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Renewable energy's effect on bottlenecks in the electricity market

Analyzing the impact of the green transition and increased interconnectors abroad on price differences towards NO2

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Abstract

The electricity sector in Europe needs a substantial transition towards an increased share of renewable energy sources to reach the European Commission's target for Europe to be climate neutral by 2050. In this study, we explore the impact of the green transition through increased use of renewable energy. Specifically, we focus on bottlenecks in the electricity market between the NO2 price area in Norway and its interconnectors abroad to Denmark (DK1), Germany (DE), the Netherlands (NL), and the United Kingdom (UK). Further, this study is set to give an understanding of Europe's evolving energy landscape related to price fluctuations affected by interconnectors and a focus on more renewable energy in response to climate change imperatives.

Using a combination of Ordinary Least Squares (OLS) and Pooled OLS regression models, the study analyzes correlations between daily spot price differences, weather conditions, and power generation data from 2020 to 2023. Further, we investigate the implications of increasing the use of intermittent renewable energy sources, such as wind and solar, in price areas abroad that NO2 has interconnectors with and the effect this has on price differences. Before 2020, there have not been many bottlenecks between NO2 and abroad, meaning few constraints on the flow of electricity in the power grid. Therefore, the demand to expand capacity in the grid has not been substantial. With the increasing production of energy from wind and solar sources, we see an immense increase in fluctuations in price differences as a result of the increased exchange of power.

The findings in our regression results indicate that wind power has a significant correlation with price difference and substantiates that weather has an effect on bottlenecks. Intermittent production from renewable energy sources constitutes an increasingly larger share of the power production mix among energy suppliers. Our findings show that using intermittent renewable energy sources might contribute to more substantial problems concerning bottlenecks and fluctuations in price difference. However, we also explore how this can be balanced using dispatchable energy sources such as hydropower in Norway.

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1 Introduction

In today's evolving energy landscape, the importance of increasing the use of renewable energy sources has grown significantly due to the concerns about climate change. An important factor leading to the increasing use of renewable energy in Europe is that the EU aims to be climate neutral by 2050 (European Commission, 2023). In July 2021, the European Commission adopted a set of proposals to make the EU's climate, energy, transport, and taxation policies fit for reducing net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels (European Commission, 2023). A key target is to shift the share of renewable energy from 32% to 42.5%. Another important reason is the UN Sustainability Goal number 7: Affordable and clean energy (UNDP, 2023). The aim is to ensure access to affordable, reliable, sustainable, and modern energy for all. Countries are therefore required to take action, shifting towards more renewable energy and integrating markets, to achieve these goals.

An issue in the Norwegian grid is that it does not have sufficient capacity to transmit power from price areas north to south in Norway (Statnett, 2022). When there is congestion in the grid, and power cannot be transmitted from one area to another, a bottleneck arises (NVE, 2022a). To ensure Norway continues to have a secure flow of electricity supply in the future, it has been essential to build interconnectors abroad (NVE, 2022c). The European Commission has stated that action is needed to develop interconnector capacity as a necessary condition for the development of competition and the integration of markets (European Commission, 2007). Norway has since 1960 had interconnectors abroad and is today connected to Sweden, Denmark, Finland, Germany, the Netherlands, and the United Kingdom. This thesis will focus on interconnectors that were more recently opened from NO2 to Denmark (DK1), the Netherlands (NL), Germany (DE), and the United Kingdom (UK) and their impact on price differences with the Norwegian power grid.

Plenty of research has been conducted on the effects of interconnectors. In 2013, Statnett (2013) provided a report on the impact of developing cables to Germany and the UK. Their analysis argues that the cables should lead to less price difference from hour to hour but also that there will be bottlenecks and significant price differences most of the time. Other research says that transmission cables are anticipated to bring several significant advantages, including reducing energy costs, enhancing the security of supply, and reducing reserve requirements (Sapio, 2019). Consequently, the integration of markets is expected to promote the convergence of prices. This effect has been questioned by researchers like Gianfreda et al. (2016) raising doubts. He argues that the characteristics of intermittent energy sources are forces working against price convergence, primarily due to the growing prevalence of intermittent energy within today's electricity markets. Therefore, the effects of intermittent renewable energy on price differences are interesting to investigate further.

This shift towards greener energy production and market integration has been the most significant change in Europe's electricity markets since the beginning of the markets' deregulation process in the early 1990s (Fulli et al., 2019). Our neighboring countries have historically relied more on fossil fuels as a significant energy source and are now compelled to swiftly transition to more sustainable energy sources. In Norway, hydropower accounted for 88.2% of electricity output in Norway in 2022, and wind power contributed another 10% to Norway's electricity mix (Statista, 2023c). In the EU, however, wind and solar power generated 22% of the EU's electricity in 2022, overtaking gas for the first time, and renewables nearing 40% of the total electricity generation (Halm, 2023). Transition to a greener future requires electrification and utilization of limited capacity in the grid. This limitation is also a result of industries converting to electricity from fossil energy to meet new government regulations. Using renewable energy sources includes intermittent renewable energy sources that provide a significant challenge in maintaining a stable and reliable power supply (Brouwer et al., 2014). The problem with these energy sources is that they are less flexible and cannot be regulated.

Before 2020, as we will see in our study, there have not been many bottlenecks, and therefore, the demand to expand the power grid to handle the spikes in energy transactions has not been substantial. With the increasing production of energy from wind and solar sources, challenges arise concerning efficient power supply distribution, particularly when production varies significantly due to weather conditions (Brouwer et al., 2014). This is what we want to explore further in our master thesis, and we have therefore stated the following research question:

How does the green transition, with increased use of renewable energy, affect bottlenecks between NO2 and interconnectors abroad?

The objective of this master's thesis is to conduct a comprehensive analysis of how bottlenecks have evolved in relation to the increased use of intermittent renewable energy in Norway's neighboring countries. We will focus on the green transition in the scope of increased use of wind and solar power in the countries abroad. We will use Ordinary Least Squares (OLS) and Pooled OLS regression models to estimate how these intermittent energy sources affect bottlenecks. This will give a broader understanding of how the increased use of renewable energy affects bottlenecks and analyze how focusing on employing the green transition will affect the electricity market.

2 Market Description

In this section, we explore the dynamics and structure of the electricity market. This market has transitioned from a historically state-dominated and monopolistic structure to be characterized by deregulation and competitive trading mechanisms (Necoechea-Porras et al., 2021). This significant transformation has driven the electricity market towards greater resource efficiency, focusing on the security of supply, and aims to maintain power costs at reasonable levels (Energifakta Norge, 2023a).

2.1 Power Exchanges

In 1990, Norway got a new energy law liberalizing the electricity market, encouraging competition among power suppliers (Ministry of Petroleum and Energy, 2021). Historically, the power exchange was primarily based on bilateral and long term agreements. Due to this deregulation of the electricity market, the exchanges have taken on a regular market character characterized by competition, involving multilateral trade across areas through short term agreements (Hofstad et al., 2022). Norway, for instance, is connected to Europe through multiple interconnectors, as seen in figure 2.1 (NVE, 2022b). The deregulation aims to achieve several improvements, including better resource efficiency, supply chain security, and leveling price differences across countries.

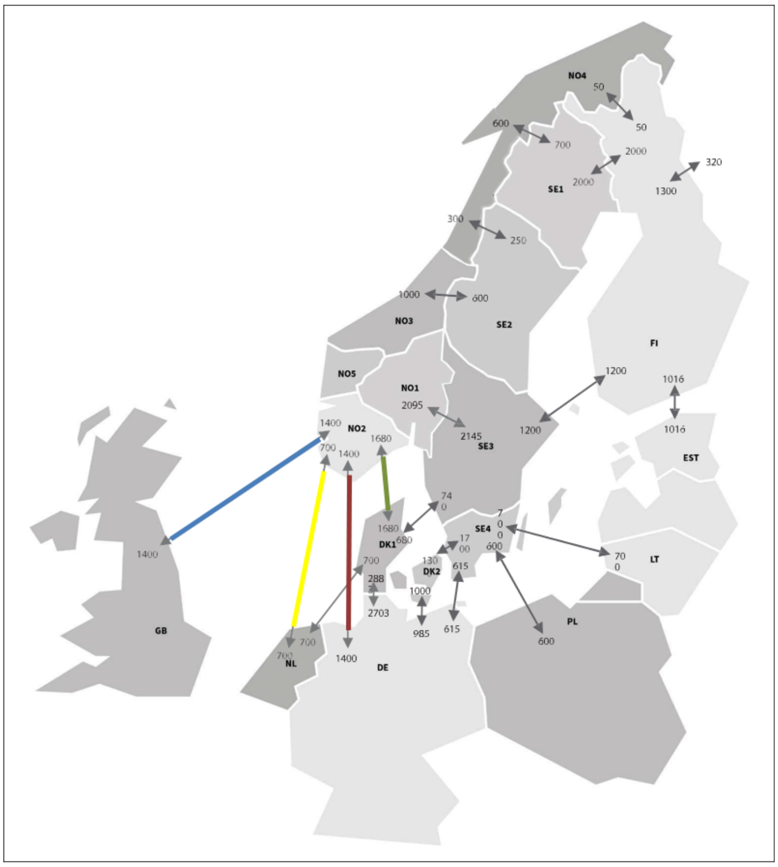

Figure 2.1: Interconnectors (Energikommisjonen, 2023)

