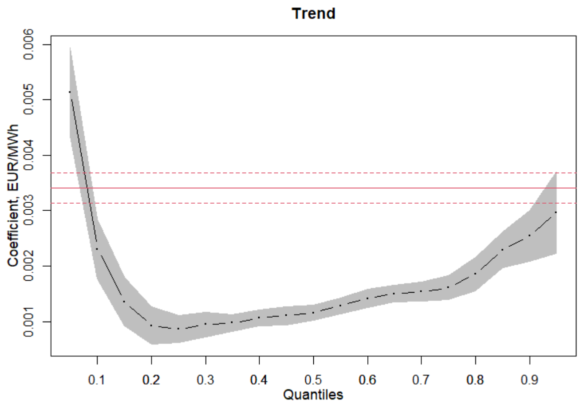
A2.3 Time Variables in NO2 and Germany

For the sake of brevity, coefficient estimates for month- and hour dummies are not reported.

As seen from Figure A2.5, coefficient estimates for the weekend- and holiday dummies in NO2 are negative across quantiles. This negative effect indicates that prices are lower when observed during the weekend or holidays, which is likely due to a low level of demand. For the time trend variable, coefficient estimates are positive, implying that electricity prices are increasing during the course of time in NO2.



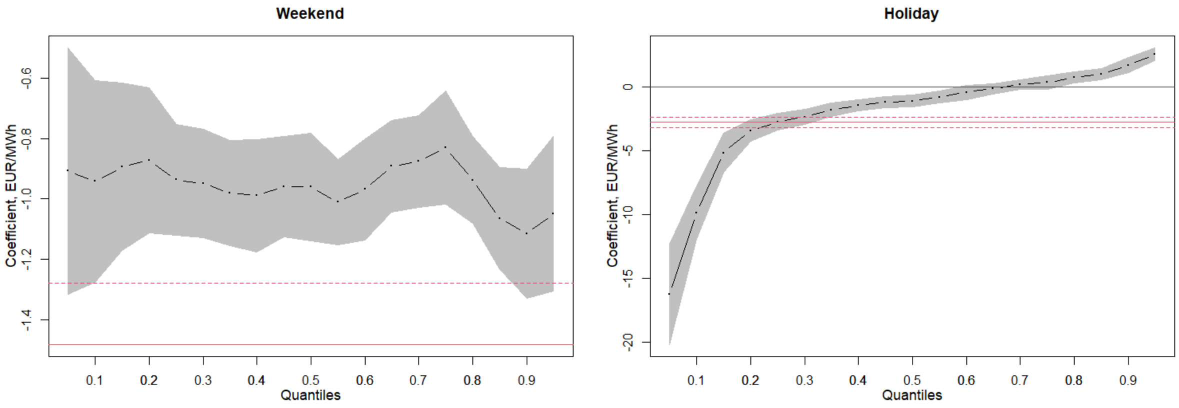
(a) Weekend dummy NO2 **(b)** Holiday dummy NO2



(c) Trend variable NO2

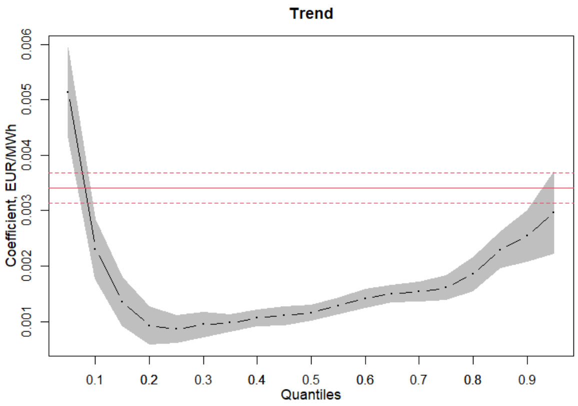
Figure A2.5: Quantile regression estimates for weekend dummy, holiday dummy and trend variable in NO2.

Coefficient estimates for weekend- and holiday dummies are generally negative across quantiles, except the highest quantiles for the holiday variable. These results are seen in Figure A2.6 and indicate that the occurrences of weekends and national holidays have a negative effect on prices. Contradictory, the time trend variable's estimates are positive across quantiles showing that electricity prices have increased during the course of time in Germany.



