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The NordLink Effect on Norwegian and German Electricity Price Convergence

A difference-in-difference approach

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Abstract

This thesis studies NordLink, a subsea interconnector, and its effect on electricity price convergence between Norway and Germany. To measure market convergence, we use the *spread*, defined as the difference between electricity prices in two countries. We employ a difference-in-difference estimation using Belgian electricity prices to estimate the counterfactual trend for German prices to disentangle the causal NordLink effect. This analysis yields the main result of the thesis, which is that NordLink has, on average, reduced the spread by €12.3 per MWh since its introduction

We further examine the drivers behind the flow of electricity in NordLink to uncover when and why prices converge. We argue that structural difference in the countries' energy mix is the primary driver determining the flow in NordLink. Germany's relatively rigid electricity production leads to a deficit during high-demand periods, which is well complimented by Norway's flexible hydropower production.

This thesis also discusses how the merit order affects electricity prices and, therefore, must be considered when analysing market convergence. We demonstrate that the merit order can have a significant impact on the electricity price spread and should therefore be considered when analysing market convergence. Overlooking this externality could lead to an overestimation of the integration effects of interconnectors like NordLink.

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Digital Appendix: https://github.com/larsalvern/NordLink_Appendix

Keywords – NordLink, Day-ahead electricity markets, Difference-in-difference, Market convergence, Interconnectors.

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1 Introduction

This thesis aims to isolate the effect of NordLink, a subsea electricity interconnector connecting Norway and Germany, on the convergence of electricity prices between the two electricity markets. To isolate the causal effect of NordLink, we employ a difference-in-difference technique and use Belgian electricity prices as a counterfactual trend for German prices. In addition to market convergence, we also analyse the underlying factors that drive this convergence, with a focus on the countries' energy mix. This analysis provides further context and increases the understanding of when and why the convergence happens. We measure the convergence of the electricity markets by using the absolute spread. Spread is defined as the difference between the electricity prices in two markets. Using absolute values for the spread makes interpretations easier compared to the raw difference in price, which can be either negative or positive.

In the existing literature on market integration, it has been shown that increased interconnector capacity between countries can lead to electricity market convergence. Our study substantiates this by finding evidence of market convergence between Norway and Germany due to increased interconnectivity. Most studies on the effects of increased interconnectivity focus directly on domestic electricity prices. However, our study takes a new approach by examining market convergence using the spread between countries and estimating the causal effect of a single interconnector. Our findings especially contribute to the discussion of how increased renewable production can reduce electricity prices and impact market convergence, as discussed by de Lagarde and Lantz. Additionally, our thesis supports the idea proposed by Gugler and Haxhimusa, suggesting that the effect of interconnectors is often overestimated in the literature, as increasingly similar energy mixes and merit orders play a significant role in market convergence.

We find that NordLink has converged the Norwegian and German electricity prices by €12.3 per MWh on average. Increased renewable production in Germany, such as wind and solar, tends to reduce the spread, while Norwegian wind production increases the spread. Periods with congestion correlate with a much higher average spread, as the two markets cannot fully converge. When NordLink is congested from Norway to Germany, the spread is, on average, €42 per MWh higher compared to periods with available transmission capacity in NordLink. Similarly, we find an average increase of €32 per MWh when the cable is congested from Germany to Norway.

Germany had the highest electricity price roughly 80 % of the time across the time frame of our data set. Therefore, on average, Norwegian prices must have increased, and German prices decreased for market convergence to occur. As a result of the increased Norwegian electricity prices due to NordLink, we estimate that the yearly electricity bill of an average household in Southern Norway has risen by between NOK 1,188 and NOK 1,584.

The electricity demand, and therefore also the prices and spread, fluctuates during the day and week, with peaks during the morning and afternoon and a general reduction during the weekends, especially in Germany. Norway's hydropower-dominated energy mix offers a unique and flexible electricity production that can match the electricity consumption pattern. In Germany, however, a more rigid power production dominated by thermal power plants, wind and solar cannot match the fluctuating demand. This inflexibility causes intraday electricity surpluses and deficits, highlighting the need for cross-border power transmission. Consequently, NordLink transmits most power and reduces the spread the most during peak demand hours when Germany relies on imports or when high intermittent renewable energy production in Germany corresponds with low domestic demand, which leads to a power surplus and export requirement.

While renewable production in Germany reduces the spread on average, we see the opposite effect when Norway has the highest electricity prices. This situation shows how the merit order effect can have a greater impact on electricity price spread than the integration effect of an interconnector. Increased renewable production in Germany leads to more exports to Norway, which lowers Norwegian prices. However, the merit order effect, which causes a decrease in German prices, is stronger than the integration effect of NordLink, resulting in an overall increase in the spread.

The soaring electricity prices in late 2021 and 2022 have sparked heated discussions in Norway regarding interconnectors. NordLink and North Sea Link[1] have received significant attention for contributing to increased Norwegian electricity prices. However, NordLink aligns well with the European Union's goal of increased electricity market integration. The EU argues for increased interconnectivity by emphasising improved supply security, more efficient utilisation of the region's power sources, more equal price levels among member states, and facilitation of the transition to more renewable energy. Because interconnectors are expected to play a significant role in the future energy system, it is important for decision-makers to understand their consequences. This thesis helps to better understand the implications of market integration by empirically estimating the causal effect of NordLink. Additionally, our thesis highlights how different energy mixes affect market convergence and interconnector capacity. The future electricity markets will be increasingly interconnected, and these insights must be considered when shaping both domestic and international energy policies.

[1] An interconnector connecting Norway and the UK, commissioned in October 2021

2 Literature Review

Gugler, Haxhimusa and Liebensteiner measured market integration between France and Germany while controlling for the countries' different generation mixes (Gugler et al., 2018). No cross-border congestion occurred only in hours when the two production mixes were similar. On the contrary, dissimilar production mixes combined with high demand led to congestion and price divergence. The increasing share of renewables in Germany has made French and German production mixes increasingly different. This development leads to more frequent congestion and increasing demand for interconnector capacity to fully harvest the benefits of access to a diversified electricity production mix. These findings are supported by Keppler et al. (2016).

A paper from earlier this year assessed the impact of NordLink on day-ahead prices in NO2 and Germany (Myrvoll and Undeli, 2022). The authors found that the introduction of NordLink led to increased electricity prices in NO2 and reduced prices in Germany, converging the markets. Furthermore, price volatility has increased in NO2 and decreased in Germany due to the important role of intermittent renewables in the German electricity production mix.

In their study from 2021, Corona et al. analyse the electricity market integration and how the increasing amount of renewable energy production impacts this integration. Limited physical transmission capacity is the main challenge when developing a common European electricity market (Corona et al., 2021). Increased cross-border capacity would reduce occurrences of congestion and increase price convergence. Additionally, homogenisation of the electricity production mix is favourable to price convergence. This finding implies that the merit order effect impacts electricity price convergence.

Another article on the importance of the merit order effect and electricity market integration was written in 2018 by Gugler and Haxhimusa (Gugler and Haxhimusa, 2018). The authors concluded that the impact of integration on European electricity markets is frequently overstated in the literature. In their study, they discovered that 31% of the convergence in electricity prices between France and Germany was due to similarities in electricity generation methods rather than electricity arbitrage

3 Background

3.1 Power Market Integration in Europe

In a report from 2015, a European Commission Expert Group concluded that a well-integrated energy market is necessary to achieve the EU's energy and climate goals in a cost-effective manner (European Commission, 2022b). The EU aims for its member states to have an interconnector capacity of at least 15% of their domestic electricity generation capacity by 2030.

3.1.1 NordLink: Connecting Norway and Germany

An electricity interconnector is a high-voltage cable that connects the electricity systems of two neighbouring countries (NationalGrid, 2022). NordLink is a subsea interconnector with a maximum transmission capacity of 1400 MW that, for the first time, directly connects the Norwegian and German electricity markets (Statnett, 2022b). The TSO[2]s in Norway and Germany financed and now own and operate NordLink. The interconnector began transmitting electricity on December 9$^{\text{th}}$ 2020.

In 2013, the Norwegian TSO Statnett concluded that NordLink would result in a significant socioeconomic benefit for both Norway and Germany (Statnett, 2013). This is because the interconnector would enable the two countries to better take advantage of their respective power generation capacities, with Germany using thermal power plants and intermittent renewables, and Norway using flexible hydropower. Statnett also estimated that NordLink would result in an electricity price increase of around €4 per MWh in Southern Norway.

3.1.2 The "Price Contagion" Effect of Interconnectors

"Price contagion" is a phenomenon in which electricity prices converge as a result of an interconnector connecting two markets (Gugler et al., 2018). This is because electricity flows from the cheaper to the more expensive price area. For example, if Norwegian producers can sell their power for a higher price in Germany than they can domestically,

[2]Transmission System Operator: an organisation committed to transporting electrical power on a national or regional level, using fixed infrastructure (ENTSO-E, 2022)

they will do so in order to maximise their profits.

Since the NordLink introduction, German electricity prices have been higher than Norwegian ones about 80% of the time (ENTSO-E, 2022a). This means that Norwegian consumers must pay more for domestic electricity in order to prevent it from flowing out of Norway and being sold in Germany at a higher price. As a result, Norwegian electricity becomes slightly more expensive while German electricity becomes somewhat less expensive, leading to price convergence between the two markets.

3.2 The European Energy Crunch

Disentangling the NordLink effect on electricity market convergence requires an understanding of the factors that affect these markets. Currently, a range of global and regional factors contribute to imbalances in the Norwegian and European electricity markets. The overall situation is a tight energy supply side struggling to meet demand. Additionally, because European markets are physically and institutionally integrated, problems in one country often spread to others.

3.2.1 Structural and Geopolitical Challenges

Regarding energy supply, Europe's largest challenge has been the decreased natural gas supply from Russia (Clean Energy Wire, 2022). According to Argus, Russia cut its gas supplies to EU states by 88 % between September 2021 and 2022 (BBC, 2022). This demise is a problem for Europe because Russian gas used to represent about 40% of Europe's gas supply, translating to approximately 14 % of Europe's total energy demand (IEA, 2022a). The situation has created a large gap between energy supply and demand in Europe which is difficult to fill in the short term.

Germany, for example, has for many years relied heavily on natural gas imports from Russia for heating, cooking and electricity production (Clean Energy Wire, 2022). In 2021, Russian gas made up roughly 55% of Germany's natural gas supply (World Economic Forum, 2022). Because of the demise, German electricity production from natural gas decreased by 42% from the first quarter to the second quarter of 2022 (Statistisches Bundesamt, 2022a).

Another factor contributing to Europe's tight energy supply situation has been the high number of offline nuclear power plants in France (Reuters, 2022a). In the summer of 2022, a record 57% of French nuclear power plants were offline due to overdue maintenance. As a result, the French electricity company EDF estimates that French electricity production from nuclear power in 2022 will be the lowest in almost 30 years.

3.2.2 Weather-Induced Challenges

In addition to the above-mentioned structural obstacles, unfavourable weather conditions have increased power demand and reduced power production both in Europe in general and Norway specifically.

The cold winter of 2020/2021 led to increased natural gas demand in Europe and Asia for electricity production and heating purposes (Popkostova, 2022). Additionally, the summer of 2022 has been marked by hot and dry weather, with temperature records in the UK, Germany and other parts of Europe (Copernicus, 2022). These temperatures led to increased power demand to operate air conditioning units in both homes and public buildings.

The hot and dry weather has also had implications for the energy supply. For example, decreased river depth in the Rhine in Germany meant that river-born barges could only carry partial coal loads to the coal-fired power plants through the summer, leaving the power plants unable to operate at maximum capacity (Reuters, 2022b). Additionally, unfavourable wind conditions led to a 13% decline in German wind power production in 2021 compared to 2020 (Statistisches Bundesamt, 2022a).

Low Norwegian hydro reservoir levels have also contributed to the tight energy supply situation in 2022. The storage levels fell significantly throughout 2021, partly due to a record year for Norwegian electricity exports (Statistics Norway, 2022a). Additionally, Norwegian water reservoirs experienced the lowest inflow levels since 2010 (Norwegian Ministry of Oil and Energy, 2022b). Figure 3.1 shows the Southern Norway filling degree development.

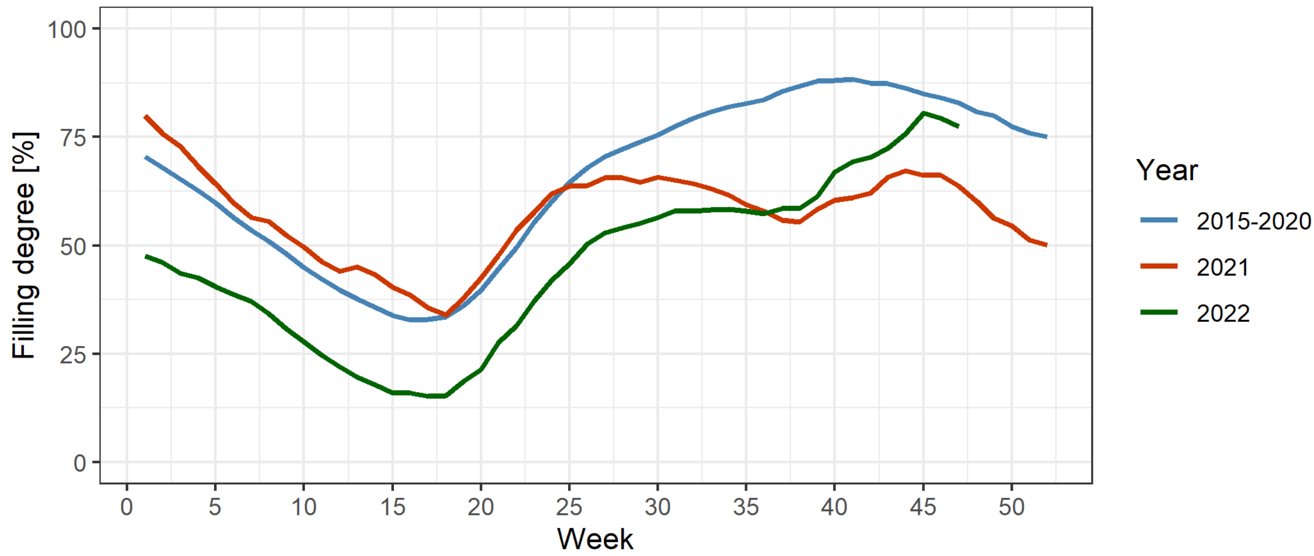

Figure 3.1: Southern Norway reservoir filling degree

3.3 Power Market Characteristics

3.3.1 Supply and Demand in the Power Market

The power market pricing mechanism is called marginal pricing (Hirth, 2022). Marginal pricing means that the electricity price is decided by the production cost of the most expensive power plant required to meet electricity demand. This pricing mechanism makes the most expensive power plant needed to meet demand the "price setter" for the area. The specific power plant that sets the price can vary depending on demand and supply and can change on an intraday, intraweek, or seasonal basis.