Norway's first interconnector was established in 1960 to Sweden, and the number of interconnectors has expanded thereafter (NVE, 2021b). More recently the NorNed interconnector from NO2 to the Netherlands opened with a maximum capacity of 700 MW in 2008 (Tennet, 2023). Towards Denmark, there are four interconnectors called Cross-Skagerrak. The newest interconnector named Skagerrak 4 opened at the end of 2014 and increased the capacity with 700 MW to a total of 1700 MW (Statnett, 2020c). NO2 also transfers electricity with Germany through NordLink which opened at the end of 2020 but was operational from 2021 with a capacity of 1400 MW (Statnett, 2023a). NO2 is connected to the UK as well, transferring electricity through North Sea Link, which was stated to be operational in 2022 with a capacity of 1400 MW (Statnett, 2023b). With the increase of interconnectors abroad between Norway and other countries, the annual transfer of exports and imports has increased between NO2 and abroad. This opens for the possibility of increased export from Norway in years when power production is high, and increased import when production in Norway is lower (Energifakta Norge, 2023b).

The power production mix in each country varies and depends on several factors, including resource accessibility and different weather conditions. For instance in Norway, 88% of power production stems from hydropower, resulting in electricity surplus during periods with much snowmelt and precipitation (Energifakta Norge, 2023b). Denmark, with its substantial reliance on wind energy, would most likely experience increased power production during windy weather conditions. However, the capacity to exchange electricity across regions evens out the accessibility to electricity throughout the seasons as it allows for importing electricity when in shortage of resources, and exporting in periods with excess of resources. In other words, the interconnectors make differences in power production mixes beneficial by optimizing the resources on both sides of the cables. This improves supply security, enhancing value creation through maximizing returns of surplus power, as well as contributing to efficient resource utilization mitigating price differences (Statnett, 2023a).

2.1.1 Nord Pool

The liberalization of the electricity market in 1990 was introduced and applied in other Nordic countries with the desire to integrate the physical electricity market with regulations (Ministry of Petroleum and Energy, 2021). After the deregulation process, Nord Pool was established in 1996 as the world's first international electricity exchange, opening for the possibility of trading electricity across regions. Initially, Nord Pool was established as a Norwegian company under "Statnett Marked AS". Later, the entity expanded to incorporate Sweden as a joint owner with 50%, changing the name to Nord Pool. Today, Nord Pool is a neutral entity that facilitates electricity trading based on supply and demand through publicly known price signals. Nord Pool has further expanded to include several other countries such as the Baltic nations, Germany, Poland, France, the Netherlands, the UK, Belgium, Luxembourg, and Austria. Through a common marketplace such as Nord Pool, electricity can be sold from areas characterized by high production and lower pricing to areas with comparatively lower production and higher prices. This ensures optimized allocation of power resources and converging prices.

2.1.2 EPEX SPOT

European Power Exchange (EPEX SPOT) is a power exchange similar to Nord Pool, established in 2008 following the consolidation of the spot power operations of the German Energy Exchange (EEX) and the French Power next, each holding a 50% equity share (Rosvold, 2019). This exchange was initially tasked with establishing spot prices for electricity market integration within Europe. However, since 2014, it has expanded to include the Nordic countries, the UK, Belgium, the Netherlands, Estonia, Latvia, Lithuania and Poland.

2.1.3 The Day-ahead (Elspot) and Intraday (Elbas) market

The day-ahead market is where power market participants submit their predicted bids for purchase or sale for a given amount of electricity for the next 24 hours in a closed auction (Nord Pool, 2023a). The price in the day-ahead market, known as the spot price, is set by the equilibrium between the bid and ask price from participants. The spot price is announced the day before the trading occurs, usually at noon. While the day-ahead market is the primary market, the intraday market works as a supplement and helps the participants balance their positions, as the trading closes only one hour before the physical delivery of the electricity (Nord Pool, 2023b). Through the green transition with increasing amounts of renewable intermittent resources, interest in trading in the intraday markets is increasing. This is due to the intermittency of renewables that depend on variable weather conditions, which poses challenges for the desired balance. Therefore, the intraday market offers participants the flexibility to adjust their bids based on the latest market information, such as unexpected weather shifts or grid closures, which is crucial for producers that are dependent on unregulated renewable energy sources.

2.1.4 Price Determination

At Nord Pool, the market equilibrium price, also known as the system price, is determined by matching the aggregated demand and supply curve. The price is calculated without considering transmission constraints and serves as a pivotal reference for various financial contracts (Nord Pool, 2023c). To visualize this process, we present a supply and demand curve, where the x-axis represents quantity, and the y-axis represents price, see figures 2.2

and 2.3. The green curve (D) indicates the demand side, and the blue curve (S) indicates the supply side. The point where these curves intersect (Q, P), indicates the market-clearing price where the buyer's demand and supply are equal. The shape and position of these curves can be influenced by various factors further leading to price changes, including weather conditions that affect both supply (e.g., wind or solar production) and demand (e.g., winter or summer season). When an energy source is in surplus, the electricity production increases whereas the supply curve shifts outwards from S to S1 illustrated in figure 2.2, leading to increased quantity and decreased market price (Q1, P1). However, when the energy source is in scarcity, the supply curve shifts inward from S to S1 in figure 2.3, leading to higher prices and lower demands (Q1, P1).

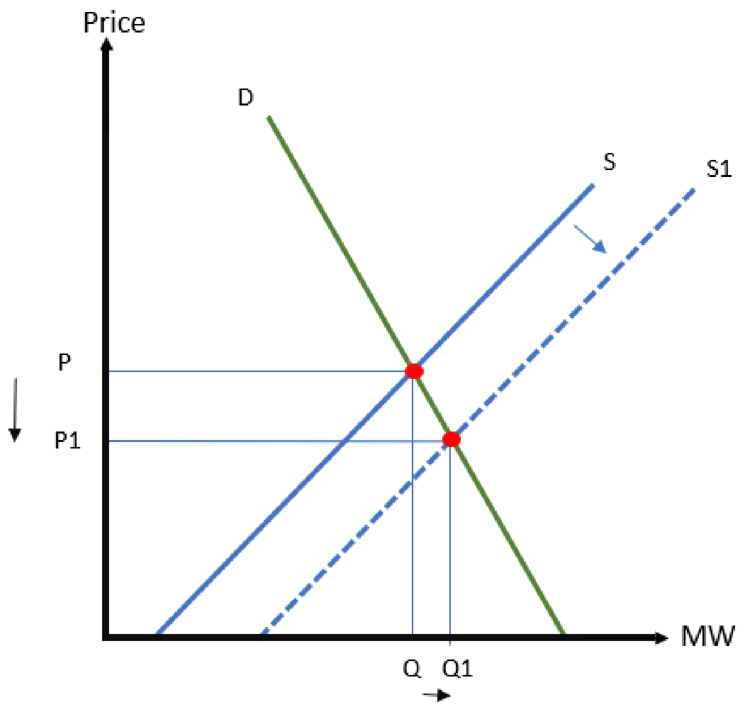

Figure 2.2: Increased access to energy sources

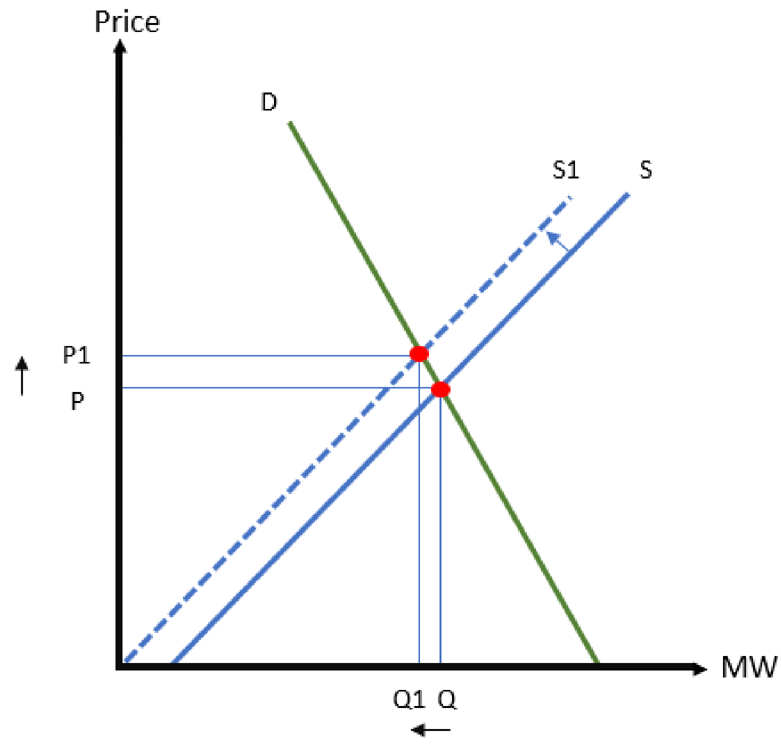

Figure 2.3: Decreased access to energy sources

2.1.4.1 The Merit Order Effect

In addition to supply and demand theory, other factors influence the price determination in the electricity market, for instance, the merit order effect. In the open market, the most cost-effective energy sources are utilized first (Energifakta Norge, 2023a). This concept is referred to as the merit order effect, describing how prices are determined by the bid of the last unit needed to satisfy total demand. This is where the market price is set, whereas the cheapest energy sources are utilized first as illustrated in figure 2.4. As the production of electricity derives from a variety of sources, production costs vary between different sources, which subsequently influences the determination of prices.