(a) Weekend dummy for Germany

(b) Holiday dummy for Germany

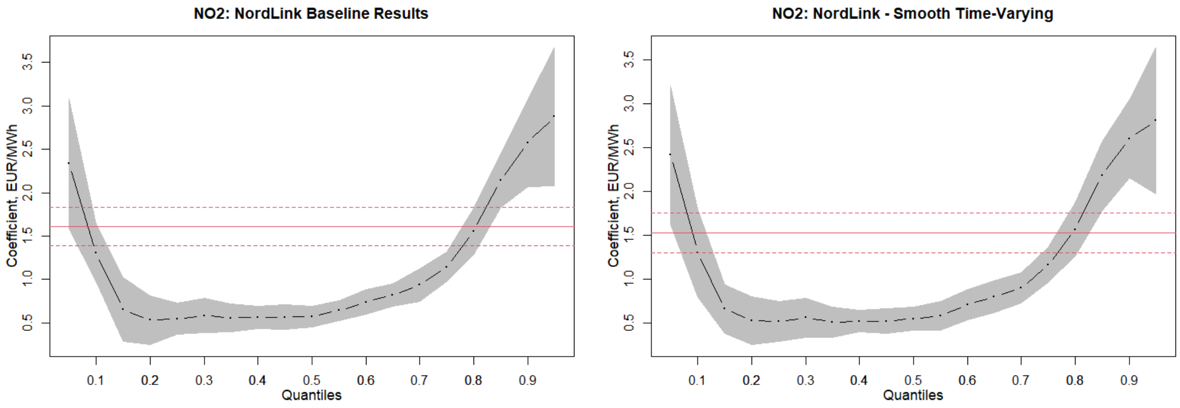


(c) Trend variable for Germany

Figure A2.6: Quantile regression estimates for weekend dummy, holiday dummy and trend variable in Germany.

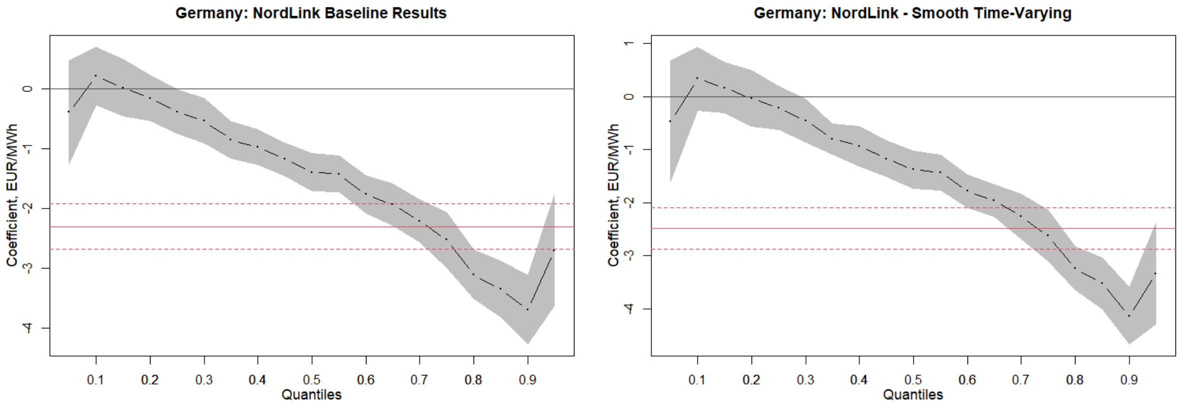
A2.4 Robustness

The convergence of the smooth time-varying variable is performed by using the logistic function $\frac{pz}{1+pz}$. In the function, $z = 1$ for the first hour of December 9th, 2020, and increases by 1 for each hour until the last trading hour on March 31st, 2021, reaching a value of $z = 2712$. p is a parameter, which through experimenting, is chosen to have a value of 0.04.



(a) Baseline **(b)** Smooth Time-Varying

Figure A2.7: Quantile regression estimates for NordLink time-varying variable in NO2. Showing the baseline results of the NordLink dummy variable to the left and results from the robustness test to the right.



(a) Baseline **(b)** Smooth Time-Varying

Figure A2.8: Quantile regression estimates for NordLink time-varying variable in Germany. Showing the baseline results of the NordLink dummy variable to the left and results from the robustness test to the right.

As seen in Figure A2.7 and A2.8, the pattern from coefficient estimates for both NO2 and Germany is relatively similar to our baseline results. The variable is significant at a 5%-level across quantiles in NO2, while only being significant beyond the 30% quantile in Germany. Thus, the significance of the cable variables has not changed from the baseline results.