Since the introduction of NordLink, natural gas-fired power plants have primarily been Germany's most expensive power plants (Köln University, 2021). This means that the European natural gas price will directly determine the German electricity price in hours with high electricity demand and gas-fired power production in Germany.

Electricity Demand

Electricity market demand is rather inelastic in the short run, implying that consumers are not very sensitive to changes in electricity prices (Csereklyei, 2020). This is because we have grown accustomed to and reliant on electricity, and our society is built around this access. However, the recent surge in electricity prices has forced European electricity consumers to change their behaviour (European Commission, 2022a). The European Commission has proposed that the Member States aim for a 10% reduction in total electricity demand until March 2023 to minimise the chance for power rationing and forced shutdowns of industry. Nevertheless, due to the short-run inelasticity of demand, the supply side is the primary driver of electricity prices.

Electricity Supply: the Merit Order

Different energy sources have distinct marginal production costs (MPC), which are the costs associated with producing an additional unit of electricity (de Lagarde and Lantz, 2017). In electricity markets, the "merit order curve" illustrates these differences by ranking the different energy sources from low to high MPC, thus creating an electricity supply curve. The higher the MPC of a power plant, the higher the electricity price the plant requires for breakeven production. Thermal power plants' marginal production costs are mainly influenced by the costs of fuels like coal, gas, oil, or uranium. In contrast, wind and solar power have almost zero marginal production costs.

A price area's merit order is dynamic and will change on an intraday, seasonal, and annual basis (Hirth, 2022). The availability of natural resources and strategic political decisions are the primary factors that determine the merit order. However, other factors such as commodity prices, interconnector capacity, carbon permit prices, climate, and weather can also affect the merit order.

The Merit Order Effect

The electricity price reduction due to increased renewable energy capacity is called the "merit order effect" (Antweiler and Muesgens, 2021). Intermittent renewable energy sources like solar and wind power differ from other energy sources not only in terms of MPC but also in terms of production planning. A hydro-driven power plant will seek to maximise its profit by carefully planning when to produce electricity and in what quantity (Norwegian Energy Regulatory Authority, 2022). The hydro producers consider the opportunity cost of water, which is the expected value of saving water for future production, and weigh this against the benefits of producing electricity now.

In contrast, solar and wind producers do not have the luxury of planning their production and will seek to produce as much electricity as possible (de Lagarde and Lantz, 2017). This production pattern, combined with low MPCs, is why an increased share of renewable energy production can lead to increased volatility and decreased electricity prices. In Figure 3.2, the width of the different production types represents the different energy sources' share of the electricity generation mix. The figure shows how the price-setting power source, and therefore the electricity price, can vary even though demand remains the same and highlights how wind and solar reduce electricity prices.

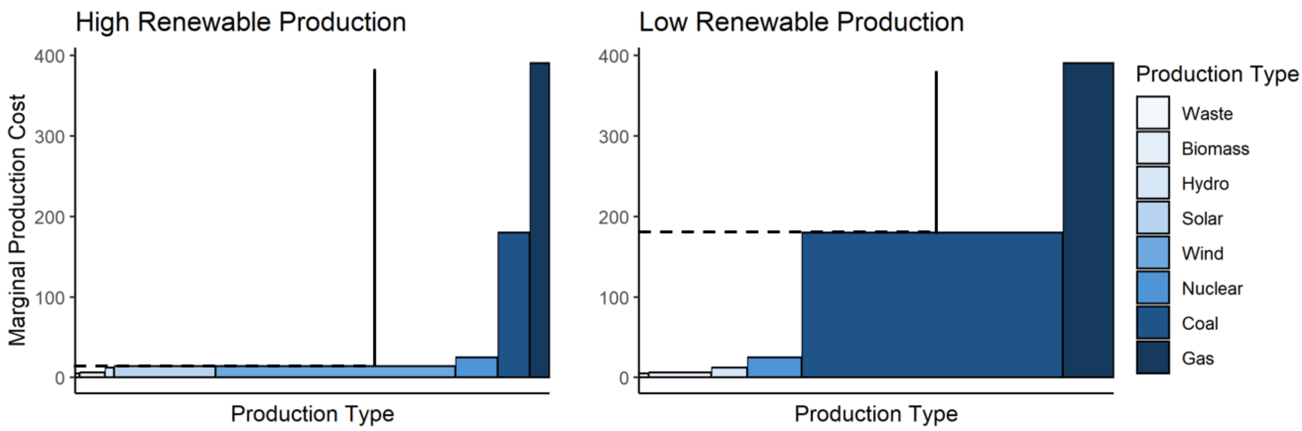

Figure 3.2: Two different merit orders meeting the same demand

3.3.2 The Day-Ahead Market

Wholesale electricity markets are divided into three separate markets with different purposes: the day-ahead, the intraday and the balancing market (Norwegian Ministry of Oil and Energy, 2022a). The day-ahead market is by far the largest of the three and provides consumers and producers with the electricity prices and corresponding volumes for the following day on an hourly basis (Epex Spot, 2022a). The intraday and balancing markets are needed to balance and fine-tune the grid but are less relevant to our thesis and will not be covered further.

NordPool and EPEX Spot are the two exchanges where market participants trade Norwegian and German electricity, respectively (Epex Spot, 2022b). The day-ahead market, on both NordPool and EPEX Spot, is operated through a blind auction that takes place once a day, all year round (NordPool, 2022a). The auction starts at 10.00 when grid operators publish the data on available power transmission capacities. Then, electricity buyers and sellers have until 12.00 to submit their bids for each hour of the following day.

The exchanges form a supply curve by ranking the suppliers according to their MPC and a demand curve by ranking the buyers by their willingness to pay for electricity.

At 12.00, when the auction is completed, an algorithm called EUPHEMIA starts computing the hourly prices for most of Europe, considering cross-border transmission capacities (EPEX Spot, 2018). Finally, the power exchange announces the day-ahead prices at 12.45 am (NordPool, 2022a). We cover EUPHEMIA in detail in section 3.6.

3.3.3 Price Areas

The power market in Europe is divided into several electricity price areas, which the individual countries' TSOs and governments decide (NordPool, 2022b). Many of Europe's national borders correspond with these power price areas, but Norway, Sweden, and Italy have multiple domestic price areas (Mevatne and Michel, 2022). Electricity transmission between price areas can cause congestion, which occurs when the demand for electricity trade exceeds the physical capacity of the transmission cables, limiting electricity trade between the two areas (Gugler et al., 2018). Congestion hinders price convergence and therefore prevents fully integrated electricity markets. Contrary, if the electricity flow between two price areas is within the transmission capacity of the cables, prices should, in theory, be identical (Norwegian Ministry of Oil and Energy, 2022a). With unlimited transmission capacity between two areas, these markets would merge into one.

Differences in area prices can have an impact on both short- and long-term behaviour within the areas. Persistently high electricity prices in an area can lead to increased investments in production capacity or power grid development (Mevatne and Michel, 2022). On the other hand, sustained low power prices due to a surplus of power in an area can attract large consumers, such as power-intensive industries.

3.3.4 Congestion Revenue

Congestion revenues arise when power flows between areas with different prices (Statnett, 2022c). The income is calculated from the price difference between the areas multiplied by the flow (MW) in the transmission cable. When congestion occurs internally within Norway, Statnett, as the local TSO, collects the revenue. However, when congestion occurs on an interconnector between two countries, the two countries split the income evenly.

Increased price differences between areas lead to increased congestion revenue, demonstrated by comparing Statnett's congestion revenue from NordLink in 2021 versus 2022. The average 2021 spread between Norwegian and German electricity prices was significantly lower than the spread of 2022 has been so far. As a result, Statnett's congestion rent from NordLink in 2021 was €80.4 million, while January to October 2022 has left the TSO with €153.8 million (Statnett, 2022c).

3.3.5 Unscheduled Electricity Flows

When electricity flows from a source to a user, it takes the path of least resistance, regardless of the price areas it passes through (German Federal Network Agency, 2021). This can lead to unscheduled electricity flow, which is inevitable in a zonal electricity system. Due to unscheduled flows, the amount of electricity traded between two given countries does not always match the physical amount of electricity flowing between them. The differences can be significant and cause disruptions in the interconnector trade and cross-border pricing mechanisms (THEMA Consulting, 2020).

3.4 The Norwegian Electricity Market

Norway's first transmission cable went operational in 1960, allowing power transfer to and from Sweden (NRK, 2022). Since then, an additional 16 transmission cables have integrated the Norwegian electricity market with its neighbouring countries. Traditionally, Norway has been a net exporter of electricity, averaging about 10 TWh of net exported electricity per year (Norwegian Ministry of Oil and Energy, 2022b).

Norway is divided into five price zones, named NO1 through NO5 (Norwegian Ministry of Oil and Energy, 2022a). The transmission capacity between the three southern zones, NO1, NO2 and NO5 (Southern Norway), is sufficient to keep the average price difference between the areas minimal (NordPool, 2022a). Southern Norway has experienced significantly higher prices than the northern zones, NO3 and NO4, in late 2021 and 2022 (NordPool, 2022a). This price difference results from North/South grid congestion.

Table 3.1 shows important data related to the Norwegian electricity market (Statistics Norway, 2022a). In 2021, the majority of electricity consumption in Norway was distributed between the industrial sector (46%), households (30%) and the service sector (19%).

Production	Consumption	Installed cap	Interconnector cap	Renewables
157 TWh	140 TWh	39 GW	9 GW	98.7%

Table 3.1: Norwegian electricity data (2021)

3.4.1 The Norwegian Energy Mix

Hydropower is the dominant energy source in Norway and has helped the country achieve one of the highest percentages of renewable electricity production in the world (IEA, 2022b). Furthermore, hydropower plants are flexible and can be used to meet both baseload and peak electricity demand, as they can quickly and inexpensively adjust their output (Thuner Energy, 2022). In the last 12 years, Norway has seen rapid growth in onshore wind power, slightly reducing the dominance of hydropower (Norwegian Ministry of Oil and Energy, 2022b). In 2020 and 2021, wind power accounted for 86% and 55% of new power production, respectively.

Table 3.2 shows the Norwegian energy mix's development (Statistics Norway, 2022a). The high share of renewables and the dominance of hydropower in Norway's energy mix have resulted in a consistently flat merit order curve and low average MPC. Figure A1.2 in Appendix A1 shows Norway's average merit order in 2022.

Year	Hydro	Wind	Gas
2010	94.8	0.7	4.5
2015	95.8	1.7	2.5
2020	92.0	6.4	1.6
2021	91.5	7.5	1.0
2022[3]	89.0	9.7	1.3

Table 3.2: Norwegian energy mix development. Numbers in %

The high energy storage capacity is a unique feature of the Norwegian energy mix (Norwegian Ministry of Oil and Energy, 2022b). During periods of high inflow to reservoirs, producers can store excess potential energy in the water to generate electricity later. This means that a hydropower reservoir can function as a large battery. Norway has almost 90 TWh of storage capacity, which represents about 50% of Europe's hydro reservoir capacity. The high storage capacity was one of the reasons for investing in NordLink, which aimed to allow Norway to play a larger role as "Europe's green battery" (Statnett, 2013).

[3]First half of 2022

3.5 The German Electricity Market

Germany is the largest producer and consumer of electricity in Europe, and it exchanges electricity with ten nearby countries (German Ministry for Economic Affairs and Climate Action, 2022). This, combined with the country's location, gives the German electricity market and energy policy influence on large parts of the European continent. Furthermore, no other EU country has more interconnector capacity than Germany (Clean Energy Wire, 2018).

Table 3.3 shows key characteristics of the German electricity market (IEA, 2022a; German Federal Network Agency, 2021; Statistisches Bundesamt, 2022c). In terms of electricity consumption, the three largest groups in 2021 were industry (44%), services (27%), and households (26%) (EnerData, 2021). Germany has been a net exporter of electricity in recent years, with annual net exports ranging from 3 to 55 TWh between 2003 and 2021 (IEA, 2022a).

Production	Consumption	Installed cap	Interconnector cap	Renewables
588 TWh	568 TWh	234 GW	23 GW	39.7%

Table 3.3: German electricity data (2021)

3.5.1 The "Artificial" German Price Area

Germany is divided into four price areas, but they all have the same price (Epex Spot, 2022a). This "single price area" policy has caused imbalances in the German power situation, impacting both the country itself and its interconnected neighbouring countries (THEMA Consulting, 2020). The imbalances are linked to the domestic power situation. Whereas Northern Germany has a relatively low electricity demand and a large power generation capacity, Southern Germany suffers from a power deficit which will increase when the region shuts down its two last nuclear power plants in April 2023 (World Nuclear Association, 2022).

Furthermore, the north-south electrical highways in Germany are often congested, making it difficult to transfer the necessary electricity from north to south (THEMA Consulting, 2020). If Germany were split into multiple price areas, this domestic congestion would lead to cheaper electricity in the north and more expensive electricity in the south.

However, the current "artificial" single-price policy prevents these market-driven price signals from occurring. The lack of proper price signals also affects the trade in Germany's interconnectors and the price convergence with neighbouring countries (Tennet, 2022). Therefore, local TSOs are currently reviewing Germany's price areas and considering the effects of splitting the country into multiple price areas to see if this could increase socioeconomic welfare.

3.5.2 The German Energy Mix

In late 2010, Germany launched "Energiewende", a major shift in energy policy that aimed to increase electricity production from renewable sources and reduce production from fossil fuels and nuclear power. Table 3.4 shows the rapid growth of wind and solar power since 2005, replacing both fossil fuels and nuclear power. Germany's diverse energy mix, with a high share of wind and solar, has resulted in a merit order and a marginal production cost of electricity that varies with the weather conditions. Figure A1.1 in Appendix A1 shows Germany's average merit order for 2022.