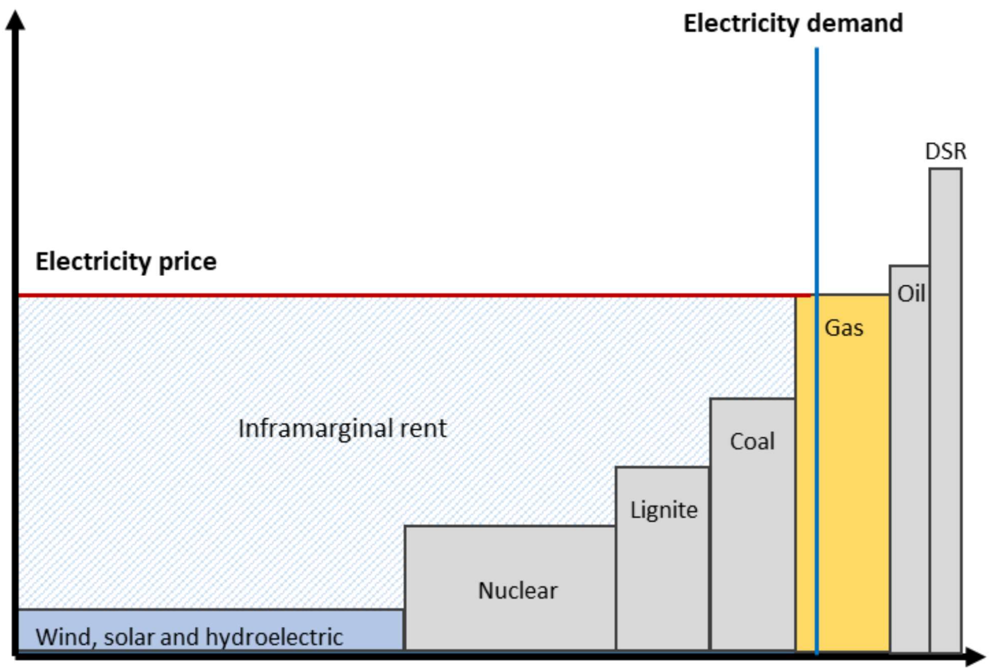

Figure 2.4: Simplified merit order supply demand stack (European Commission, 2023)

In the transition to a greener future, numerous sources based on fossil fuels are being replaced by renewable alternatives. The growth of such renewable sources, characterized by lower production overheads, could exert a downward pressure on wholesale electricity prices (Morales & Pineda, 2017). For instance, in conditions of strong winds, wind turbines operate at full capacity, providing an opportunity to meet the demand with an increased share of wind power. This leads to a reduced share of fossil sources, as the marginal cost of production is higher for fossil fuels compared to wind power. The last unit needed to satisfy total demand could therefore be a less costly source, and the market price is lower than if the last unit would be more costly.

2.1.5 Pricing mechanism: In Norway

In most commodity markets, storage contributes to offset fluctuations in production and demand (Green, 2021). Without this ability, demand and supply usually fluctuate leading to more volatile prices. Electricity is a product that cannot be stored, potentially leading to more fluctuations in demand and supply as it must be used when it is produced. However, the source used for the electricity production can potentially be stored, such as water can be stored in magazines for hydro production. This allows for the strategic release of electricity at times when it is most convenient, adjusting the production of electricity based on fluctuations in demand. Even though hydro as an energy source is dispatchable, it is important to note that the inflow of water for hydropower is dependent on precipitation and snowmelt, which are quite fluctuating throughout the year.

Despite the challenges concerning weather fluctuations, the ability to store water allows hydropower plants to continue producing electricity even when precipitation levels are low during dry seasons. This comes from storing water during wet seasons with surplus water access and excessive amounts of precipitation or snowmelt (Green, 2021). This strategic management of water facilitates a more consistent supply of electricity from hydroelectric sources. Further, it allows for adjusting the supply of electricity to when it is more profitable for the producers, during higher electricity prices. The opportunity cost in this context is the potential revenue that could be lost when water is used for electricity production now, rather than being saved for future utilization. When water is plentiful, the opportunity cost will be low, and during times of scarcity, it can be high and continue to stay high until the next wet period reloading the reservoirs. In other words, the strategic management of water can lead to more profitable outcomes, which contributes to the explanation of why water is usually stored during wet seasons and used during dry seasons.

To explain the dynamics of hydroelectric production with reservoirs, we use two simplified models based on (Førsund, 2007) methodology, known as the bathtub model. Figure 2.5 describes wet seasons, and figure 2.6 describes dry seasons, illustrating weather's impact on demand and supply of electricity.

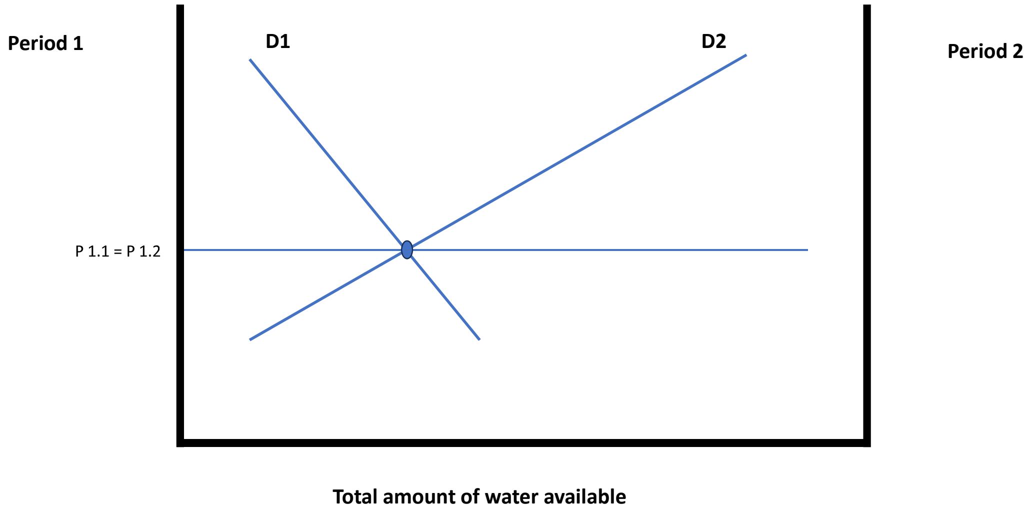

Figure 2.5: Bathtub model - Wet Season

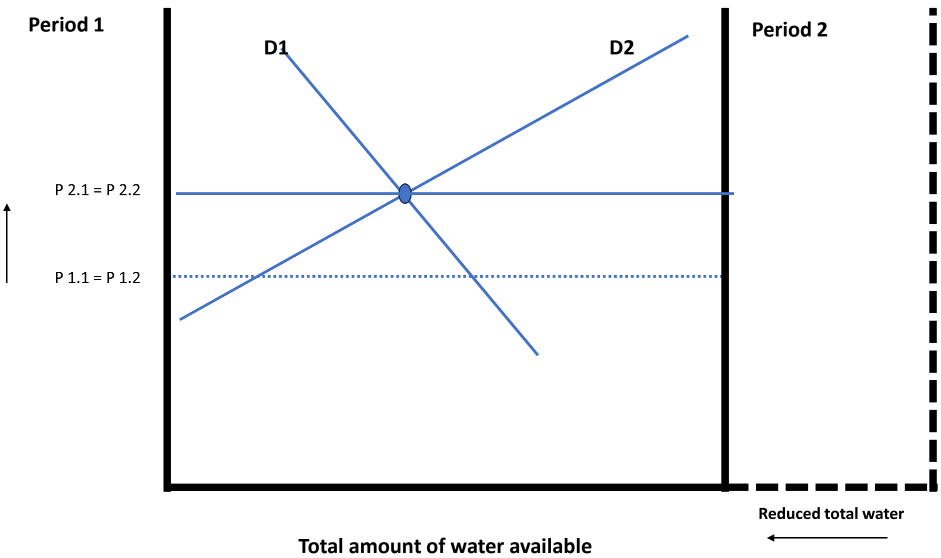

Figure 2.6: Bathtub model - Dry Season

In the models above the time frame is one year. As water inflow affects the average price over a year, there are different inflows in different periods that the producers reallocate the production. The amount of water accessible in both periods 1 and 2, is shown by the lengths of the horizontal axis, with inflow in period 1 from the left, and inflow for period 2 from the right. On the left side of the diagram, we have a conventional downward sloping demand curve (D1) for the first period, measured from the left vertical axis where the price is decided by the total amount of water available. On the opposite side, we have the demand curve for period 2 (D2) measured from the right axis and slopes in the opposite direction to D1. The electricity price is set where D1 and D2 intersect, where the price is equal in both periods. As hydro producers can reallocate water throughout different seasons, fluctuations in both production and demand reduces. This leads to arbitrage opportunities as suppliers can store water and sell electricity in high price periods, and the convergence of prices between two different periods.