A2.5 Renewable Production Timelines

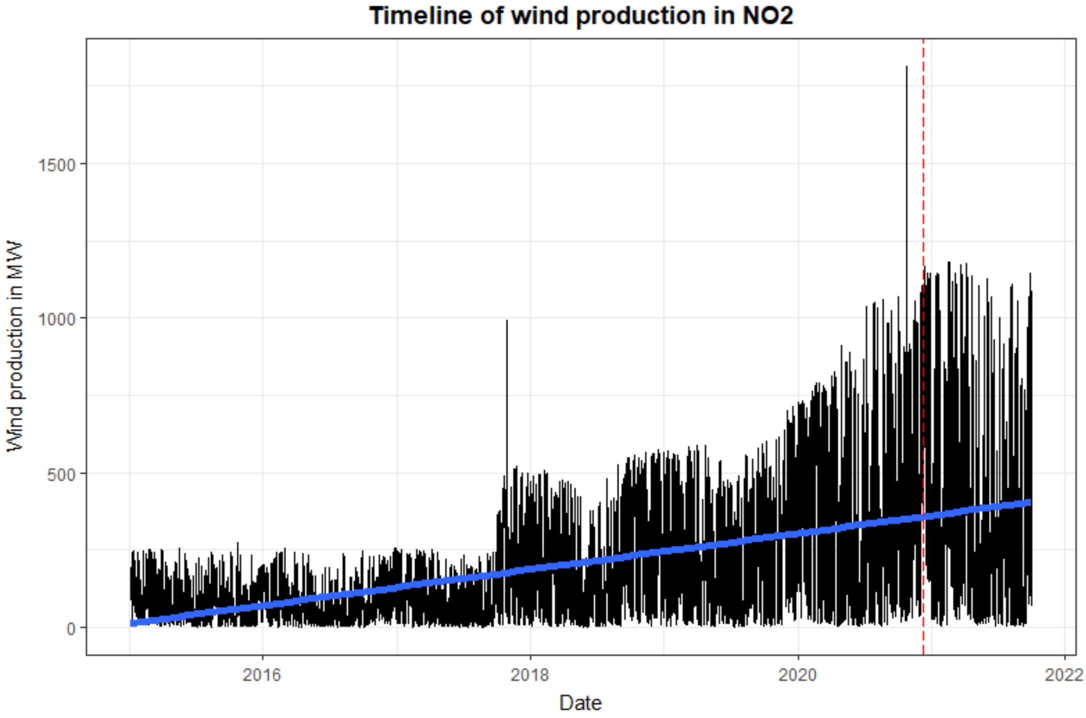


Figure A2.9: Timeline of wind production in NO2. Red dotted line showing the inception of NordLink, blue line is a linear trend line of production.

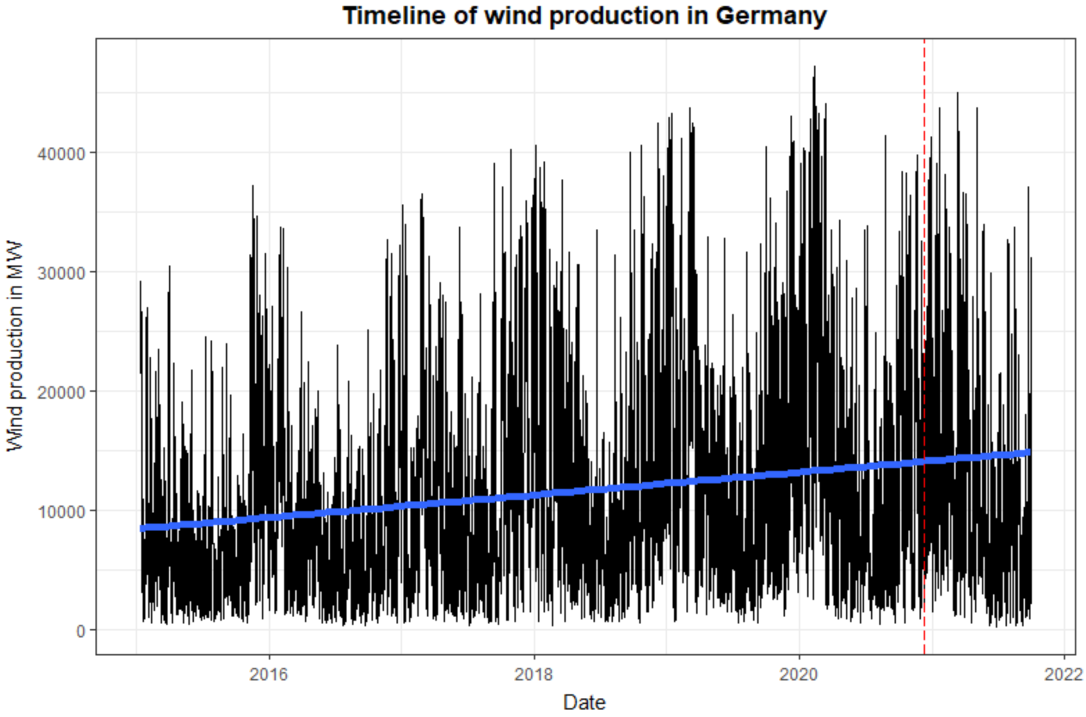


Figure A2.10: Timeline of wind production in Germany. Red dotted line showing the inception of NordLink, blue line is a linear trend line of production.