Year	Fossil	Wind & Solar	Other Renewables	Nuclear
2010	58.8	7.9	11.0	22.2
2015	54.4	18.4	13.0	14.2
2020	43.4	31.2	14.3	11.1
2021	43.0	29.0	14.7	13.3
2022[4]	42.0	41.0	11.0	6.0

Table 3.4: German energy mix development. Numbers in %

Germany's energy policy also includes a plan to phase out nuclear power by April 2023, and there are currently only three operational nuclear power plants in the country (EnergyMonitor, 2022). Three nuclear plants were shut down in December 2021. Another part of Energiewende is a plan to completely phase out coal-fired power plants by 2038 (NaturStrom, 2021). As a result, coal power has gradually declined in importance in Germany in recent years. However, due to the natural gas shortage in 2022, coal has seen a resurgence in 2022 compared to 2021 (Statistisches Bundesamt, 2022a).

[4]First half of 2022

3.6 EUPHEMIA: Cross-Border Pricing

The Price Coupling of Regions (PCR) project was launched by several European power exchanges in 2009 with the aim of calculating electricity prices in the same way across Europe (Epex Spot, 2022b). Today, 24 European countries, including Norway and Germany, are part of the PCR project. The EUPHEMIA (Pan-European Hybrid Electricity Market Integration Algorithm) is the core of PCR and is responsible for optimising the use of the power grid. This complex algorithm was developed to address the challenges of coupling different day-ahead power markets and to maximise social welfare while taking into account factors such as estimated electricity production and consumption, power grid maintenance, and cross-border transmission capacity.

The algorithm's output is the market-clearing prices for all price areas in the PCR, along with the corresponding volumes for all hours the following day. It also provides information about local deficits or surpluses and the required flow through interconnectors to address these imbalances (EPEX Spot, 2018).

4 Data

We obtained all of the data for our analysis from the ENTSO-E transparency platform. We constructed panel data with a time and country dimension, covering a three-year period from January 1st 2020 to September 1st 2022. This includes roughly one full year of pre-NordLink data and the available post-NordLink observations.

We use the NO2 prices for Norway as NordLink stretches from Tonstad, Norway, located in price area NO2. Because NO1, NO2, and NO5 are well interconnected, we include data from all these price areas when constructing control variables for Norway, such as load and wind production. We choose to exclude the price areas NO3 and NO4 (Mid and Northern Norway) from our analysis due to insufficient transmission capacity between them and NO1, NO2 and NO5 (Southern Norway).

We use the raw prices for our analysis instead of transforming the data for two main reasons. Firstly, raw price levels provide a clearer interpretation of the results compared to transformed data. Secondly, we rely on the empirical strategy to disentangle the NordLink effect from the surging electricity prices in late 2021 and through 2022. Therefore, we do not find it necessary to transform our data to reduce this surge in the spread of the data. However, we include the analysis with the transformed data in section A7 of the Appendix to display the robustness of our results.

4.1 Outcome Variable

We want to analyse the market convergence and therefore use *spread* as our outcome variable. Spread is the difference between the electricity prices in two markets. We choose to use the absolute spread as it is sufficient for modelling market convergence and will make the interpretation of control variables easier. When measuring the spread, we do not care which country has the highest price, only the difference in prices. As our primary focus is the Norwegian electricity market, we define $Y_{i,t}^{abs}$ as the price difference between electricity price in country i and NO2 price for time t:

$$Y_{i,t}^{abs} = abs(\text{electricity price}_{i,t} - \text{electricity price}_{NO2,t}) \tag{4.1}$$

4.2 Control Variables

The difference-in-difference approach controls for many fundamental factors. We add control variables to either identify the NordLink effect more precisely or to reduce the error variance in our estimations. Control variables should account for differences between Germany and Belgium to increase precision in estimating the causal effect. Table 4.1 shows the control variables used in our analysis:

Variable	Unit	Hourly	Daily	Weekly	Source
Day-ahead prices	€/MWh	X			ENTSO-E
Load forecast	GWh	X			ENTSO-E
Forecasted wind production	GWh	X			ENTSO-E
Forecasted solar production	GWh	X			ENTSO-E
Norwegian water reservoirs	TWh			X	ENTSO-E

Table 4.1: Data overview

We use forecasted data for both load and renewable production instead of the actual load or production data for the given day. Day-ahead prices, and therefore also spread, are determined on day $t-1$. Using actual load or production for day t to predict the spread is not sensible, as this information is not available to the market participants when they determine the prices. Forecasted data, available on day $t-1$, better represents the information available to the market participants and is therefore preferable to control for the spread.

4.2.1 Load Forecast

We include the forecasted load (demand) as a control variable because the load will impact the price levels. With varying price levels, we will also see varying spread levels. As German prices tend to be more volatile compared to Belgian prices, we also make the load forecast an interaction term with the $group_t$ variable, allowing for a different coefficient for the Belgian and German spread.

We include only the Norwegian load forecast as a control variable and not German and Belgian load forecasts. There are two main reasons for this. Firstly, the demand patterns in the different countries are similar, and we would expect a strong correlation between load forecast in Norway and Germany or Norway and Belgium, which in turn harms the integrity of the regression results. Secondly, Norwegian load data can be used as a control variable for both the German and the Belgian spread and therefore contributes to a less complex model. Allowing for different coefficients will account for differences between the countries and can therefore allow for a more precise estimation of the causal effect.

4.2.2 Forecasted Renewable Energy Production

We include wind and solar production in both Germany and Belgium to consider the distinct renewable production in the two countries and more precisely identify the NordLink effect. This also allows us to understand how renewable production in Germany affect the spread between the Norwegian and German market.

In addition, we have included wind production in Norway to investigate how this affects the spread. Because this variable is duplicated for both the German and Belgian spread, there is no need to allow for different coefficients in this case. Because the forecasted Norwegian wind production does not account for differences between Germany and Belgium, this control variable will not contribute to estimating the causal effect more precisely but rather make the findings more robust and reduce error variation.

4.2.3 Norwegian Water Reservoirs

The water level in Norwegian hydro reservoirs is a fundamental factor in explaining Norwegian electricity prices and should be used to examine the spread. As the water reservoir level mainly affects Norwegian prices, and we use absolute values for the spread, it is unnecessary to allow for differences in coefficients between the Belgian and German data in this case.

The water reservoir data is available every week from ENTSO-E. We linearly extrapolate the missing values from the weekly data points to construct hourly data. This extrapolation implies that the week-on-week changes in water levels happen linearly, which is a strong assumption. The extrapolated data will likely contain less variance compared to the actual values, which will lead to an overestimation of the coefficient in this case[5]. However, the extrapolated data should not be far from the actual values.

[5]In a simple regression, the coefficient is estimated by: $\beta = \frac{cov(x,y)}{var(x)}$.

4.2.4 Seasonality and Congestion

We add dummy variables to help capture recurring effects and seasonality in the data. We include controls for each season, days of the week, and hourly effects. These dummy variables capture the variation we wish to exclude from other control variables. For example, we want solar production to reflect actual solar production, not just the recurring pattern of a higher spread during mid-day compared to nighttime. Adding hourly dummy variables will absorb the recurring effects of having a higher spread during peak hours and leave the actual variation, which is due to solar production, to be absorbed by this control variable. Adding these effects should increase the interpretability of the other control variables.

We also include dummy variables for congestion to/from Norway, which in theory, should be linked with spikes in the spread.

4.3 Descriptive Spread Statistics - $Y^{abs}_{DE,t}$

Figure 4.1 shows $Y^{abs}_{DE,t}$in the time frame of our data. The dotted line marks the introduction of NordLink. In late 2021, the spread between the two markets began to increase dramatically both in scale and volatility. Figure 4.2 shows the reason for this. When we use raw values of the prices to calculate the spread, the spread will increase simply because prices have increased, as a similar relative difference will have higher raw values.

Between the introduction of NordLink and the energy crisis in late 2021, there is a clear period with a spread decrease. From Figure 4.2, it looks like the spread reduction just after NordLink was mostly due to increased Norwegian electricity prices.

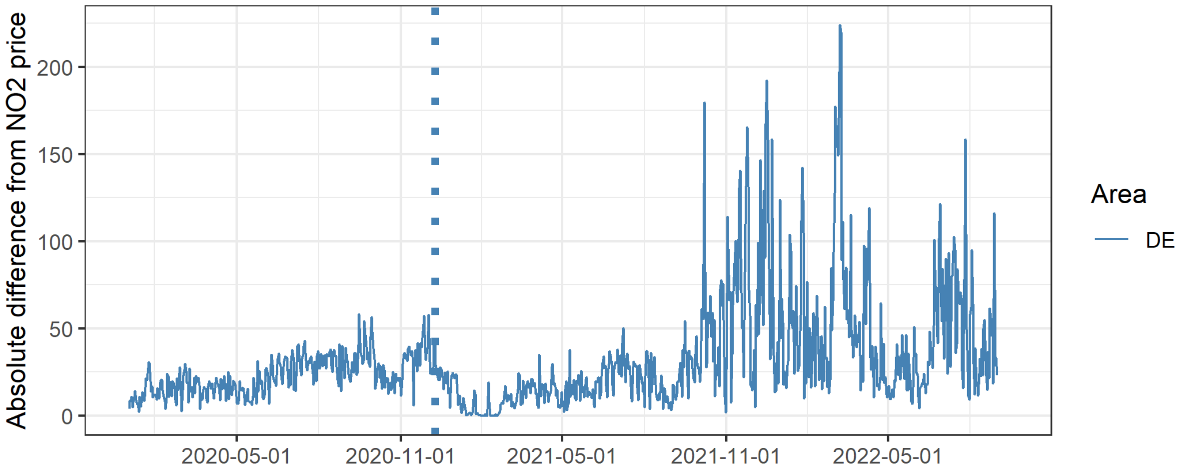

Figure 4.1: Spread - absolute difference between German and NO2 electricity prices

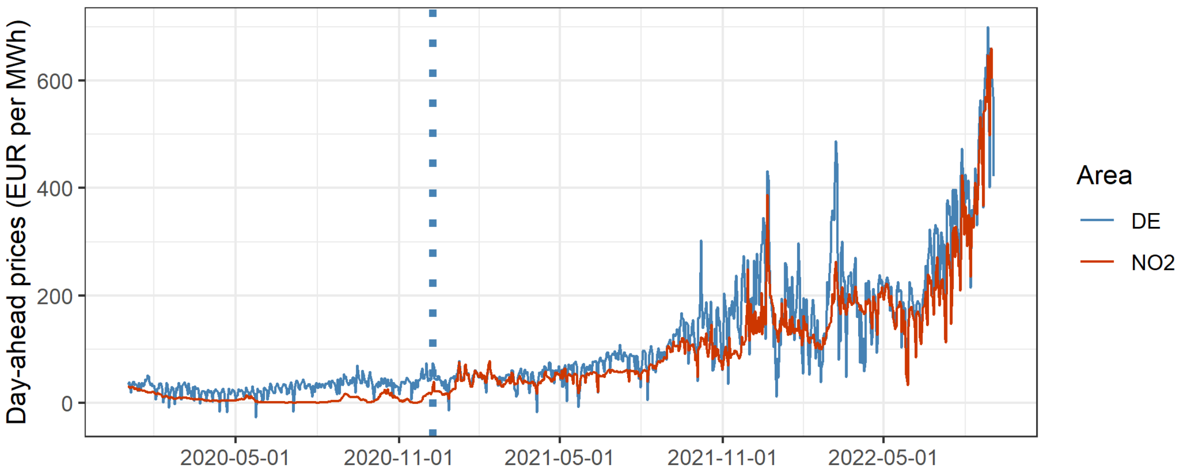

Figure 4.2: German and NO2 day-ahead electricity prices

4.3.1 Distribution

Figure 4.3 illustrates the spread distribution. Over 90% of the spread observations are below €100 per MWh. However, the distribution has a very long tail, indicating some extreme values. $Y_{i,t}^{abs}$ resembles a gamma distribution with a shape parameter of around $k = 2$.

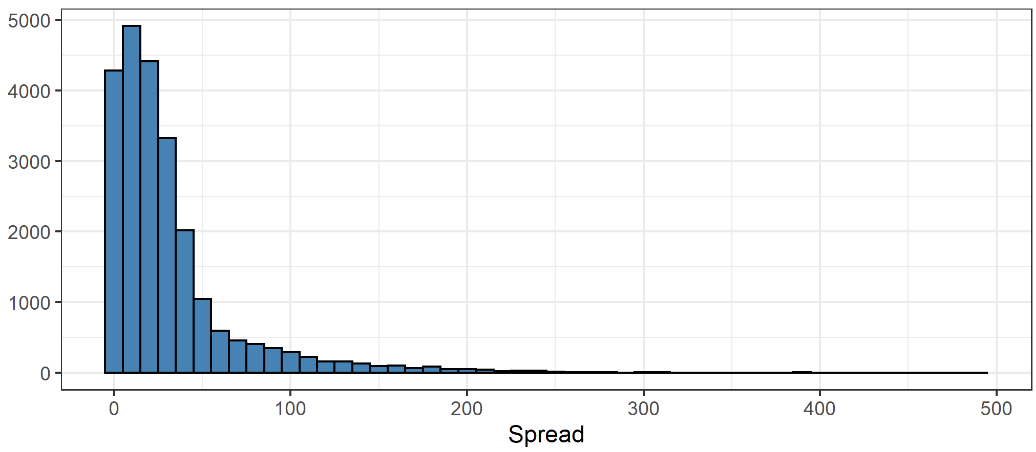

Figure 4.3: Distribution of the absolute spread $Y_{i,t}^{abs}$

4.3.2 Seasonality

Data seasonality can be measured over different periods. The following discussion revolves around the seasonality considerations discussed in section 4.2.4, where we include the weekday- and hourly seasonality and actual seasonal differences.

The actual seasonal differences are pronounced, with the lowest spread occurring during the spring and the winter. However, there are only three years of data, perhaps making it difficult to estimate seasonal trends reasonably. External factors, such as how the energy crisis played out during different parts of the year, might affect this average spread.

Figure 4.4 shows the clear intraday hourly pattern in the data. The spread peaks during morning hours and in the afternoon when demand, and therefore prices, are the highest. We see this pattern in both the Norwegian and German prices. However, German electricity prices are more volatile, contributing to most of the spread changes.