The opportunity to store water also leads to different prices between dry and wet seasons, as the total amount of water available differs. As you can see by comparing figure 2.5 and 2.6, the average price is lower during wet years compared to dry years, illustrated in the equilibrium where D1 and D2 cross in both figures. During wet seasons suppliers will store water as the opportunity cost is higher during dry seasons, leading to lower prices during wet seasons.

Having a large share of dispatchable hydropower within the power production mix makes the supply of electricity more predictable. During seasons with low wind and sunshine, electricity is produced from hydro reservoirs to make the supply and electricity prices more stable. On the other side, when the share of intermittent energy resources increases, hydro suppliers tend to reduce production to ensure relatively high electricity prices as producing more might lead to lower prices. This also depends on producers' analysis and expectations of water inflow and the filling of water reservoirs. It is therefore reasonable to question whether other energy sources than hydro will have a significant impact on price differences in countries that have a large share of hydro production, such as Norway.

2.1.6 Bidding areas

To address the limitations related to transmission capacity and bottlenecks, regions are divided into different bidding areas. Norway is divided into NO1, NO2, NO3, NO4 and NO5, and Denmark into DK1 and DK2 (NVE, 2022a). Bidding areas are important to reduce bottlenecks within the power grid, and the areas are consequently established where there is long-term limited capacity. By using these bidding areas, we account for the physical limitations present in the power system. In Norway, for each five bidding areas, a separate electricity price called the area price is determined.

2.1.7 Bottlenecks

The electricity demand across bidding areas and regions often differs from the areas with the highest electricity production capacity. As a result, electricity must transfer from areas of surplus to regions of deficit (NVE, 2022a). However, the power grid is limited by the amount of electricity that can be transmitted through the cables. These limitations lead to inefficiencies in directing all the electricity to the areas with the highest demand. This point of congestion and constraint within the power grid, where the transmission capacity is restricted, are conventionally known as bottlenecks. Bottlenecks occur when the market desires to transfer electricity between areas above the network's capacity.

2.2 The Norwegian Market

Historically, Norway‘s electricity market had a monopolistic structure, where consumers were required to purchase power from their local, municipally administered power plants (EnergiFakta Norge, 2023). However, due to rising price differences based on geographical and seasonal factors, the Energy Act was established in 1991, initiating competition and liberalization among electricity suppliers, anticipating to improve efficiency and stabilizing electricity prices (Ministry of Petroleum and Energy, 2021). Today the market is deregulated whereas the number of suppliers has significantly increased, making the market less monopolistic.

Production Type	**Share**
Hydro	88.20%
Wind Power	10.10%

Table 2.1: Renewable energy production mix in Norway, (Statista, 2023c)

As previously mentioned, the power production mix in Norway primarily consists of hydropower, contributing 88,2% of total electricity production in 2022, wind 10,1%, and thermal power 1,6% (Statista, 2023c). The flexibility afforded by significant hydropower reservoirs, offers a unique advantage in the energy market, allowing for the storage and regulation of electricity in response to fluctuating demands (NVE, 2023a). This gives the opportunity to hedge against dry seasons where precipitation levels are low. Furthermore, the integration with the European market through interconnectors abroad allows Norway to trade power efficiently by importing during periods of resource scarcity, and exporting when there is a surplus.

2.3 The Denmark Market

In Denmark, the liberalization process started in 1996 and is still evolving with regulatory developments concerning monopolies and enhancing the retail market (Danish Energy Agency, 2023b). Today, Denmark has a leading position in the green transition concerning the integration of large amounts of renewable energy.

Production Type	Share
Wind Power	55.03%
Solar	5.78%

Table 2.2: Renewable energy production mix in Denmark (Statista, 2023a)

Historically, Denmark‘s electricity market was primarily based on thermal power such as coal and gas. Today, wind and solar power in combination with flexible thermal power plants and international transmission networks, supplies the Danish electricity demand. This leads to lower electricity prices and security of supply (Danish Energy Agency, 2023a). Even though they already have a leading position within the green transition, Denmark is aiming to quadruple the production of onshore solar and wind by 2030 and increase offshore wind power production during the same period (Energikommisjonen, 2023).

2.4 The German Market

Before the deregulation, the German electricity market was vertically integrated with local monopolies (Niederprum and Pickhardt, 2002). As liberalization began in the 1990s, several mergers and acquisitions took place, whereas four new vertically integrated utilities were established: REW, EON, Vattenfall, and EnBW, owning around 80% of the production capacity (Agora Energiewende, 2023).

Production Type	Share
Wind Power	22%
Solar	10.40%

Table 2.3: Renewable energy production mix in Germany(Statista, 2019)

Historically, the German electricity power system featured a substantial presence of thermal power such as coal and oil. Today the energy mix is more diversified (Energikommisjonen, 2023). Germany aims to transition towards a low-carbon and nuclear-free industrial economy through their strategy “Energiwende”, which has been effective for nearly a decade and yielded notable outcomes. One of the key features is to gradually phase out thermal power and replace it with wind and solar, as well as investing in offshore wind expansion and scaling up hydrogen production.

2.5 The Netherlands Market

The electricity market in the Netherlands underwent liberalization in 2004, adopting a policy of more separated ownership. The intention was to separate power production companies from network ownership entities, fostering a competitive environment (Deloitte, 2015). Their cables have historically transferred electricity made by power from gas and oil, but now an increasing share comes from wind and solar.

Production Type	**Share**
Wind Power	17.43%
Solar	14.57%

Table 2.4: Renewable energy production mix in the Netherlands(Statista, 2023b)

The Netherlands was historically the fifth largest natural gas exporter in the world and one of the most carbon intensive countries in the EU, where petroleum and natural gas accounted for more than 80% of the gross inland consumption in 2012 (Deloitte, 2015). However, they are aiming for a rapid transition to a carbon neutral economy, focusing on bringing down greenhouse gas emissions with a target to reduce them by 49% by 2030 and by 95% by 2050 compared with 1990 levels (International Energy Act, 2020).

2.6 The UK Market

Following the introduction of competition in the UK‘s electricity market in the 1990s, improvements were made in reducing prices and operating costs (Department for Business, Energy and Industrial Strategy, 2021).

Production Type	**Share**
Wind Power	24.19%
Solar	4.21%

Table 2.5: Renewable energy production mix in the UK Statista, 2023d

The UK has one of the most diverse ranges of electricity generation in Europe (The Guardian, 2023). Even though the historical energy landscape has been characterized by a dominance of fossil fuels and some nuclear power, today they are one of the leading nations in offshore wind energy production. As seen in table 2.5, it constitutes approximately 24,19% of total energy production in the UK (Our World in Data, 2023). In April 2022, the British government launched the strategy British Energy Security Strategy aiming to secure long term supply security through the expansion of renewable energy sources (Energikommisjonen, 2023). Simultaneously, they are aiming to diversify the renewable energy mix, with an emphasis on a combination of hydrogen, offshore wind, and cross-border interconnections to ensure decarbonization and achieve their goal of net-zero emissions by 2050.

3 Data

Our data sample comprises aggregated daily spot price difference, power generation, and weather condition observations spanning from January 1st, 2020, to the last observation on September 1st, 2023. This choice of time frame corresponds to when bottlenecks between NO2 and abroad began to occur more prominently. We have collected data for the defined price areas in the five relevant countries: Norway (NO2), Denmark (DK1), Germany (DE), the Netherlands (NL), and the United Kingdom (UK). We first describe the spot price data used as the basis for our defined dependent variable and then present descriptive statistics for bottlenecks and the control variables we find relevant to analyze.

3.1 Dependent Variable

To understand the influence of intermittent renewable energy sources on bottlenecks, we have chosen to use price differences between defined price areas as our dependent variable. Day-ahead spot prices for NO2, DK1, DE, NL, and UK are retrieved from the Montel data platform. We used daily spot price data to develop a holistic understanding of the development of bottlenecks over time. Spot prices are observed per day and measured in EUR/MWh. As mentioned in the market description, a bottleneck in the power grid arises when a part of the grid experiences transmission limitations in connection to connected areas (NVE, 2022a). Further, this is when electricity is transferred between areas with different power prices. Based on this, we believe it is reasonable to set the dependent variable as the price difference between Norway's price area NO2 and price areas abroad.

Dependent variable:

$$\text{Price difference} = \text{Spot Price NO2} - \text{Spot Price Abroad(DK1/DE/NL/UK)}$$

3.1.1 Interconnectors and time frame

Initially, we wanted to analyze all interconnectors connected to NO2, which also includes NO1 and NO5 domestically. We therefore analyzed the number of bottlenecks and the share relative to the number of days the interconnector has been operational, viewed in table 3.1.