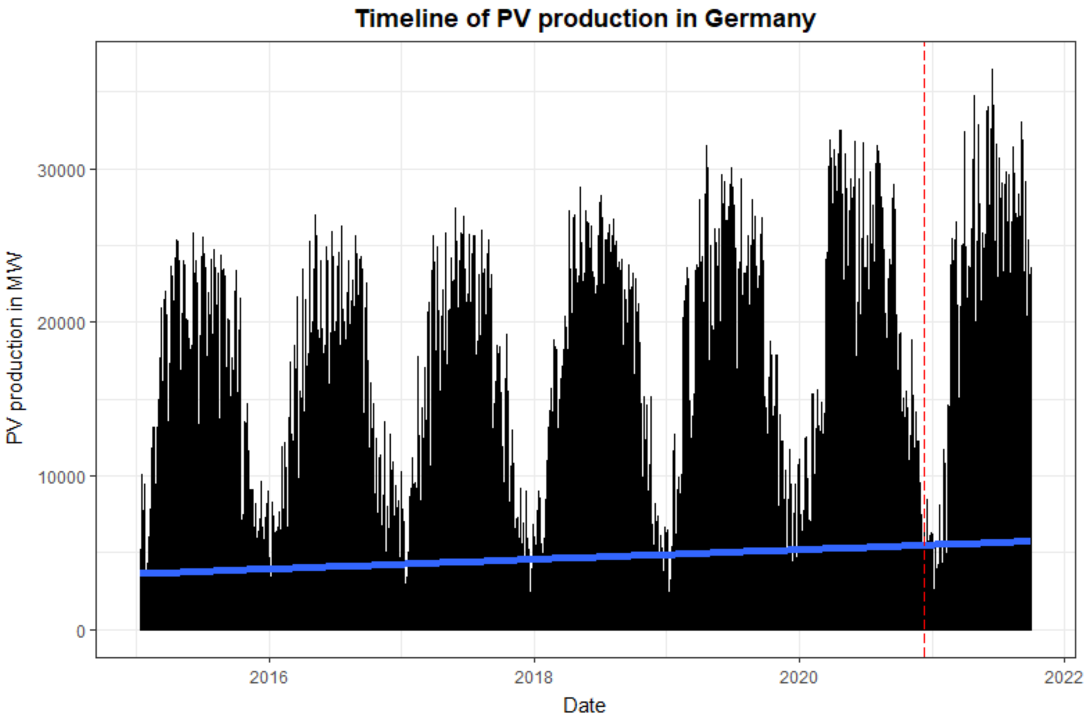


Figure A2.11: Timeline of PV production in Germany. Red dotted line showing the inception of NordLink, blue line is a linear trend line of production.

A2.6 Physical Flow: NordLink

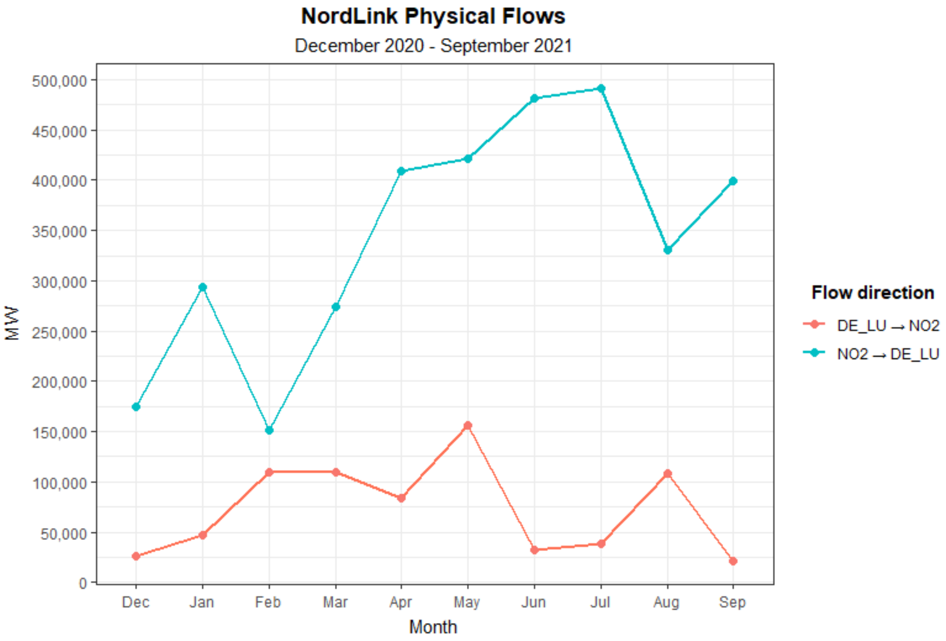


Figure A2.12: Sum of physical flows over NordLink for each month in our sample size.