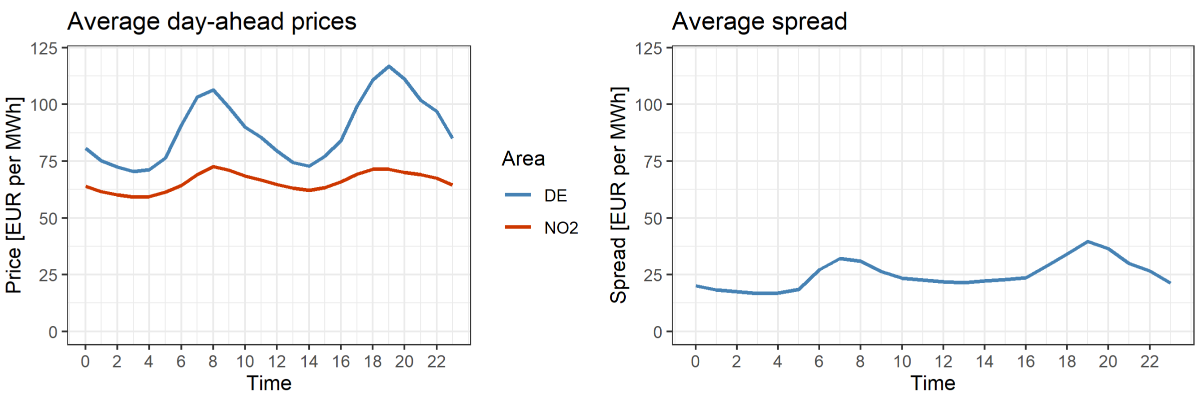

Figure 4.4: Average prices and resulting spread

There is also some clear seasonality between the different weekdays. However, the main differences are between weekdays and weekends, as Figure 4.5 illustrates. We see that the spread is lower on average during the weekend, as there are more observations centred around zero. In addition, there are differences in the spread distribution. During the weekend, Norway tends to export less and import more, as the negative tail of this distribution is larger.

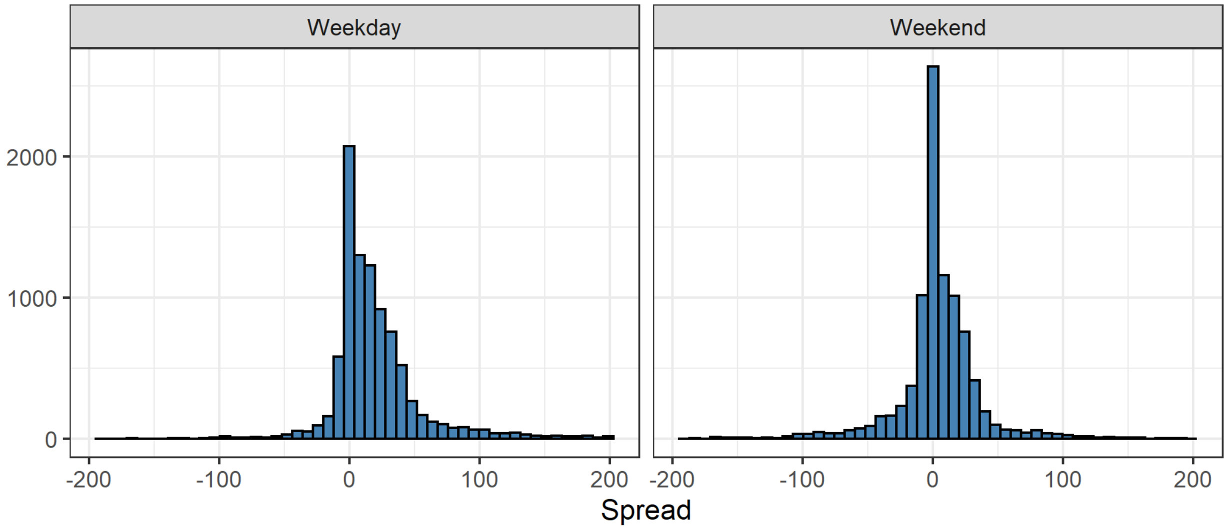

Figure 4.5: Spread distribution: Weekday vs Weekend

5 Methodology

Figure 4.2 shows how the electricity prices, and hence the spread, have reached new heights because of the energy crisis in Europe. This price surge is challenging when we aim to estimate the causal NordLink effect, as many other factors impact the spread between the markets. Naïve models, which only consider the spread before and after the introduction of NordLink, will indicate that the spread has increased significantly. One example of such a naïve model could be a simple OLS[6] regression of a dummy variable indicating whether NordLink has been introduced or not, using only the German data:

$$Y^{abs}_{DE,t} = \alpha + \beta_1 * \text{NordLink}_t + \epsilon_t \tag{5.1}$$

However, this increase we expect to see from a naive model could be due to the external forces discussed in section 3.2, and not necessarily NordLink. Therefore, to circumvent these structural challenges, we employ a difference-in-difference estimation to disentangle the NordLink effect on market convergence between the Norwegian and German electricity markets.

5.1 Empirical Strategy

The general idea behind the difference-in-difference estimation is to construct a counterfactual spread between Norway and Germany. We use the trend in Belgian electricity prices to create the counterfactual German electricity prices and hence the spread. We can then estimate the causal effect as the difference between the actual case, where NordLink was built, and the estimated counterfactual case, where NordLink was not built.

5.2 Regression Estimations

We estimate two models: one simple model without control and one complete model including control variables. The regression estimation is based on an interaction term between two dummy variables, $group_t$ and $post_t$. The $group_t$ variable indicates if an

[6]Ordinary Least Squares

observation belongs to the treatment group, which in this case is Germany, as NordLink is considered the treatment. The $post_t$ variable takes the value one if the observation happened after the treatment.

The causal effect is given by α, the coefficient of the interaction term between the two dummy variables. This interaction term only takes one for the observation in Germany after the introduction of NordLink, yielding the causal effect of the treatment. Table 5.1 shows how the dummy variables interact and which regression coefficients belong to which observations.

	$post_t = 1$	$post_t = 0$
$group_t = 1$	Germany post NordLink: $\mu + \gamma + \lambda + \boldsymbol{\alpha}$	Germany pre NordLink: $\mu + \gamma$
$group_t = 0$	Belgium post NordLink: $\mu + \lambda$	Belgium pre NordLink: μ

Table 5.1: Difference-in-difference set-up

5.2.1 Simple Difference-in-Difference Model

The simple model, presented in equation 5.2, includes only the $group_t$ and $post_t$ variables discussed above. The causal effect, α, from this regression will be identical to a manual approach, where we compute the mean spread for each combination of the $group_t$ and $post_t$ and then actually calculate the "difference in difference", see equation 5.3:

$$Y_{i,t}^{abs} = \mu + \gamma * \mathrm{group}_t + \lambda * \mathrm{post}_t + \boldsymbol{\alpha} * (\mathrm{group}_t * \mathrm{post}_t) + \epsilon_{i,t} \tag{5.2}$$

$$\boldsymbol{\alpha} = (\mathrm{Germany}_{\mathrm{Post}} - \mathrm{Germany}_{\mathrm{Pre}}) - (\mathrm{Belgium}_{\mathrm{Post}} - \mathrm{Belgium}_{\mathrm{Pre}}) \tag{5.3}$$

5.2.2 Complete Difference-in-Difference Model

For the complete model, we add control variables to identify the causal effect more precisely. $X_{i,t}$ represents a vector of all control variables for country i at time t, while ω_t represents dummy variables controlling for seasonality and congestion. The vector ω_t does not have a country dimension, as we assume the recurring effects are similar for Germany and Belgium. This yields the following regression estimation:

$$Y_{i,t}^{abs} = \mu + \gamma * \text{group}_t + \lambda * \text{post}_t + \boldsymbol{\alpha} * (\text{group}_t * \text{post}_t) + X_{i,t} + \omega_t + \epsilon_{i,t} \quad (5.4)$$

Where $X_{i,t}$ and ω_t is defined as:

$$\begin{aligned} X_{i,t} = {} & \beta_{i,1}\text{WindProd}_{i,t} + \beta_{i,2}\text{PVProd}^{7}{}_{i,t} + \beta_3\text{WaterReservoirs}_{NO,t} + \\ & \beta_4\text{WindProd}_{NO,t} + \beta_{i,5}\text{LoadForecast}_{NO,t} \end{aligned} \quad (5.5)$$

$$\omega_t = \beta_6\text{Season}_t + \beta_7\text{Day}_t + \beta_8\text{Hour}_t + \beta_9\text{Congestion}_t \quad (5.6)$$

5.3 Parallel Trend Assumption

Ideally, we would know the outcome for German electricity prices if NordLink was not built. Knowing this, we could easily see the causal effect as the difference between the case with and without NordLink. However, we can only estimate this counterfactual scenario. To do so, we use the Belgian electricity market as a proxy for the German market in the counterfactual case where NordLink was never constructed. The parallel trend assumption states that the German electricity prices would follow the same trend as the Belgian electricity prices if NordLink were not built.

We choose Belgium to estimate the counterfactual trend based on the energy mix and geographical location. The Belgian energy mix differs from the German in some aspects, but mainly regarding base load production and not which energy source is the marginal price setter. The "Energiewende" in Germany has led to reduced nuclear power production, for which they have compensated with increased power production from renewables, natural gas and recently, coal. Belgium, however, has focused on keeping nuclear power going and completely removed coal from its energy mix. Table 5.2 shows the similarities and differences between the two energy mixes.

[7] PV = photovoltaic (solar) power

Production Type	Belgium	Germany
Gas	21.0	10.3
Coal	00.0	30.0
Wind	11.3	23.3
Solar	06.2	10.5
Nuclear	49.2	10.4
Hydro	01.7	04.9
Biomass	02.3	07.3
Waste	02.2	01.3

Table 5.2: Belgian and German Energy Mix 2022. Numbers in % (ENTSO-E)

Due to the marginal price-setting mechanism of electricity prices, we argue that this difference in the energy mix does not strongly affect how the German and Belgian prices are influenced. Natural gas has, except for periods with excessive renewable production, been the marginal price setter during the relevant period for both countries, as discussed in section 3.3.1 (Köln University, 2021). Therefore the prices in both Germany and Belgium are predominantly determined by the European natural gas price.

Figure 5.1 shows the Belgian and German electricity prices pre-NordLink. Even though German electricity prices are more volatile due to the larger share of renewable production, there is a clear correlation between the two prices. They follow the same general trend, making it reasonable to assume they would continue doing so in the following period if we did not introduce NordLink.

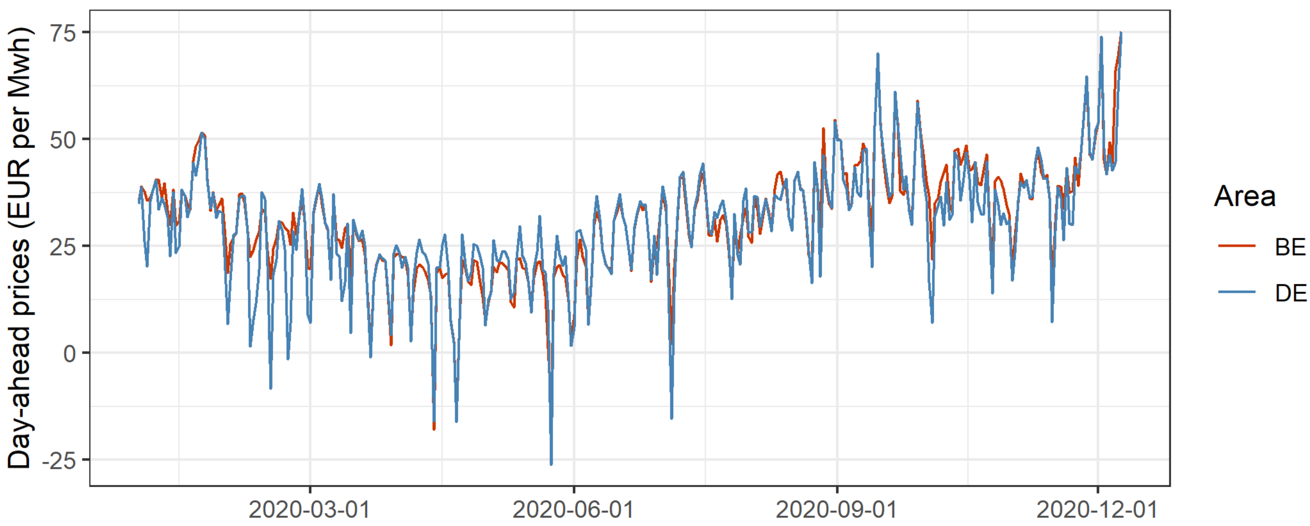

Figure 5.1: Belgian and German day-ahead electricity prices pre-NordLink

6 Results

On the following page, Table 6.1 presents results for all models from equations 5.1, 5.2, and 5.4 mentioned in section 5. The results from the naïve model are as expected, indicating that the spread has increased due to NordLink. This result contrasts what we would expect based on the current scientific literature.

The simple difference-in-difference model indicates a spread reduction due to NordLink. We see that the $post_t$ term absorbs the effect of increased spread due to the energy crisis. The causal NordLink effect is absorbed by the interaction term, represented by "NordLink" in Table 6.1. Notice that the sum of $post_t$ and the interaction term (NordLink) equals the total change in means after the introduction of NordLink, as we see in the Naive model:

$$19.66 + (-6.91) = 12.75$$

When we add control variables as described in equation 5.4, NordLink's effect remains significant and increases in magnitude. This result more accurately identifies the actual causal effect, an average spread reduction of €12.3 per MWh.

These results must be seen in the context of the surging natural gas and electricity prices. The electricity price spikes also inflate NordLink's effect on the spread. If we were to have a more stable electricity market during our sample period, the absolute NordLink effect in our results would have been less. Appendix A8 shows these estimations.

	Dependent variable:		
	Spread		
	(Naive)	(Simple)	(Control)
NordLink	12.75***	−6.91***	−12.27***
	(0.40)	(0.58)	(0.52)
Group		−0.28	5.53***
		(0.22)	(1.35)
Post		19.66***	9.43***
		(0.42)	(0.37)
Norwegian Water Reservoirs			−0.93***
			(0.02)
Forecasted Wind Production - Norway			17.67***
			(0.59)
Forecasted Wind Production - Belgium			−6.63***
			(0.27)
Forecasted Wind Production - Germany			−0.17***
			(0.01)
Forecasted PV Production - Belgium			−8.09***
			(0.46)
Forecasted PV Production - Germany			−0.23***
			(0.01)
BE:Norwegian Load Forecast			2.07***
			(0.16)
DE:Norwegian Load Forecast			1.71***
			(0.15)
Constant	23.07***	23.35***	57.54***
	(0.15)	(0.16)	(1.84)
Observations	23,351	46,724	46,724
R^2	0.025	0.043	0.238
Adjusted R^2	0.025	0.043	0.237
Note:	*p<0.1; **p<0.05; ***p<0.01		
Seasonal Control Dummies:	No	No	Yes
Daily Control Dummies:	No	No	Yes
Hourly Control Dummies:	No	No	Yes
Congestion Control Dummies:	No	No	Yes

Table 6.1: Main regression results

6.1 Interpretation of Control Variables

A one-hour production increase of 1 GW results in a 1 GWh production increase. Because we deal with hourly data, we solely use the measurement unit GWh when interpreting the coefficients of our control variables.