	NO2 - NO1	NO2 - NO5	NO2 - DK1	NO2 - DE	NO2 - NL	NO2 - UK
Number of bottlenecks	373	480	1313	993	1340	701
Share of bottlenecks	28%	36%	98%	99.6%	100%	100%
N	1340	1340	1340	997	1340	701

Table 3.1: Number and share of bottlenecks for interconnectors towards NO2 (2020-2023)

From table 3.1 we see that from Norway to abroad, there have almost been bottlenecks present each day that the interconnectors have been operational between 2020 and 2023, and for NL and UK it has been present every single day. As bottlenecks are much more prominent abroad than domestically, we chose to exclude NO1 and NO5, and rather focus on the interconnectors abroad as this would be more interesting to analyze due to the large shares of bottlenecks. Fewer bottlenecks domestically could be due to that weather and production are much more similar and therefore have less effect on the price differences measured between the areas. It could also lead to problems with multicollinearity and most likely not have that much effect on the price differences in our regression model. Based on this, we will therefore focus on the interconnectors between NO2 and countries abroad. In figure 3.1 we can see the evolution of bottlenecks abroad, viewed as the daily price difference between NO2 and abroad.

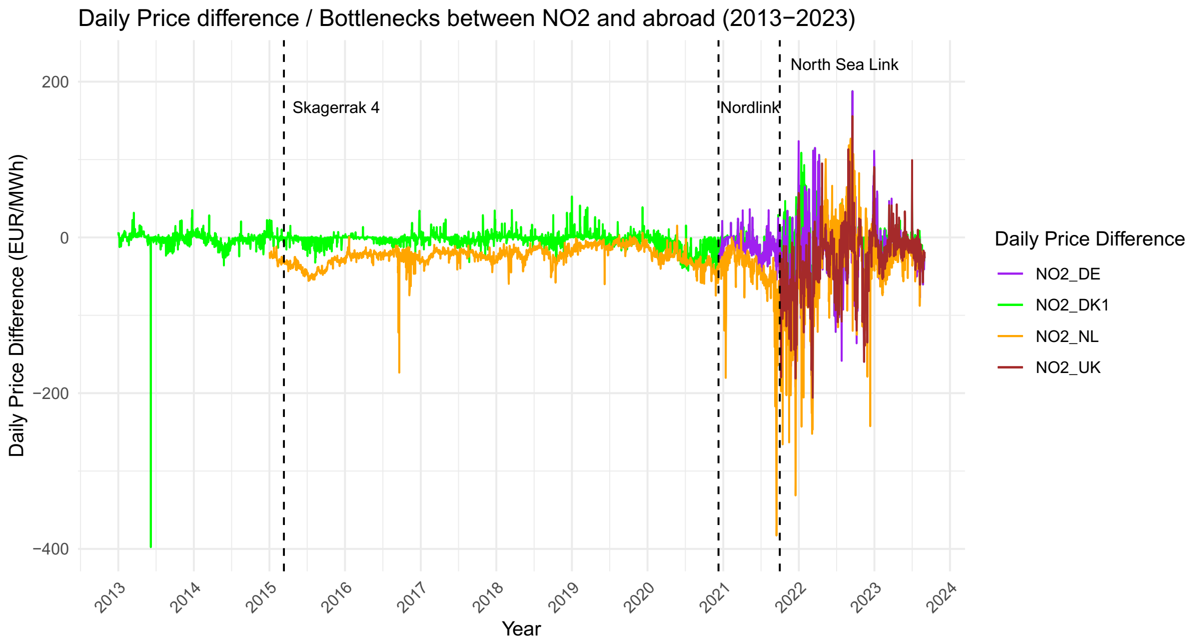

Figure 3.1: Daily Price Difference / Bottlenecks between NO2 and interconnectors abroad (2013-2023)

Each price area is represented in different colors, showing the development of each price area's spot price. Before 2020, price differences appear to be quite stable with less severe spikes, particularly between NO2 and DK1, and NL, apart from a few outliers. This stability could indicate a period with fewer bottlenecks or a more stable grid interaction between these countries. After 2020, we observe that the spot price increases drastically. This may be due to the fact that production and access to resources within each country mutually influence other countries to a greater extent after the interconnectors went into operation. We also observe a more frequent presence of price spikes since the initiation of the NordLink cable with Germany at the end of 2020 and North Sea Link with the UK in October 2021. Based on this, we decided for the data to begin in 2020 to correspond to when bottlenecks between NO2 and the other price areas (DK1, DE, NL, and UK) began to occur more prominently and lasts until September 1st, 2023.

As the occurrence of bottlenecks is dependent on the existence of a cable that transmits power between the countries, we have used different starting dates for the cables in different countries. Skagerrak, the cable between NO2 and Western Denmark (DK1) has existed since 1977 with a new cable becoming operational in 2015, and NorNed, the cable between NO2 and the Netherlands (NL) has existed since 2008 (Statnett, 2020b). As they both are operational before 01.01.2020 we use this as the starting point for data from NL and

DK1. NordLink, the cable between NO2 and Germany (DE) has been in trial operation in the power market since 09.12.2020 (Statnett, 2020a), and we therefore use this date as the start date. North Sea Link, the cable between NO2 and the United Kingdom (UK) has been operational since 01.10.2021 (Statnett, 2021), and we therefore use data from this date. For DE and UK, we have chosen to use the trial operation start date instead of the date for the ordinary operations, because the date of the trial operation is when the cables between the countries started to open for trading on the power exchange. From then on, one should observe bottlenecks if there are different prices between the price areas.

3.1.2 Descriptive statistics of the data set

In figure 3.2, we can see the daily price difference between NO2 and abroad, based on the days that the price areas have had physical energy flows through the interconnectors from 2020-2023. In table 3.2, there are more descriptive statistics for our data set.

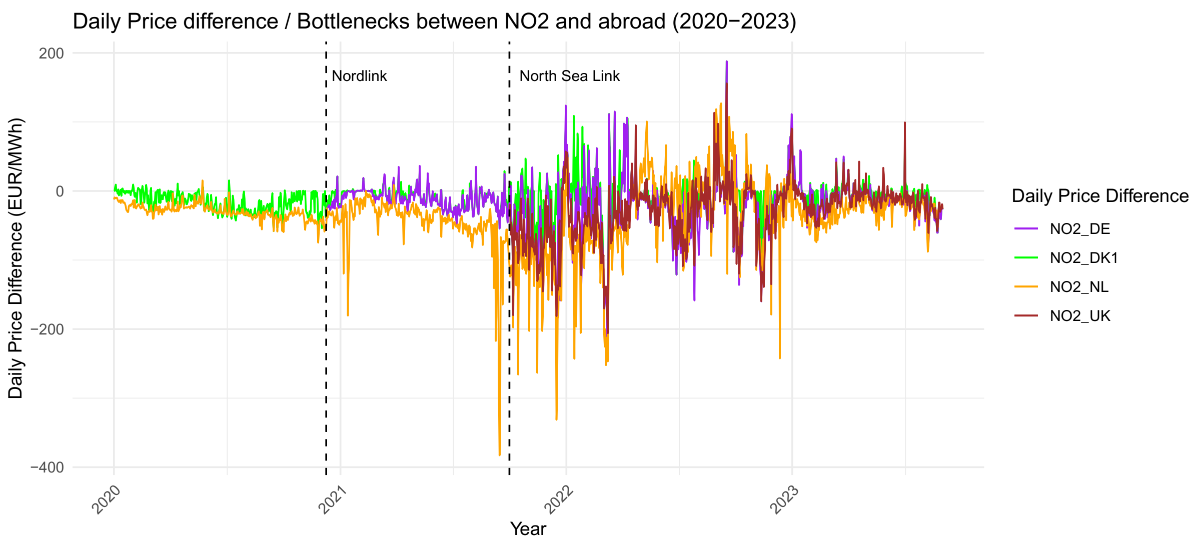

Figure 3.2: Daily Price Difference / Bottlenecks between NO2 and interconnectors abroad (2020-2023)

Price Difference	NO2 - DK1	NO2 - DE	NO2 - NL	NO2 - UK
Minimum	-217.46	-224.02	-382.83	-205.95
Maximum	187.88	187.88	126.95	155.87
Mean	-11.05	-20.40	-38.15	-29.46
Median	-8.06	-14.56	-31.52	-20.52
Standard Deviation	30.10	39.95	46.84	42.27
N	1340	997	1340	701

Table 3.2: Descriptive statistics for bottlenecks with cables between NO2 and abroad

In general, as our dependent variable is defined as the price difference between NO2 and each price area abroad, the values are mostly negative because the prices abroad most of the time are higher than in NO2. This is shown in the mean and median, as the values for all combinations are negative. For the price difference between NO2 and DK1, the mean and median are closer to zero compared to the other combinations, suggesting a more balanced price difference over time. The standard deviation is the lowest among the combinations, indicating less volatility. Further, the introduction of the NordLink cable on 09.12.2020 seems to have had an impact on the price differences between NO2 and DE. Although the mean is negative, indicating that on average prices were lower in NO2 than in Germany, the maximum price difference is equal to the one with Denmark, and the standard deviation is higher, suggesting greater volatility. The NO2 and NL combination exhibits the largest negative mean, suggesting lower prices at NO2 compared to the Netherlands. The standard deviation is the highest, indicating the greatest volatility, which could suggest significant bottlenecks. Lastly, the cable to the UK opened on 01.10.2021 and therefore has fewer observations. Despite this, the price differences show considerable volatility and a negative mean, suggesting the presence of bottlenecks that may have been addressed by the new cable.