6.1.1 Forecasted Renewable Production

Overall, higher renewable production in Germany is correlated with a lower spread. Both German solar and wind production tend to converge the electricity prices. A 1 GWh production increase of German solar and wind power reduces the spread by €0.2 per MWh and €0.17 per MWh, respectively.

However, a 1 GWh wind production increase in Norway tends to increase the spread, having the opposite effect of German wind and solar production. Norway tends to export a lot of this energy which, in theory, should decrease the spread as electricity flows to a price area with a higher price. However, we find that high wind production in Norway often leads to congestion in NordLink. The regression in Appendix A5 shows how NordLink congestion increases the spread, as the cheap electricity generated from wind must be sold at a low price to Norwegian consumers. Because Norwegian prices are usually lower than German prices, the spread increases on average.

6.1.2 Water Reservoirs

Higher levels of Norwegian water reservoirs correlate with lower spread levels. This might be due to the high flexibility of Norwegian electricity production when we have an abundance of water reserves. Norway can, during these times, ramp up production and generate electricity when Germany experiences periods of lower renewable production. In contrast, when water reservoirs are low in Norway, producers will be reluctant to produce electricity as the opportunity cost of the remaining water will be higher, leading to less market convergence.

6.1.3 Norwegian Load Forecast

The forecasted Norwegian load is unsurprisingly correlated with a higher spread, as higher demand periods will have higher prices and, therefore, a higher absolute spread. However, the interpretation is less interesting for this control variable, as it is included primarily to increase the identification accuracy of the causal effect.

6.1.4 Seasonality and Congestion

Appendix A6 shows the coefficients for the dummy variables in ω_t from equation 5.4. The coefficients of the recurring effects are as expected from the seasonality discussion in section 4.3.2. We leave out the autumn dummy to avoid perfect collinearity and let the constant absorb this effect. Spring and winter have a lower general spread than autumn, with an average spread reduction of €37 and €27 per MWh, respectively. Summer is closer to autumn but still statistically significantly lower, with an average spread decrease of €10 per MWh compared to autumn.

The hourly recurring effects typically follow the intraday trend we see in Figure 4.4 where the spread is highest during peak demand hours during the morning and afternoon. Regarding the different days of the week, there are slight statistical differences between the days. Most noteworthy is that the weekends tend to have a significantly lower spread than the weekdays, as illustrated by Figure 4.5.

Congestion is distinctly linked to spread spikes. If NordLink is congested from Norway to Germany, we find that, on average, the spread increases by €42 per MWh. When NordLink is congested from Germany to Norway, the spread increases by €32 per MWh.

6.2 Result Validity

6.2.1 Robustness Check

To check the robustness of our results, we include additional results for different transformations of our dependent variable. We check two versions of log transformations and percentage differences between prices as a definition of the dependent variable.

$$Y_{i,t}^{log} = log(\text{electricity price}_{i,t}) - log(\text{electricity price}_{NO2,t}) \tag{6.1}$$

$$Y_{i,t}^{log2} = log(abs(\text{electricity price}_{i,t} - \text{electricity price}_{NO2,t})) \tag{6.2}$$

$$Y_{i,t}^{percent} = \frac{\text{electricity price}_{i,t} - \text{electricity price}_{NO2,t}}{\text{electricity price}_{NO2,t}} \tag{6.3}$$

Each analysis yields statistically significant results consistent with our main regression, indicating robustness for different data transformations. In addition, the NordLink effect is not significantly affected by adding or removing different control variables. While the magnitude of the effect differs slightly, we always experience consistent results. We show the complete representations of these models in section A7 in the Appendix .

6.2.2 Standard Error Issues

Because the data is a time series, there is undoubtedly serial correlation between the observations, and we have issues with heteroscedasticity in our error terms. Although heteroskedasticity does not bias the OLS results and our difference-in-difference estimate, it does lead to bias in the variance-covariance matrix meaning the standard errors are affected (Kennedy, 2008). Figure 6.1 illustrates the heteroskedasticity.

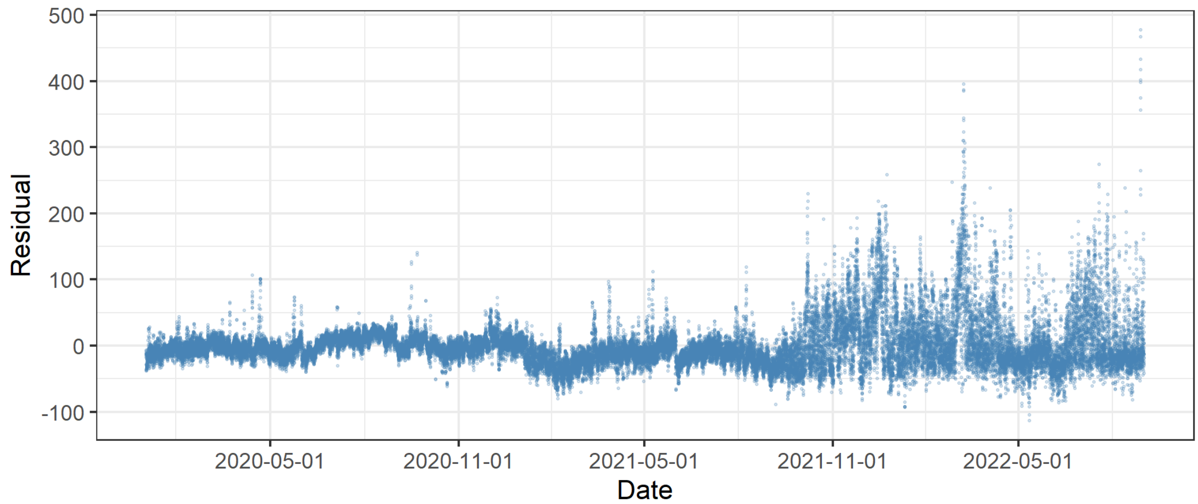

Figure 6.1: Difference-in-difference control model: residuals

To deal with this issue, we present bootstrapped standard errors in our main results, Table 6.1. Bootstrapping standard errors is fit for a non-parametric approach. First, we estimate

1000 replications of the model, using only a sample of the data. From the variation in these 1000 replications, we can then estimate the standard errors (James et al., 2013). Adding lagged versions of the spread, $Y^{abs}_{i,t-1}$, as control variables could prevent autocorrelation issues and heteroscedasticity. However, we find that this approach accounts for too much of the data variation and affects the results too much to be preferable to adjust the standard errors post-estimation.

In addition, we present Newey-White standard errors in Appendix A7.3 as a robustness check. These are estimations of the standard errors that are both heteroskedasticity- and autocorrelation-consistent and should, therefore, account for the issues from the time-series data.

6.3 Critique and Limitations

6.3.1 North Sea Link

North Sea Link (NSL), a subsea cable between Norway and the United Kingdom with the same 1400 MW transmission capacity as NordLink, was put into operation on the 1st of October 2021 (Statnett, 2022a). This is in the middle of our analysis and could affect our results, as NSL will affect Norwegian electricity prices. However, Norwegian price changes are mostly unproblematic, as we compare German and Belgian spread, $Y^{abs}_{i,t}$, in our analysis. Both these metrics are affected similarly by changes in Norwegian prices, as equation 4.1 shows. Equal changes in German and Belgian spread do not affect the results of the causal analysis.

However, the UK is interconnected with Belgium through a subsea cable called Nemo Link with a capacity of 1000 MW (National Grid & Elia Group, 2022). Consequently, NSL indirectly connected NO2 and Belgium and could potentially impact the Belgian/Norwegian spread. Following the established market convergence effect of integration, we argue that NSL would, if anything, reduce the Belgian/Norwegian spread.

This could disturb our parallel trend assumption. In our difference-in-difference analysis, we find that the German spread $Y^{abs}_{DE,t}$ has been reduced compared to the Belgian spread $Y^{abs}_{BE,t}$ after the introduction of NordLink. Therefore, if the Belgian/Norwegian spread was reduced due to NSL, it could be lower than the actual counterfactual case, leading to an underestimation of the causal effect. Therefore, the NordLink effect could, if anything, be larger than the €12.3 per MWh we found in our main regression.

6.3.2 ALEGrO

ALEGrO is a cross-border interconnector between Germany and Belgium with a 1000 MW transmission capacity (Amprion, 2022). The interconnector was commissioned on the 18th of November 2020, just before NordLink. ALEGrO also indirectly connects Norway and Belgium in the same way as NSL. Because ALEGrO was introduced in our dataset's time frame, it represents an imperfection in the parallel trend assumption because it could have reduced the Belgian/Norwegian spread. As with the effect of NSL, this would make the impact of NordLink more difficult to disentangle and might lead to an underestimation of the NordLink effect.

7 Discussion

Our difference-in-difference result shows a statistically significant spread reduction of €12.3 per MWh because of NordLink. The following section offers valuable context to this result and provides a broader understanding of how, why and when the two electricity markets converge.

First, we discuss how NordLink affects Norwegian and German electricity prices individually. Following this, we examine the actual electricity flow in NordLink. We analyse when and in which direction the electricity flows, which gives us a better understanding of the NordLink effect. At the end of this section, we discuss the relationship between the merit order effect and the NordLink effect.

7.1 Effect on Electricity Prices

Using our empirical strategy, it is impossible to estimate which portion of the spread decrease is an increase in Norwegian prices versus a reduction in German prices. However, we argue that the size of the two electricity markets will influence which price is affected more. While NordLink's transmission capacity represents 3.6% of the total Norwegian production capacity, it only represents 0.6% of the German capacity (Statistisches Bundesamt, 2022a; Statistics Norway, 2022a). Furthermore, the transmission cable, when introduced, represented a 23% increase in Norway's total interconnector capacity, compared to a 6% increase in German interconnector capacity. Because of the larger German electricity market and NordLink's relatively higher share of Norwegian interconnector capacity, we argue that the Norwegian price increase has been more substantial than the German price decrease. We present calculations on interconnector capacity increase in Appendix A2.

In addition, Germany has the highest price about 80% of the time in our data. Table 7.1 shows the annual NOK change of an average Norwegian and German household bill for electricity because of NordLink, for different Norwegian "shares" of the spread. Norwegian household bills are more sensitive to electricity price changes than German household bills because the average Norwegian household uses more than five times the electricity than an average German household. We show these calculations in Appendix A3.

NO2 "share" of spread decrease	Price increase NO2	Price decrease Germany
20%	396	306
40%	792	229
60%	1,188	153
80%	1,584	76
100%	1,980	-

Table 7.1: Yearly electricity bill change due to NordLink for different scenarios. Per household. All values in NOK

However, NordLink also leads to increased income for the Norwegian TSO Statnett, which is on track to surpass NOK 1.8 billion in 2022 (Statnett, 2022c). This income goes directly into maintaining and developing the Norwegian power grid. If this income were not collected from NordLink, it would have to be collected from Norwegian consumers through, for example, increased grid tariffs or taxes.

7.2 NordLink Flow

The flow in NordLink is essential for understanding market convergence as the physical electricity flow in NordLink facilitates the convergence of the electricity prices. The flow is a result of differences in electricity load (demand) and production (supply). Here we examine the structural differences between load and production in Norway and Germany from an intraday perspective. This allows us to better understand the drivers behind the market convergence of €12.3 per MWh we find in Section 6, as well as how and when the individual prices are affected.

7.2.1 Load

The electricity demand is similarly distributed throughout the day in Norway and Germany. Both countries show increased electricity demand during the morning and afternoon. During the weekend, the demand is lower compared to the weekdays. The German demand reduction during weekends is significantly larger than the Norwegian one. Comparing weekdays and weekends during peak demand hours, Germany reduces its electricity demand by 22% and Norway by only 12%. See Figure A9.1 in Appendix A9 for illustrations.

7.2.2 Power Production

Where Norway can quickly and affordably increase or decrease its electricity production to match demand due to a large share of hydropower, Germany cannot (Thuner Energy, 2022). Thermal power plants driven by natural gas, oil, coal, nuclear and biofuels represent almost 60% of the German energy mix. These power plants cannot change electricity production as quickly and must produce more evenly throughout the day. Additionally, intermittent wind power production does not always coincide with peak demand periods, and solar only produces during the day. As a result, German production is more static and bell-shaped, whereas the Norwegian production pattern correlates more with the demand pattern. Germany increases its power production during midday, primarily due to increased solar production (ENTSO-E, 2022b). See Figure A9.2 in Appendix A9 for illustrations.

7.2.3 Net Export Requirement

Figure 7.1 shows the net export requirement to meet domestic demand based on load and production data. Germany has distinct domestic power deficits during peak demand hours and surplus during weekends when demand is low, as Germany's rigid production mix cannot accurately follow the demand pattern. Norway, which can fine-tune production more precisely, is a net exporter most hours of the week. Norway's domestic surplus even increases during peak demand hours, when neighbouring countries need electricity and exporting is the most profitable.