3.2 Interconnectors

To capture the effect of the opening of interconnectors in the relevant period from 2020-2023, we have introduced two dummy variables for NordLink and North Sea Link. We find it interesting to analyze 1) the effect prior to the first new interconnector between 2020-2023, 2) between the first and the second new interconnectors, and 3) after the second interconnector. NordLink was opened on December 9th, 2020, and observations prior to this date will serve as the base period. The first dummy is given the value 1 for every observation after NordLink was opened on December 9th, 2020, until before North Sea Link opened on October 10th, 2021, and a value of 0 for every observation before NordLink opened, and after NSL opened. The second dummy is given the value 1 for every observation after North Sea Link was opened on October 1st, 2021, and a value of 0 for every observation after.

Both NordLink and North Sea Link are built for a maximum capacity of 1400 MW. However, in the trial periods which is the starting point in our data, they were in the beginning restricted to a maximum capacity of 700 MW to maintain the safe operation of the Norwegian power grid (Statnett, 2021). The trial period for NordLink lasted until 31.03.2021, and for NSL until 10.09.2022, before they were in ordinary operation (Statnett, 2023a; Statnett, 2023b). As there has been physical electricity flowing through the interconnectors since the starting date of the trial period, it has been open for trading power, and we therefore find it relevant to include all observations from the starting date for each interconnector in the dummy variables. Both NorNed and Skagerrak were opened before 2020. We do therefore not control for them through dummies, but transmission through measuring price difference between these interconnectors and NO2 are still included in our analysis.

According to economic theory, the establishment of a new interconnector is expected to bring local prices closer to marginal costs, improve security of supply, and reduce reserve requirements (Sapio, 2019; Neuhoff and Newbery, 2005; Newbery et al., 2016; Boffa and Sapio, 2015). Concerning the effects of implementing a new interconnector, it is therefore expected that market integration exercises a downward pressure on electricity prices. This requires a marked-based pricing with no interference from governments.

3.3 Control variables

To control for different factors that affect spot price, we have included several control variables that are relevant to understand how intermittent renewable energy sources affect bottlenecks. In table 3.3 fundamental variables such as weather and production are presented with data granularity and from which source the data is gathered from.

Variables per category	Daily	Data source
Weather data		
Daily Mean Windspeed, m/s	X	NCCS, DMI, DWD, KNMI, Met Office
Daily Precipitation Amount, mm	X	
Daily Sunshine Duration, hours	X	
Production data		
Wind production, MW	X	Elhub, Entso-E, National Grid ESO
Solar production, MW	X	
Hydro production, MW	X	

Table 3.3: Variables in data set

When estimating the models for NO2, DK1, DE, NL, and UK, it is important to note that the variables for weather data and production data are consistently measured in the same unit, either meters per second (m/s), millimeters (mm), hours, or megawatt (MW).

3.3.1 Weather data

To control the effect weather has on spot prices in NO2, DK1, DE, NL, and UK, we assess that the relevant variables to look at are data on wind speed, sunshine duration, and precipitation amount. We have chosen to only include sources for each country that constitute a substantial share of their power production mix. For Norway, this means that we exclude sun and solar variables as this energy source contributes with minimal production, and abroad we exclude precipitation and hydro, as there almost is no hydro production in the relevant countries abroad. As we want to analyze daily price differences, these variables are all measured daily. The relevant measurements of the variables for each area are as presented in table 3.3.

To find representative locations for weather stations with measurements of the variables used, we have been in contact with each country's meteorological institute. The decision on which weather station to use is based on a trade-off between the areas with the highest density of production of intermittent energy sources, proximity to the area where the cable is located, that the location is representative of several types of weather and access to data at the station. This decision basis gives representative weather measurement data for our analysis, as they are near where the energy production is located.

As previously mentioned, hydropower allows for strategic management of water resources, adjusting the supply of hydroelectricity when it is more profitable. This is highly relevant for understanding weather variables in NO2, as hydropower stands for about 90% of the Norwegian power mix (Statista, 2023c). Based on the presented bathtub diagram by Førsund (2007), water is reallocated by producers to high-price periods, and this arbitrage leads to identical prices. As water inflows affect the average price over a year, different inflows in different periods are reallocated, which is a process over a year. Therefore, precipitation per day in NO2 is not expected to have a direct effect on price difference, but rather that the total amount of water available per year affects the price change. Further, we understand that when about 90% of the Norwegian energy production comes from hydro and can be managed strategically, daily change in wind in NO2 is expected not to have a significant effect on electricity prices. When there is no wind, hydro producers will produce electricity, and when there is a lot of wind, the hydro producers will most likely stop or reduce production to save water for future more profitable production. This is because a surplus of electricity would implicate reduced prices, which is not profitable from a supplier's point of view. Based on this, hydro reduces fluctuations in production and balances total production and might lead to wind in NO2 not having a significant effect on the price difference.

For weather variables abroad, the interconnected countries have a larger share of intermittent renewable energy sources, where wind and sun as electricity cannot be stored. We therefore expect that more wind and sun should lead to increased production of renewable energy, and further reduce the price in the country where it is produced. Therefore, the price difference should be positively affected, as the price in the relevant area is reduced whenever production of less costly renewable electricity increases.

3.3.2 Renewable energy production data

In addition to seeing what effect weather has on the price difference, it is clear from the tables with shares of energy production in the Market Description that renewable energy sources stand for a significant share of the total electricity production in the Norwegian, Danish, German, Dutch, and UK market. For Norway, hydro and wind power are the two most prominent renewable energy sources, while wind and solar are most prominent for Germany and the Netherlands, and wind is most prominent in Denmark and the UK. Given that our analysis studies data of a daily unit, we had to transform the data accordingly. For some of the countries, power generation was provided for a 15-minute-and 30-minute time interval in the period 2020-2023, and we therefore aggregated the data to daily observations.

3.3.2.1 Wind and solar power

Brouwer et al. (2014) finds that when the share of intermittent renewable energy production increases, the shares of other generators are reduced, which primarily depends on the merit order where the most expensive conventional generators are displaced first. In addition, existing literature by Ballester and Furió (2015) and Sapio (2019) confirm the merit order effects, which find that renewables crowd out more expensive conventional units and therefore put a downward pressure on market-clearing prices (Jensen and Skytte, 2002). Wind and solar power have lower operational costs and produce power when there is access to the relevant power source. Given the accessible production data, we have gathered actual generation for wind and solar production. Based on the literature, we expect that an increase in wind- and solar production abroad should reduce the price locally and that this has a positive effect on price differences from abroad.

3.3.2.2 Hydro production

Hydropower is a highly flexible and stable energy source, namely what we call a dispatchable energy source, contrary to intermittent energy sources that are non-dispatchable. For hydropower, water can be stored in reservoirs until needed, allowing for quick changes in production and low start and stop costs (Statkraft, n.d.). It is therefore one of the energy sources in the merit order to produce low-cost electricity when production is sufficient to meet demand. In addition, we know from the bathtub model that producers decide when they want to reallocate the production of hydropower, based on when the prices are high (Førsund, 2007). We therefore expect the coefficient for hydro production to be negative in NO2, as an increase in production should lower the price, and expect this variable to be highly significant.

Hydropower in NO2 consists of both hydroelectric power plants and hydro run-of-river power stations. After an inquiry with NVE, we were enlightened that the hydro run-of-river production is intermittent, but in some of the larger river systems, there can be power stations that benefit from regulated hydro reservoirs that are located higher up in the river system. The variable for hydro production from Elhub data is the aggregated total hydro production in Norway. We were therefore not able to find data that splits hydropower and hydro run-of-river power and we have chosen to use the hydro variable for NO2, even though we are aware that some of this power to some degree is intermittent. It is also relevant to mention that hydro run-of-river exists in the countries abroad (Germany and the UK), but as mentioned previously, due to the small amount of the total share (2.9% or less), we would expect it to have a limited effect on the daily spot price difference.

3.3.3 Season variables

The models include monthly dummy variables to control for seasonal effects on price differences. Seasons can impact by affecting weather and production, as it is more likely to be much more sun in the summer months, and more wind and rain in the winter months. January will serve as the base period for the monthly dummies, and we therefore include dummies for February to December. We expect different countries to experience seasons differently due to their geographic and climatic conditions, which would influence energy production, especially with renewable sources like wind and solar. Also, consumption patterns can vary significantly due to cultural, economic, or social reasons, which may not be equal across the regions.