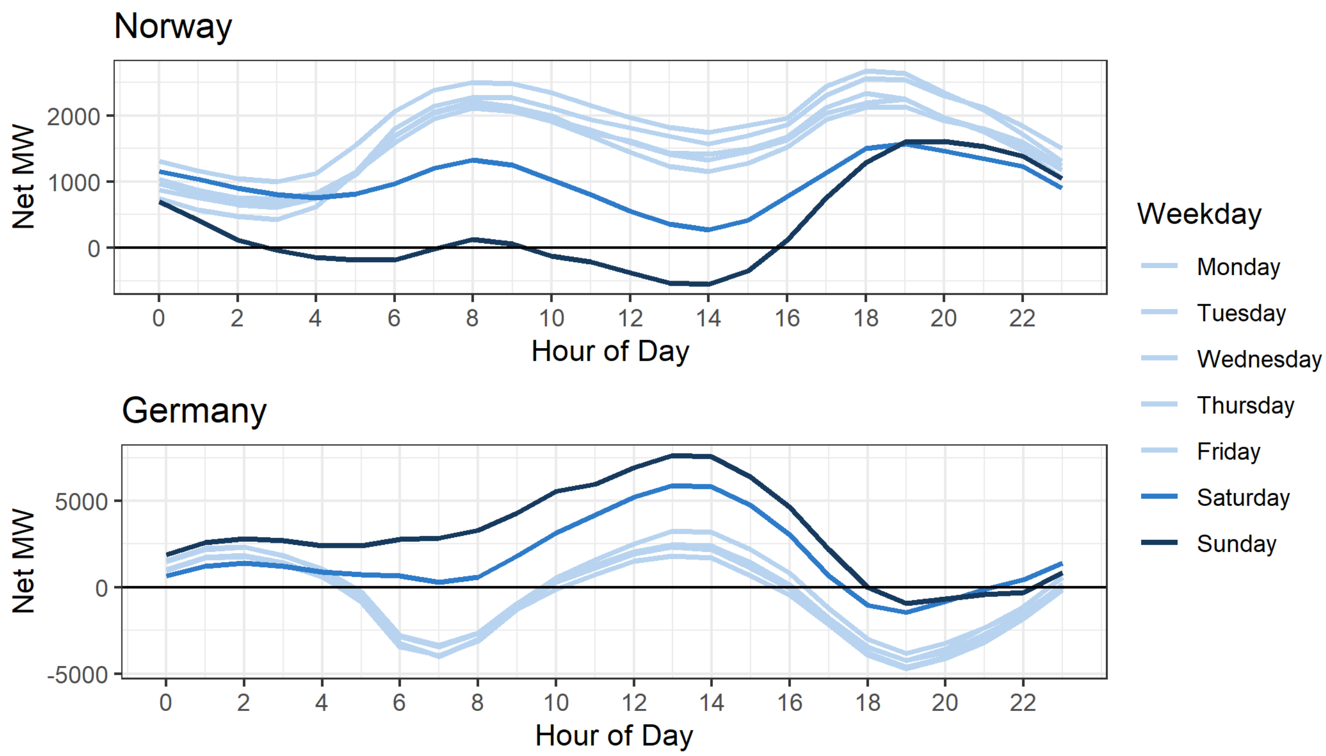

Figure 7.1: Net export/import required to match domestic demand

7.2.4 NordLink Flow and Market Convergence

The structural differences throughout the day and week partially explain how the electricity flows through NordLink. Based on Figure 7.1, there should be a substantial flow in NordLink during peak demand hours, when Germany has a power deficit and Norway has the available electricity to export. This change in required flow during different parts of the day relates to the market convergence effect of NordLink. Figure 7.2 shows the causal NordLink effect, $\boldsymbol{\alpha}$, for each individual hour of the day. We obtain these coefficients by running the difference-in-difference estimation presented in equation 5.4 24 times, each time only on data for the relevant hour.

The NordLink effect correlates with the need to transfer electricity, with peaks in the morning and afternoon. This correlation substantiates the idea that increased electricity flow between Norway and Germany leads to increased market convergence. Consequently, we argue that NordLink is the most useful during periods when there are differences between the countries' needs to export or import energy. Unique energy mixes can be beneficial if complemented with sufficient transmission capacity to other countries.

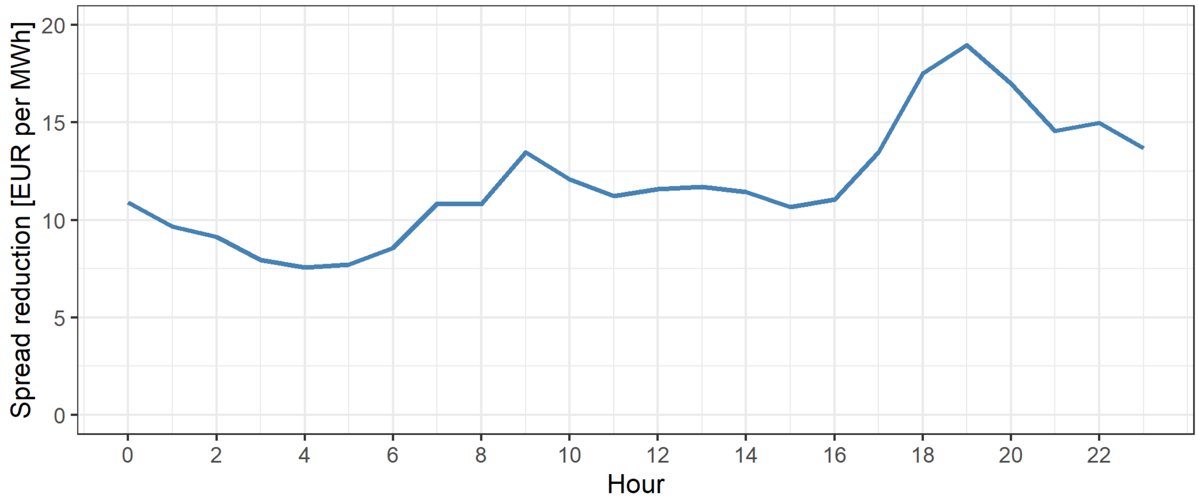

Figure 7.2: The NordLink effect during different hours of the day

7.2.5 Electricity Market Imperfections

According to theory, prices will fully converge if transmission capacity is a non-binding constraint (Norwegian Ministry of Oil and Energy, 2022a). Figure 7.3 shows how the spread differs from zero, even though NordLink has available transmission capacity. We believe this non-convergence is partially due to the relatively inefficient domestic German electricity market discussed in Section 3.5.1. Due to the German domestic congestion and the uniform German electricity price, the natural price convergence mechanisms between NO2 and Germany can not fully play out. Even in situations where NordLink has available transmission capacity, which could converge prices if exploited, German domestic congestion can make increased NordLink transmissions infeasible.

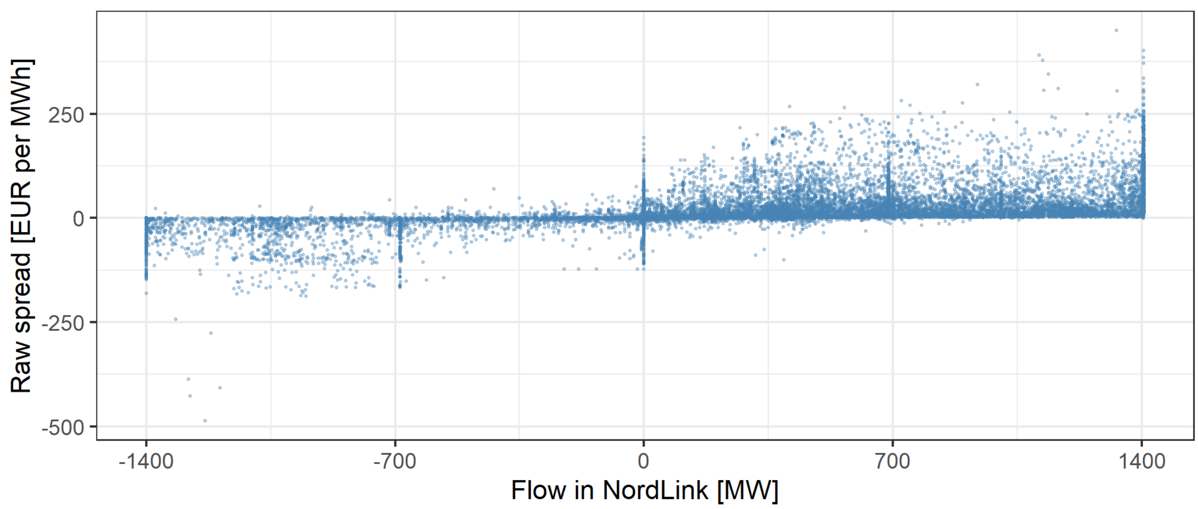

Figure 7.3: Correlation between NordLink flow and the raw spread

7.3 Merit Order Effect

When we analyse the flow in NordLink and its effect on electricity price convergence, we must also consider other factors impacting the spread. There is a clear correlation between periods with the flow in NordLink and the merit order in Germany due to wind and solar production changes[8]. Because the merit order affects German electricity prices, it will also impact the spread and our understanding of market convergence.

Increased renewable energy production in Germany makes the German merit order more similar to the Norwegian one[9]. This merit order transformation will, in itself, lead to lower German electricity prices and reduce the Norwegian/German spread. Consequently, even without NordLink, the Norwegian and German electricity markets would converge during periods of high renewable production in Germany. Figure 7.4 shows the merit order in the two hours in our data with the most (left) and the least (right) combined wind and solar production in Germany. This illustrates how the German merit order and, consequently, the German electricity price can vary between periods of different renewable production.

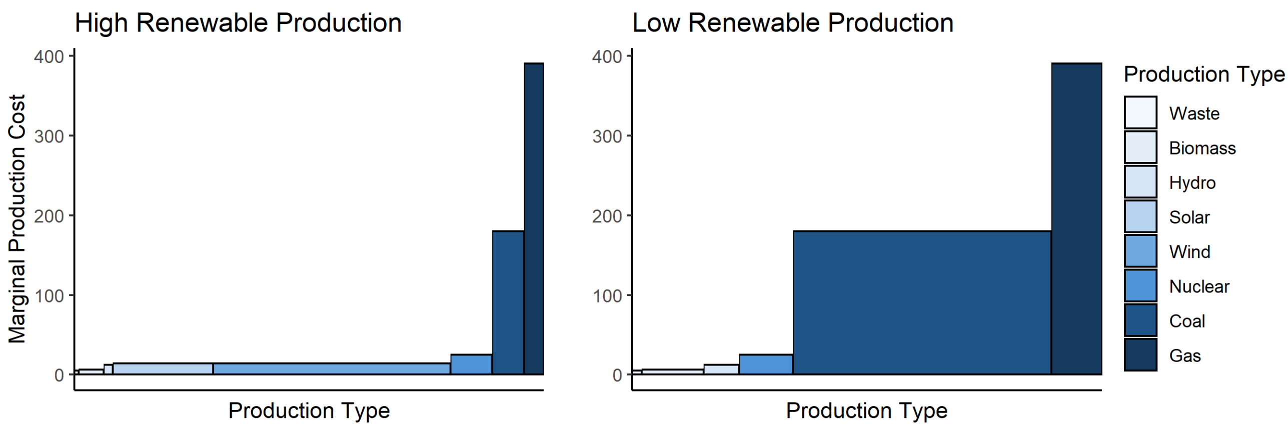

Figure 7.4: German merit order comparison

7.3.1 Renewable Power Production in Germany

The correlation between the spread and renewable production in Germany behaves differently depending on which country has the highest price. When Germany has the highest price, renewable production in Germany reduces the spread. However, when

[8]See Appendix A5
[9]See Figure A1.2 in Appendix A1 for the average Norwegian merit order for 2022

Norway has the highest electricity price, increased renewable production in Germany tends to increase the spread. Table A10.2 in Appendix A10.1 shows these regression results.

This discovery shows how the merit order effect can outweigh the effect of an interconnector. When Norway has the highest prices and wind and solar production in Germany increases, the merit order effect and the NordLink effect will have the opposite impact on the spread. The increased wind and solar production, with a low marginal production cost, transforms the German merit order, lowers domestic German prices and, thus, increases the spread. On the other hand, the NordLink effect decreases the spread because electricity flows from the cheaper (Germany) to the more expensive (Norway) price area. If the NordLink effect were the main driver for the changes in the spread, $Y^{abs}_{DE,t}$, we would expect a net spread decrease. However, in this scenario, we see a net increase in spread, indicating that the merit order effect outweighs the NordLink effect.

In the other scenario, where Germany has the highest electricity prices, increased German renewable production does not lead to increased flow through NordLink. This is expected and according to theory, as energy should not flow from a low-price area to a high-price area. The merit order effect, which has a downward pressure on German electricity prices, will, in this case, reduce the spread. The entire reduction in the spread in this scenario is due to the merit order effect and not NordLink flow.

Because Germany has the highest electricity price about 80% of the time, the reduction effect dominates on average and yields the results discussed in section 6.1. Therefore, a part of the market convergence effect we see in our main results is actually due to merit order changes and not NordLink flow. While our empirical strategy does not allow us to quantify this effect, Gugler and Haxhimusa, who investigate the German and French electricity markets, estimate that the merit order effect accounts for 31% of the total convergence in their study (Gugler and Haxhimusa, 2018). As Norway and Germany have comparatively more dissimilar energy mixes than France and Germany, we expect 31% to be the minimum in our case. Regardless, this effect must be considered when reviewing the market integration effect of interconnectors.

8 Policy Implications

8.1 Social Welfare

Even though interconnectors increase net social welfare in total due to efficiency gains, there will be both winners and losers when a transmission cable connects different price areas. In the NordLink case, Norwegian producers and German consumers are the winners, while Norwegian consumers and German producers are the losers. With electricity flowing from low-price to high-price areas, the outcome of NordLink was predictable, mainly because the electricity price in Germany has been persistently higher than in Southern Norway in recent years (NordPool, 2022a). Policy- and decision-makers should consider the potential effects of interconnectivity on different groups and how to manage the anticipated consequences before integrating with neighbouring electricity markets.

8.2 Increased Influence by Foreign Energy Policy

The energy crisis in Europe and Russia's reduced natural gas exports was hard to predict when Statnett presented the idea of NordLink to the Norwegian Government in 2013. Nevertheless, the situation highlights the importance of energy "due diligence" with countries before interconnecting with them. With interconnectors, one becomes more influenced by the other country's energy strategy, for better or worse. Increasing interconnectivity will, to a certain degree, reduce a country's control over the domestic electricity prices as these will also depend on the energy policy and power situation in the interconnected countries. Because of this co-dependence, policymakers must understand the long-term energy policy of the government in question and the consequences this will have for their domestic electricity price behaviour. Understanding this is important to make informed decisions and ensure the stability and affordability of their country's electricity supply.

8.3 Domestic Power Grid Congestion

To reap the full benefits of power exchange through interconnectors and maximise total social welfare, countries must aim to eliminate domestic congestion (THEMA Consulting, 2020). For example, suppose the German domestic power grid had a higher transmission capacity or were split into price areas according to the current power grid's constraints. In that case, THEMA Consulting assesses that we would see increasingly converging prices between Southern Norwegian and Northern German electricity prices and, thus, more efficient utilisation of NordLink. Furthermore, if the Norwegian domestic power grid had a higher north-south transmission capacity, the power surplus in Northern Norway would benefit not only Southern Norway but also Germany, the UK, Denmark and Southern Sweden through the interconnectors (Norwegian Ministry of Oil and Energy, 2022a).

8.4 Should Integration Lead to Specialisation?

The benefits of interconnectors are the largest when countries have dissimilar generation mixes and experience domestic power imbalances (Corona et al., 2021). Our findings support this idea by showing that NordLink transfers the most power and reduces the spread the most when Germany has a power deficit during peak demand hours, and Norway can help to reduce this deficit by transmitting electricity through NordLink.