3.3.4 Country variables

To control for the effect each country has on price difference we include a dummy for each country, with Denmark (DK1) serving as the base country. The country variables take the value of 1 if the interconnector area is DE, NL, or UK, and a value of 0 if not. As Denmark is the country that Norway exports most power to, we expect the coefficients for DE, NL, and UK to be negative as they relative to DK1 should have a lower effect on price difference (SSB, 2022).

4 Methodology

In this study, we have chosen to apply Ordinary Least Squares (OLS) and pooled OLS regression to analyze the effect of weather on the price difference between various price areas. Our choice of method is based on several key considerations that we will explain in more detail below.

Different approaches can be applied to study the effect of weather and production on price differences between price areas. Looking at similar research that studies the effect of interconnectors on electricity prices, such as Sapio (2019), the most common regression model used is quantile regression. Quantile regression was first introduced by Koenker and Bassett (1978). It is a method that seeks to estimate the conditional relationship between the dependent variable and the independent variables for different quantiles. The advantage of quantile regression lies in its ability to model a linear regression line for each quantile. This approach facilitates the examination of any given position within the distribution and offers a richer insight into how the dependent variable distribution is affected by the independent variables (Hao and Naiman, 2007). Further, it allows for a more comprehensive understanding of the independent variables' effect.

However, even though quantile regression gives insight into the whole distribution of the dependent variable it is in our case important to understand the average effect of weather on price difference rather than specific points in the distribution. This is because both weather, production, and price data are extremely volatile, and the time frame is over several years. Hence, using the OLS approach seems more reasonable as it models the relationship between the independent variables and the conditional mean of the dependent variable. Besides, there are several difficulties with quantile regression. The downside is that its interpretation is less intuitive than linear regression. Quantile regression coefficients indicate how much a specific quantile in the outcome distribution shifts with a one-unit increase in the control variable, which can be more complex to understand and convey than the average difference of linear regression. Furthermore, interpreting multiple quantile regression coefficients across the entire range of quantiles can be more complicated than interpreting a single measure from linear regression (Beyerlein, 2014).

In addition to quantile regression, we discussed modeling bottlenecks as a binary dependent variable, with 1 indicating the presence of bottlenecks and 0 denoting their absence, a logistic regression model. However, we believe that would exclude interesting information about the signs and sizes of the coefficients as they would only give us the likelihood of the presence of bottlenecks from different weather patterns, and not in which direction the bottleneck would occur. Hence, by using a discrete dependent variable as price difference being an indicator of bottlenecks we could find in what way the bottleneck occurs. Where the price difference is equal to zero there are no bottlenecks, and both negative and positive values for price difference indicate the existence of a bottleneck. With a logistic regression model, this would not be captured.

Our discussion also included the decision between using absolute or relative values for the dependent variable, the price difference. By conducting regression analyses using both methods, we determined that absolute values were more fitting for our purposes. This decision was driven by the observations that relative values yielded results of minimal size that were more challenging to interpret.

4.1 OLS

The OLS regression framework is used to analyze the effects of weather and production on the price difference for each country connected to NO2. In our model, we have decided to have two OLS regression models for each interconnection combination with NO2, one for weather variables and one for production variables. This is to account for potential multicollinearity between weather and production variables. When electricity production comes from hydro, solar, or wind production, it most likely correlates with the different weather conditions, respectively precipitation, sunshine, and wind. In addition to taking multicollinearity between weather conditions and production data into consideration, we have included seasonal dummies to control for regular patterns in the data that correlate with weather conditions, thus isolating the unique effects of our variables of interest. Based on this we present our OLS regression model, individually for DK1 but the same setup applies for NL, DE, and UK as well:

Weather

$$
\begin{aligned}
P^{NO2} - P^{DK1} = \beta_0 &+ \beta_{w_{NO2}} \text{Wind}^{NO2} + \beta_{P_{NO2}} \text{Precipitation}^{NO2} \\
&+ \beta_{W_{DK1}} \text{Wind}^{DK1} + \beta_{S_{DK1}} \text{Sunshine}^{DK1} \\
&+ \gamma_{Feb} D^{Feb} + \gamma_{March} D^{March} + \gamma_{April} D^{April} \\
&+ \gamma_{May} D^{May} + \gamma_{June} D^{June} + \gamma_{July} D^{July} \\
&+ \gamma_{Aug} D^{Aug} + \gamma_{Sept} D^{Sept} + \gamma_{Oct} D^{Oct} \\
&+ \gamma_{Nov} D^{Nov} + \gamma_{Des} D^{Des} + \varepsilon
\end{aligned} \tag{4.1}
$$

Production

$$
\begin{aligned}
P^{NO2} - P^{DK1} = \beta_0 &+ \beta_{w_{NO2}} \text{Wind}_{\text{prod}^{NO2}} + \beta_{H_{NO2}} \text{Hydro}_{\text{prod}^{NO2}} \\
&+ \beta_{W_{DK1}} \text{Wind}_{\text{prod}^{DK1}} + \beta_{S_{DK1}} \text{Solar}_{\text{prod}^{DK1}} \\
&+ \gamma_{Feb} D^{Feb} + \gamma_{March} D^{March} + \gamma_{April} D^{April} \\
&+ \gamma_{May} D^{May} + \gamma_{June} D^{June} + \gamma_{July} D^{July} \\
&+ \gamma_{Aug} D^{Aug} + \gamma_{Sept} D^{Sept} + \gamma_{Oct} D^{Oct} \\
&+ \gamma_{Nov} D^{Nov} + \gamma_{Des} D^{Des} + \varepsilon
\end{aligned} \tag{4.2}
$$

4.2 Pooled OLS

To assess the collective impact of interconnectors on price difference with NO2, we implement a pooled OLS regression. This approach enables the examination of how bottlenecks vary based on weather and production, not only over time but also across different geographical areas. This model is beneficial for analyzing data that spans multiple entities and time periods (Baltagi, 2020). By pooling the data, we leverage a larger sample size, increasing the robustness of our findings. We therefore present our Pooled OLS regression model in equations 4.3 and 4.4. The inclusion of season dummies accounts for seasonal trends as mentioned above. Country dummies control for the individual effects of each country, and interconnector dummies account for the effects of a new interconnector.

Weather

$$
\begin{aligned}
P^H - P^A = {} & \beta_0 + \beta_{w_{NO2}} \text{ Wind}^{NO2} + \beta_{P_{NO2}} \text{ Precipitation}^{NO2} \\
& + \beta_W \text{ Wind}^{\text{abroad}} + \beta_S \text{ Sunshine}^{\text{abroad}} \\
& + \gamma_{DE} D^{DE} + \gamma_{NL} D^{NL} + \gamma_{UK} D^{UK} \\
& + \gamma_{Feb} D^{Feb} + \gamma_{March} D^{March} + \gamma_{April} D^{April} \\
& + \gamma_{May} D^{May} + \gamma_{June} D^{June} + \gamma_{July} D^{July} \\
& + \gamma_{Aug} D^{Aug} + \gamma_{Sept} D^{Sept} + \gamma_{Oct} D^{Oct} \\
& + \gamma_{Nov} D^{Nov} + \gamma_{Des} D^{Des} \\
& + \gamma_{\text{Post\_NordLink}} D^{\text{Post\_NordLink}} + \gamma_{\text{Post\_NSL}} D^{\text{Post\_NSL}} \\
& + \varepsilon
\end{aligned} \tag{4.3}
$$

Production

$$
\begin{aligned}
P^H - P_A = {} & \beta_0 + \beta_{w_{NO2}} \text{Wind}_{\text{prod}^{NO2}} + \beta_{H_{NO2}} \text{Hydro}_{\text{prod}^{NO2}} \\
& + \beta_W \text{Wind}_{\text{prod}^{\text{abroad}}} + \beta_S \text{Solar}_{\text{prod}^{\text{abroad}}} \\
& + \gamma_{DE} D^{DE} + \gamma_{NL} D^{NL} + \gamma_{UK} D^{UK} \\
& + \gamma_{Feb} D^{Feb} + \gamma_{March} D^{March} + \gamma_{April} D^{April} \\
& + \gamma_{May} D^{May} + \gamma_{June} D^{June} + \gamma_{July} D^{July} \\
& + \gamma_{Aug} D^{Aug} + \gamma_{Sept} D^{Sept} + \gamma_{Oct} D^{Oct} \\
& + \gamma_{Nov} D^{Nov} + \gamma_{Des} D^{Des} \\
& + \gamma_{\text{Post\_NordLink}} D^{\text{Post\_NordLink}} + \gamma_{\text{Post\_NSL}} D^{\text{Post\_NSL}} \\
& + \varepsilon
\end{aligned} \tag{4.4}
$$

5 Results

Based on the presented model and data, we can look at the effect weather and production have on the price difference between NO2 and the countries abroad. As mentioned previously, hydropower introduces a different dynamic to the analysis as it can be strategically managed. We will therefore firstly present how hydropower affects price difference, and why weather variables in Norway are likely not to have meaningful coefficients as hydro can balance total production in Norway. Thereon we will present the results of our regressions and the effect of weather and production abroad on price differences.