The 2022 REPowerEU plan aims to increase the share of electricity production from renewable energy sources to 45% within 2030, up from 22% in 2020 (European Commission, 2022c). Most of this new capacity will come from solar and wind, replacing fossil fuels and nuclear energy. We argue that a more diversified energy mix across Europe would reduce electricity production risks associated with weather conditions and increase electricity supply security. From an interconnector utility maximisation perspective, the EU should aim to maintain a diverse energy mix among member states, including both baseload and intermittent production.

With regard to NordLink, Norwegian hydro storage can function as a battery for storing excess German solar and wind power (Mauritzen, 2013). Following the argument for increased specialisation, Norwegian energy policy should aim to maximise its hydropower capacity. NVE[10] assesses the technically and economically feasible development of new hydropower in Norway to be 23 TWh (Norwegian Energy Regulatory Authority, 2020). If Norway were to develop this capacity, it would represent an increase of almost 15% compared to current production levels.

[10]Norwegian Energy Regulatory Authority

9 Conclusion

Our results are consistent with the existing scientific literature on how increased interconnectivity between countries leads to converging electricity markets. We add to the robustness of the literature by analysing the spread instead of the effect on prices and by directly estimating the causal impact of a single interconnector.

At the same time, we emphasise the significance of considering external factors that may also influence electricity markets. As the use of renewable energy sources continues to rise, the merit order effect will become more influential in shaping energy prices and interconnector market dynamics. Our discussion aligns with the findings of Gugler & Haxhimusa, which indicate that the effect of interconnectors is easily overstated in the literature examining market convergence (Gugler and Haxhimusa, 2018). Being aware of the merit order effect when seeking to identify the integration effect of interconnectors is important, and quantifying this effect would be an interesting topic for future research.

We acknowledge that the application of causal analysis techniques relies on a set of assumptions. Yet, based on the discussion and evidence presented for the parallel trend assumption in section 5.3, we believe our results are internally valid. Additionally, time-series data often leads to autocorrelation and heteroskedasticity in the error terms. While this is accounted for with robust standard errors, a critical view is always recommended when examining the significance of different variables.

The introduction of North Sea Link and ALEGrO will affect the results, and future research could benefit from a more detailed investigation of the impact of these external events. Additionally, we believe that our empirical strategy could be applied to study similar events. Future research could include investigating the introduction of other interconnectors, such as the North Sea Link connecting Norway and the United Kingdom. Considering the EU's motivation for increasing interconnectivity between member countries, developing the scientific literature on the topic of interconnectors appears more important than ever.

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Appendix

A1 2022 Average Merit Orders

We show the merit orders discussed in Sections 3.4.1, 3.5.2, and 7.3.

Figures A1.1 and A1.2 show the average merit order so far in 2022 for Germany and Norway. The different production types' breadth represents the share they have in the total electricity generation. In hours with increased German renewable production, the German merit order looks more equal to the Norwegian one. Contrary, in hours with little renewable production, the German and Norwegian merit orders become more unlike.

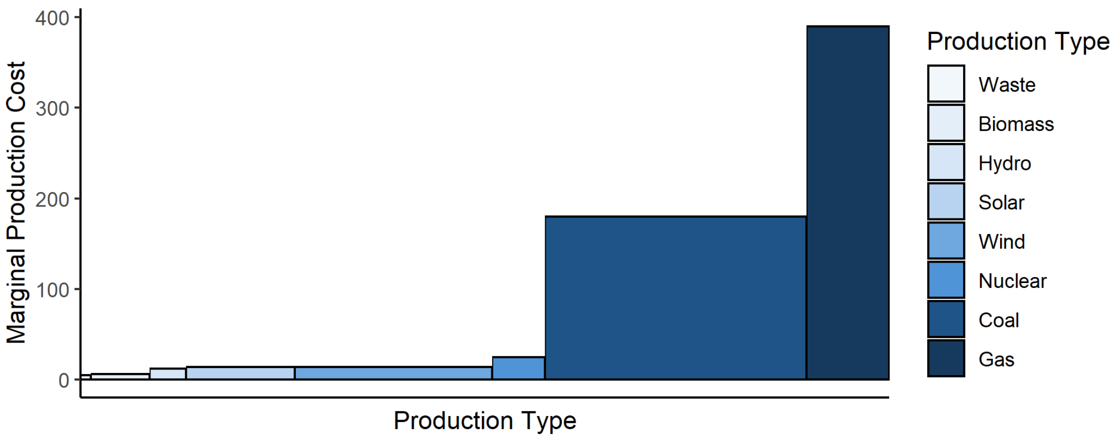

Figure A1.1: Average German merit order for 2022

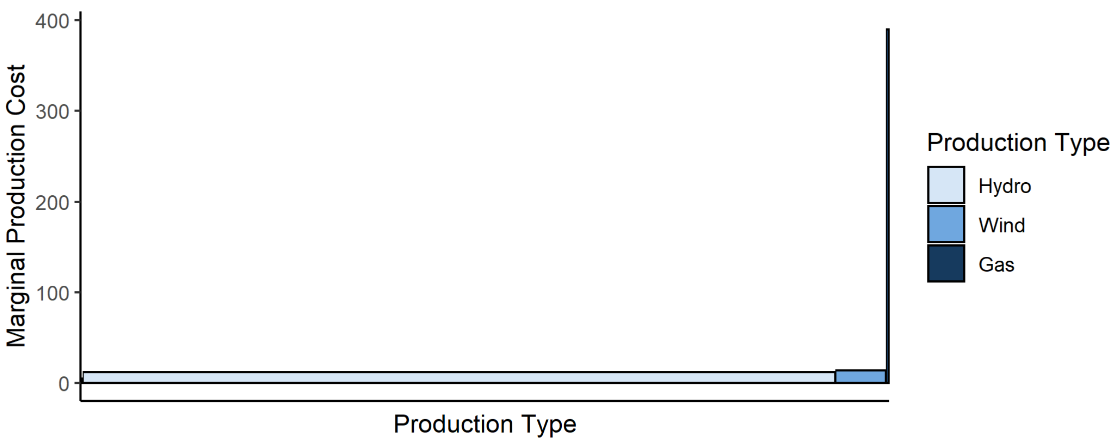

Figure A1.2: Average Norwegian merit order for 2022

A2 Existing Interconnector Capacity

We provide calculations behind the numbers in Section 7.1.

A2.1 Norway

We collected the data in Table A2.1 from Statnett (2022b), NRK (2022) and Bruvik and Hernes (2018).

	GW
Sweden	3.40
Denmark	1.74
Netherlands	0.70
Finland	0.11
Russia	0.05
Germany	1.40
England	1.40
Sum	8.8

Table A2.1: Existing Norwegian interconnector capacity

The interconnector between Norway and England, North Sea Link, was introduced in late 2021 and thus after NordLink. The two new interconnectors represented a 46.7% increase in Norwegian power exchange capacity. Note that the Norwegian interconnector capacity is listed as the physical transmission capacity of the transmission cables, unlike the German capacity in Table A2.2. Furthermore, the cables to Finland and Russia, as well as several of the Norway/Sweden interconnectors, are located in Northern Norway and have little effect on the electricity market in Southern Norway.

Equations .1 and .2 show the increase in Norwegian interconnector capacity.

$$\text{NordLink capacity / Norwegian interconnector capacity before NordLink} \tag{.1}$$

$$1.4\ GW\ /\ 6\ GW = 23.33\ \% \tag{.2}$$

A2.2 Germany

We collected the data in Table A2.2 from a monitoring report on the German power and gas market by German Federal Network Agency (2021).

	Import	Export
Switzerland	3.71	1.26
Czech Republic	1.42	1.05
Denmark	1.90	2.18
Norway	1.14	0.76
Poland	1.41	1.04
Sweden	0.52	0.32
Austria	5.03	4.86
Belgium	0.57	0.57
France	4.81	5.82
Netherlands	3.56	3.02
Sum	24.1	20.9

Table A2.2: Existing German interconnector import/export capacity. Numbers in GW

The German interconnector capacity from the report is listed as the mean available cross-border capacity that can be transmitted, calculated from all hours over the past year. Therefore, the German interconnectors' physical capacity is significantly higher than what Table A2.2 depicts.

When we calculate by how much NordLink increased the two countries' interconnector capacity, we used the nominal values in table A2.1 for Norway and the average between import and export values from Table A2.2 for Germany.

Equations .3 and .4 show the increase in German interconnector capacity.

$$\text{NordLink capacity / German interconnector capacity before NordLink} \tag{.3}$$

$$1.4\ GW\ /\ 22.5\ GW = 6.22\ \% \tag{.4}$$

A3 Calculations Behind Price Convergence

We provide assumptions and calculations behind numbers on price convergence presented in Table 7.1.

We retrieved the exchange rate we use for EUR/NOK to calculate the effect on Norwegian consumers from Norges Bank (2022).

EUR/NOK Jan-Sept 2022 avg	10.0075
Spread decrease due to NL	0.01227 EUR/KWh
Spread decrease due to NL	0.122792 NOK/KWh

Table A3.1: Calculating the spread decrease in NOK/KWh

We retrieved the statistical data in Table A3.2 from Statistics Norway (2022a), Statistics Norway (2022b) IEA (2022a), Statistisches Bundesamt (2022b) and EnerData (2021).

	Norway	Germany
Number of households, thousands	2,512	40,683
Households total consumption (TWh)	40.51	147.68
Average consumption per household (KWh)	16,128	3,113

Table A3.2: Calculating average electricity consumption per household

We show the implications of a price increase of 0.123 NOK/KWh for the households in Southern Norway in table A3.3. A 60% Norwegian share of the spread decrease means that NO2 prices, on average, have increased by 0.123 NOK/KWh $*$ 60%. We further multiply this with the average household consumption to find the price increase or decrease experienced by the households. We show an example where Southern Norway has 80% of the spread decrease in Equation .5. In our calculations, we assume that the spread decrease does not vary throughout the day, week or by season. We use the average household consumption, implying that the price increase will be greater for a high-consuming villa than for a tiny apartment.

$$80\% * 0.123 \text{ NOK/KWh} * 16,128 \text{ KWh} = 1,584 \text{ NOK} \tag{.5}$$

NO "share" of spread decrease	Price increase NO2	Price decrease Germany
0%	-	382
20%	396	306
40%	792	229
60%	1,188	153
80%	1,584	76
100%	1,980	-

Table A3.3: Yearly change in electricity bill due to NordLink for different scenarios. Per household. All values in NOK

A4 Congestion Rent From NordLink

We present calculations behind our claim in Section 7.1 on how the congestion rent from NordLink is on course to surpass NOK 1.8 billion.

Statnett congestion rent from NL	Million
From January to October	153.8 EUR
From January to October	1,545.1 NOK
Monthly average	154.5 NOK
Estimated for entire year	1,854.1 NOK

Table A4.1: Statnett's congestion rent from NordLink in 2022

A5 Norwegian Wind Production

We present evidence regarding forecasted Norwegian wind production discussed in section 6.1.1. Table A5.1 shows that "Forecasted Wind Production - Norway" tends to increase Norwegian exports, while "Forecasted Wind Production - Germany" tends to increase German exports. Flow ranges from [-1400, 1400], where positive values represent Norwegian exports/German imports and vice versa.

Additionally, we find that the increased wind production in Norway increases the chance of congestion from Norway to Germany in NordLink.

	Dependent variable:	
	Flow	Congestion to Germany
	(1)	(2)
Forecasted Wind Production - Norway	0.073^{***}	0.007^{***}
	(0.012)	(0.002)
Forecasted Wind Production - Germany	-0.010^{***}	
	(0.0001)	
Constant	836.545^{***}	0.015^{***}
	(8.056)	(0.001)
Observations	17,581	23,351
R^2	0.328	0.0004
Adjusted R^2	0.328	0.0004
Residual Std. Error	572.183 (df = 17578)	0.134 (df = 23349)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table A5.1: Regression Estimations - Wind Production on (1) Electricity flow in NordLink and (2) Congestion to Germany

A6 Recurring Effect Dummy Variables - Results

Hour 01:00	-3.84^{***}	Congestion_Norway	42.61^{***}
	(1.12)		(1.06)
Hour 02:00	-5.46^{***}	Congestion_Germany	32.55^{***}
	(1.12)		(1.75)
Hour 03:00	-6.76^{***}	SeasonSpring	-37.70^{***}
	(1.12)		(0.75)
Hour 04:00	-7.01^{***}	SeasonSummer	-10.49^{***}
	(1.12)		(0.57)
Hour 05:00	-4.78^{***}	SeasonWinter	-27.71^{***}
	(1.12)		(0.69)
Hour 06:00	5.96^{***}	DayMon	-1.60^{***}
	(1.12)		(0.60)
Hour 07:00	13.00^{***}	DaySat	-6.29^{***}
	(1.13)		(0.61)
Hour 08:00	14.38^{***}	DaySun	-8.02^{***}
	(1.15)		(0.61)
Hour 09:00	14.16^{***}	DayThu	2.25^{***}
	(1.19)		(0.60)
Hour 10:00	13.37^{***}	DayTue	1.67^{***}
	(1.24)		(0.60)
Hour 11:00	14.68^{***}	DayWed	2.43^{***}
	(1.28)		(0.60)
Hour 12:00	15.33^{***}		
	(1.30)		
Hour 13:00	14.40^{***}		
	(1.30)		
Hour 14:00	13.69^{***}		
	(1.28)		
Hour 15:00	12.23^{***}		
	(1.24)		
Hour 16:00	10.24^{***}		
	(1.20)		
Hour 17:00	14.55^{***}		
	(1.17)		
Hour 18:00	19.24^{***}		
	(1.14)		
Hour 19:00	23.94^{***}		
	(1.13)		
Hour 20:00	18.83^{***}		
	(1.13)		
Hour 21:00	10.11^{***}		
	(1.12)		
Hour 22:00	7.62^{***}		
	(1.12)		
Hour 23:00	1.80		
	(1.12)		

Table A6.1: Coefficients for dummy variables capturing recurring effects

A7 Robustness Check

Table A7.1 presents the models discussed in Section 6.2.1. The table shows the three different transformations of the dependent variable and spread in equation 6.1, 6.2, and 6.3.

	Dependent variable transformation:		
	$Y_{i,t}^{log}$	$Y_{i,t}^{log2}$	$Y_{i,t}^{percent}$
	(eq 6.1)	(eq 6.2)	(eq 6.3)
NordLink	-0.05^{***}	-0.39^{***}	-0.22^{**}
	(0.01)	(0.02)	(0.10)
Group	0.09^{***}	-0.02	0.31
	(0.03)	(0.05)	(0.21)
Post	-1.19^{***}	0.03	-5.98^{***}
	(0.01)	(0.02)	(0.08)
Norwegian Water Reservoirs	0.02^{***}	-0.02^{***}	0.12^{***}
	(0.00)	(0.00)	(0.00)
Forecasted Wind Production - Norway	0.21^{***}	0.50^{***}	1.20^{***}
	(0.01)	(0.02)	(0.07)
Forecasted Wind Production - Belgium	-0.15^{***}	-0.24^{***}	-0.31^{***}
	(0.01)	(0.01)	(0.04)
Forecasted Wind Production - Germany	-0.01^{***}	-0.01^{***}	-0.02^{***}
	(0.00)	(0.00)	(0.00)
Forecasted PV Production - Belgium	-0.21^{***}	-0.31^{***}	-0.57^{***}
	(0.01)	(0.01)	(0.05)
Forecasted PV Production - Germany	-0.01^{***}	-0.01^{***}	-0.02^{***}
	(0.00)	(0.00)	(0.00)
BE:Norwegian Load Forecast	0.02^{***}	0.03^{***}	0.17^{***}
	(0.00)	(0.00)	(0.02)
DE:Norwegian Load Forecast	0.04^{***}	0.06^{***}	0.20^{***}
	(0.00)	(0.01)	(0.02)
Constant	0.74^{***}	3.88^{***}	0.02
	(0.04)	(0.07)	(0.28)
Observations	45,428	45,487	45,390
R^2	0.582	0.234	0.436
Adjusted R^2	0.582	0.233	0.436

Table A7.1: Additional models: Three transformations of *spread*

A7.1 Removing Control Variables

We also substantiate the claims regarding our model's robustness to changes in which control variables we include. We do not see a substantial impact of removing any control variables.

	Dependent variable:				
	Spread				
	(1)	(2)	(3)	(4)	(5)
NordLink	−11.754***	−11.740***	−12.435***	−11.858***	−12.600***
	(0.699)	(0.694)	(0.701)	(0.701)	(0.685)
Group	4.780***	4.364***	5.214***	5.146***	2.503***
	(1.498)	(1.420)	(1.499)	(1.500)	(0.754)
Post	11.055***	9.008***	19.505***	10.778***	10.711***
	(0.566)	(0.563)	(0.498)	(0.567)	(0.552)
water_reservoirs	−0.863***	−0.858***		−0.973***	−0.891***
	(0.025)	(0.025)		(0.025)	(0.025)
NO_Wind	13.104***	16.961***	18.401***		18.090***
	(0.453)	(0.467)	(0.471)		(0.465)
AreaBE:Solar	−6.483***		−6.695***	−7.526***	−9.160***
	(0.368)		(0.370)	(0.372)	(0.359)
AreaDE:Solar	−0.178***		−0.186***	−0.203***	−0.253***
	(0.010)		(0.010)	(0.010)	(0.010)
AreaBE:Wind		−5.997***	−6.444***	−5.267***	−6.345***
		(0.242)	(0.246)	(0.244)	(0.238)
AreaDE:Wind		−0.150***	−0.145***	−0.109***	−0.167***
		(0.006)	(0.006)	(0.006)	(0.006)
AreaBE:NO_load_for	1.760***	2.816***	1.426***	2.421***	
	(0.154)	(0.152)	(0.156)	(0.156)	
AreaDE:NO_load_for	1.288***	2.463***	0.969***	1.896***	
	(0.154)	(0.152)	(0.156)	(0.157)	
Constant	51.299***	49.727***	16.554***	64.379***	72.890***
	(2.023)	(1.978)	(1.692)	(2.028)	(1.635)
Observations	46,724	46,724	46,724	46,724	46,724
R^2	0.217	0.228	0.216	0.215	0.236
Adjusted R^2	0.216	0.228	0.215	0.215	0.235
Note:					*p<0.1; **p<0.05; ***p<0.01

Table A7.2: Robustness in the causal effect estimation when removing different control variables

A7.2 Correlation Matrix - Control Variables

Table A7.3 presents a correlation matrix between the control variables presented in equation 5.4. There is no significant correlation between any variables.

In Table A7.3, we use the following notation for the control variables:

(1)	Wind
(2)	Solar
(3)	Congestion to Norway
(4)	Congestion to Germany
(5)	Norwegian Water Reservoirs
(6)	Norwegian Wind Forecast
(7)	Norwegian Load Forecast

Control Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)	1	0.130	−0.030	0.180	−0.020	0.210	0.190
(2)	0.130	1	0.040	0.090	−0.080	−0.050	−0.120
(3)	−0.030	0.040	1	−0.020	−0.150	−0.040	−0.010
(4)	0.180	0.090	−0.020	1	−0.050	0.010	0.020
(5)	−0.020	−0.080	−0.150	−0.050	1	−0.060	−0.110
(6)	0.210	−0.050	−0.040	0.010	−0.060	1	0.240
(7)	0.190	−0.120	−0.010	0.020	−0.110	0.240	1

Table A7.3: Correlation matrix: control variables

A7.3 Newey White - Standard Errors

The Newey White standard errors are both heteroskedasticity- and autocorrelation-consistent. The simple difference-in-difference model no longer yields statistically significant results. However, with the complete model, we can still say that we have a causal effect with clear statistical significance, even though certain control variables lose some significance.

	Dependent variable:	
	Spread	
	(Simple)	(Control)
NordLink	−6.91	−12.27***
	(4.39)	(3.39)
Group	−0.28	5.53
	(1.62)	(8.86)
Post	19.66***	9.43***
	(3.29)	(2.53)
Norwegian Water Reservoirs		−0.93***
		(0.12)
Forecasted Wind Production - Norway		17.67***
		(2.42)
Forecasted Wind Production - Belgium		−6.63***
		(1.39)
Forecasted Wind Production - Germany		−0.17***
		(0.03)
Forecasted PV Production - Belgium		−8.09***
		(1.45)
Forecasted PV Production - Germany		−0.23***
		(0.03)
BE:Norwegian Load Forecast		2.07
		(1.10)
DE:Norwegian Load Forecast		1.71
		(0.98)
Constant	23.35***	57.54***
	(1.17)	(11.59)
Observations	46,724	46,724
R^2	0.043	0.238
Adjusted R^2	0.043	0.237
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table A7.4: Main results with Newey White Standard Errors

A8 Non Energy Crisis Results

We present suggestive evidence for claims made in section 7.1. These regressions are identical to the regressions presented in equation 5.1, 5.2 and 5.4. However, we cut the data on the 1st of October 2021, before the energy crisis in Europe.

	Dependent variable:		
	Spread		
	(1)	(2)	(3)
NordLink	−6.868***	−2.037***	−3.637***
	(0.249)	(0.356)	(0.278)
Group		−0.281	2.520***
		(0.243)	(0.608)
Post		−4.831***	0.258
		(0.252)	(0.209)
Norwegian Water Reservoirs			0.442***
			(0.011)
Forecasted Wind Production - Norway			2.213***
			(0.229)
Forecasted Wind Production - Belgium			−2.407***
			(0.107)
Forecasted Wind Production - Germany			−0.096***
			(0.003)
Forecasted PV Production - Belgium			−4.997***
			(0.180)
Forecasted PV Production - Germany			−0.122***
			(0.005)
BE:Norwegian Load Forecast			−1.323***
			(0.069)
DE:Norwegian Load Forecast			−1.324***
			(0.069)
Constant	23.072***	23.353***	19.348***
	(0.170)	(0.171)	(0.845)
Observations	15,336	30,694	30,694
R^2	0.047	0.036	0.438
Adjusted R^2	0.047	0.036	0.437
Residual Std. Error	15.362 (df = 15334)	15.549 (df = 30690)	11.885 (df = 30648)
Note:			*p<0.1; **p<0.05; ***p<0.01
Seasonal Control Dummies:	No	No	Yes
Daily Control Dummies:	No	No	Yes
Hourly Control Dummies:	No	No	Yes
Congestion Control Dummies:	No	No	Yes

Table A8.1: Difference-in-difference results: pre-energy crisis data

A9 Load and Power Production

We present the load forecast and the power production used to construct Figure 7.1 - net export/import need. Figure A9.2 shows the inflexible German power production, while the Norwegian production pattern correlates more with the demand pattern.

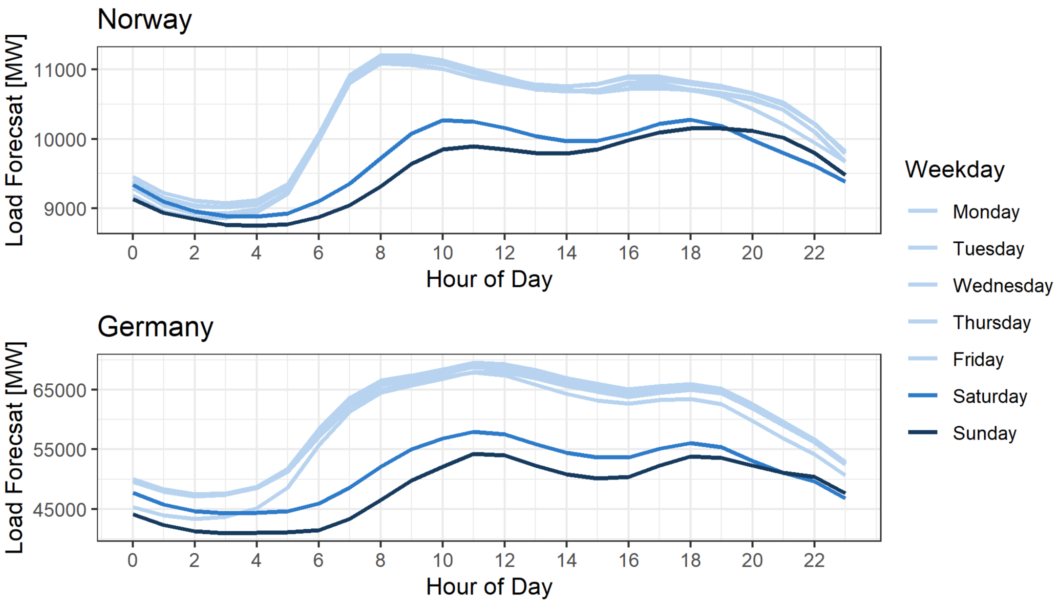

Figure A9.1: Load (demand) forecast: Norway and Germany

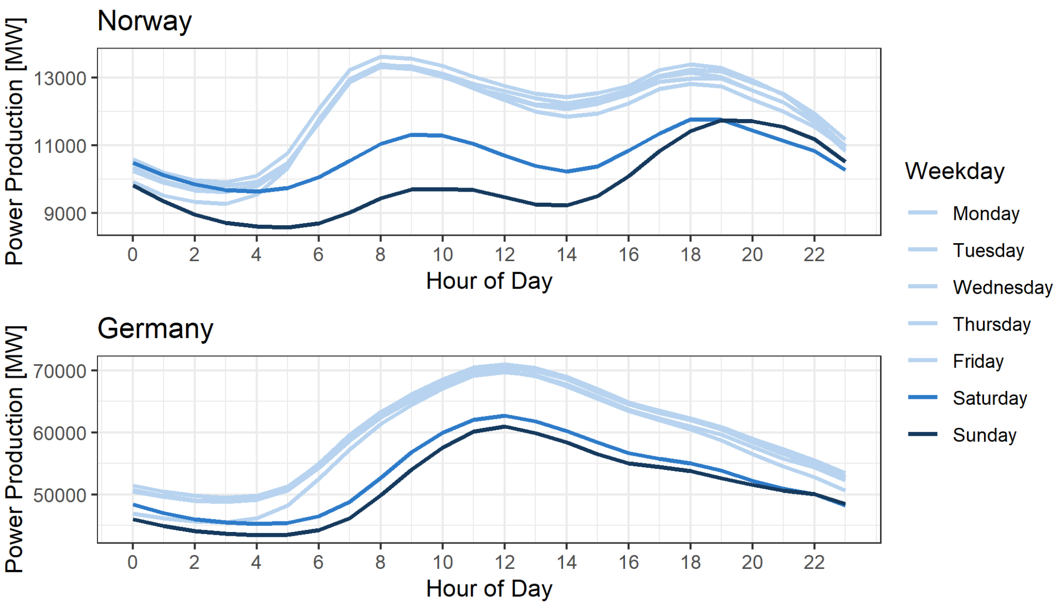

Figure A9.2: Power production: Norway and Germany

A10 Merit Order Effect

Evidence for claims made in section 7.3 regarding the correlation between changes in the German merit order, i.e. renewable production and Flow in NordLink. We see that when the German merit order becomes flatter, they produce more renewables, they also need to export more electricity.

	Dependent variable:
	Flow
Wind	3.647^{***}
	(0.133)
Solar	4.424^{***}
	(0.274)
Constant	44.608
	(38.565)
Observations	3,937
R^2	0.479
Adjusted R^2	0.474
Residual Std. Error	352.410 (df = 3900)
F Statistic	99.644^{***} (df = 36; 3900)
Note:	*p<0.1; **p<0.05; ***p<0.01
Seasonal Control Dummies:	Yes
Daily Control Dummies:	Yes
Hourly Control Dummies:	Yes
Congestion Control Dummies:	Yes

Table A10.1: Correlation between NordLink flow and German wind & solar production

A10.1 Renewable Power Production in Germany

Table A10.2 shows the result of a simple regression: $Y^{abs}_{DE,t} = \alpha + \beta_1 \text{WindProd}_{DE,t} + \beta_2 \text{PVProd}_{DE,t} + \omega_t + \epsilon_t$. We look at the absolute spread and the German wind and solar production for two scenarios. In the left column, we use only the data where Norway has the highest electricity price, and in the right column, the observations where Germany has the highest price.

	Dependent variable:	
	Absolute spread	
	(Norway > Germany)	(Germany > Norway)
Wind	0.32***	−0.28***
	(0.01)	(0.01)
Solar	0.34***	−0.52***
	(0.03)	(0.02)
Constant	−19.57***	54.13***
	(3.50)	(2.35)
Observations	3,937	11,205
R^2	0.26	0.30
Adjusted R^2	0.25	0.30
Note:		*p<0.1; **p<0.05; ***p<0.01
Seasonal Control Dummies:	Yes	Yes
Daily Control Dummies:	Yes	Yes
Hourly Control Dummies:	Yes	Yes
Congestion Control Dummies:	Yes	Yes

Table A10.2: Regression results: wind & solar production on spread - two scenarios