5.1 Hydro power's effect on price difference

To get a better understanding of how the production of electricity from hydropower in Norway affects price difference, it is relevant to present how a wet- or a dry year influences whether there is export or import. Based on this, we analyzed the direction of bottlenecks between NO2 and the countries abroad, to see whether wet years and dry years affect the price difference in our data. This is measured through, respectively, if there is a positive or negative price difference between NO2 and abroad.

From the bathtub model presented by Førsund (2007), we expect wet years with high levels of precipitation to decrease the electricity price in Norway in the relevant year, leading to more exports. This is because hydro producers can sell for a higher price abroad. During times of less precipitation, the opportunity cost of selling at that time compared to wet seasons will be high for hydro producers and they will delay production until the next wet period refills the reservoirs, leading to more import. Therefore, we expect more exports in wet seasons as the price should be lower in NO2, and more imports in dry seasons. At the end of 2020 the filling level of water magazines in NO2 was 88.6, at the end of 2021 it was 49.6, and at the end of 2022 it was 63 based on numbers from NVE (2021a, 2023b). We therefore know that 2020 was a wet year and 2021 and 2022 were drier years.

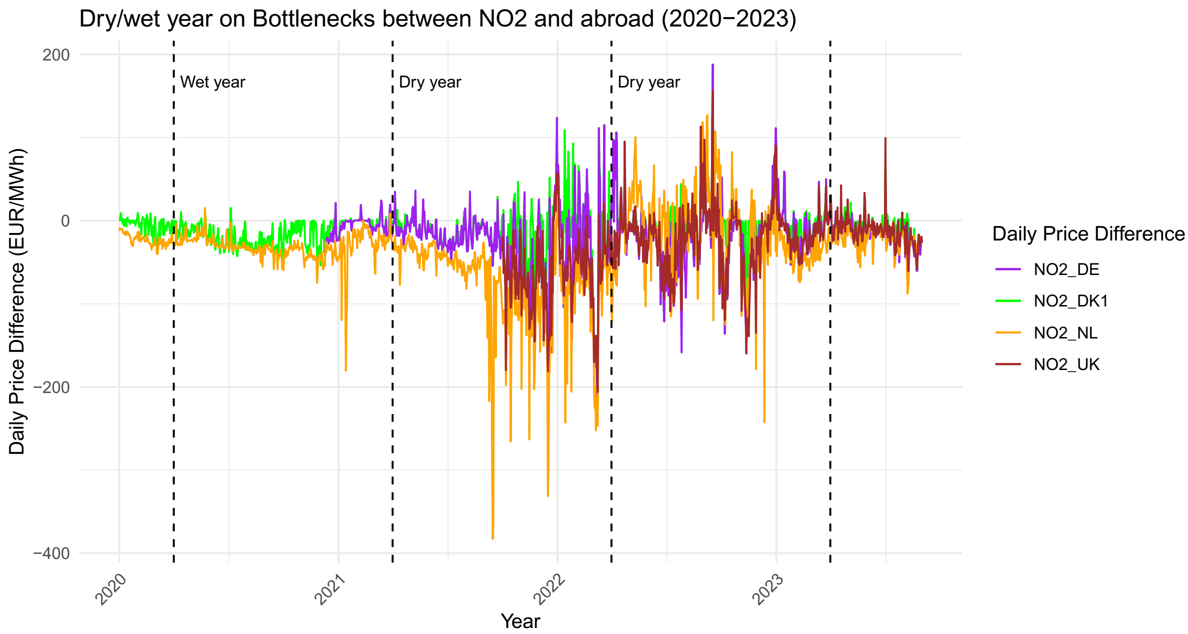

Figure 5.1: Periods for wet and dry year analysis

To get a representative measure, we divide the periods from April - March to understand how snowmelt and precipitation affect dry and wet years. We will therefore analyze three periods: from April 2020 – March 2021, April 2021 – March 2022, and April 2022 – March 2023. The analysis considers the direction of the bottleneck as export from NO2 when the price difference is negative and import to NO2 when the bottleneck is positive. This is because when the price difference is negative, the price in NO2 is lower than abroad, and NO2 can thus sell electricity at a higher price abroad. Conversely, when the price difference is positive as the price in NO2 is higher than abroad, hydro producers choose to not sell until they can be paid a higher price. We only include days when the interconnectors have been operational to get a realistic view of import and export. This share is presented in table 5.1.

Period	Connection	Positive sign (%)	Negative sign (%)
2020-04 to 2021-03	NO2 to NO2_DK1	10.41	83.01
2020-04 to 2021-03	NO2 to NO2_DE	23.01	73.45
2020-04 to 2021-03	NO2 to NO2_NL	0.82	99.18
2020-04 to 2021-03	NO2 to NO2_UK	0.00	0.00
2021-04 to 2022-03	NO2 to NO2_DK1	29.86	70.14
2021-04 to 2022-03	NO2 to NO2_DE	17.53	82.47
2021-04 to 2022-03	NO2 to NO2_NL	1.37	98.63
2021-04 to 2022-03	NO2 to NO2_UK	7.69	92.31
2022-04 to 2023-03	NO2 to NO2_DK1	33.70	66.03
2022-04 to 2023-03	NO2 to NO2_DE	23.84	76.16
2022-04 to 2023-03	NO2 to NO2_NL	34.79	65.21
2022-04 to 2023-03	NO2 to NO2_UK	21.92	78.08

Table 5.1: Percentage share of bottleneck direction (Positive=import, negative=export)

Based on data from NVE (2021a, 2023b) April 2020 – March 2021 was considered a wet year. From our analysis, we observe a higher proportion of negative price differences (export) across all connections. This aligns well with our expectations of increased exports from Norway in a wet year, as there is increased hydropower production. There was no cable between NO2 and the UK in this period, therefore resulting in no import or export.

In April 2021 – March 2022 we notice an increase in the share of positive price difference (import) and a decrease in the share of negative price difference (export) for connections to DK1 and NL. This indicates a shift to a drier year with reduced hydropower production in Norway, leading to an increased need for import. This is what we expect based on NVE data on reservoir filling levels in Norway.

However, we see a reduction in positive price difference from 23.01% to 17.53% from the wet year to the following dry year for price difference to Germany. This suggests that there was less import to Norway from Germany in 2021-2022 compared to 2020-2021. In addition, there was an increase in negative price difference, indicating more exports from Norway to Germany in 2021-2022. This observation is somewhat unexpected given the expectation that a drier year should lead to increased imports to Norway. However, a report written by Sintef (2022) gives more context to how this can be explained by the strategic decision hydropower producers in Norway made in the fall of 2021. The producers anticipated a decline in electricity prices at the beginning of 2022 in Europe based on their forecasts, and therefore increased production a lot in the fall of 2021 when the price was high, despite low water levels in the reservoirs. This is more beneficial for the producer as Førsund (2007) and the bathtub diagram explain, and leads to long periods of positive price difference (lowest price in Norway), despite it being largely a dry year. This is the explanation of why we see more exports and fewer imports in 2021 than we would expect as it largely was a dry year.

In April 2022 – Mars 2023, we see the expectations for a drier year more clearly than in the first period (2020-2021). The increase in positive price difference (increased import) and a decrease in negative price difference (reduced export) compared to the wet year (2020-2021), suggests that this was also a relatively dry year. This aligns with the expectations that in drier years, Norway would import more energy to conserve water production and export less. This period is not drier than the previous one and based on the explanation from the Sintef (2022) report, the producers probably limited their expectations of reduced price, but could also not produce that much more hydropower as the reservoir levels were low. This also contributed to more imports in the 2022-2023 period as prices were lower abroad.

To summarize, we see that in the wet year of 2020, there is a significant share of exports from Norway, while in the drier years of 2021 and 2022, there is an increase in imports. We expected to see more imports in the driest period of 2021-2022, but the increase in production and subsequently exports due to hydro producers' expectations of lower prices in the following year, explains why we do not see this in our analysis. However, our analysis still substantiates that wet years lead to more hydro production and consequently more export abroad and dry years lead to savings of water and less production, and consequently more import in Norway.

As we have seen in table 5.1, hydropower permits a regulated release of water, balancing fluctuations in supply and prices that might otherwise occur due to intermittent weather conditions, as in the two-period diagram previously presented by (Førsund, 2007). Consequently, while increased wind speed is generally expected to reduce electricity prices due to increased production, the large share of hydro production in NO2 might seem to obscure this effect. We expect precipitation in Norway not to have a direct effect on price differences as the production of hydroelectricity is regulated over a year. Similarly, we expect wind in Norway not to have an effect as hydro production accounts for the fluctuations in intermittent production.

5.2 Day-to-day regression results

In our study, we have employed both OLS and pooled OLS regression models to capture the effect weather conditions and production sources have on the price difference. An underlying premise of our analysis is that an increase in the availability of intermittent resources such as wind or solar energy leads to a corresponding increase in electricity generation. This is due to the characteristics of intermittent energy sources, as their non-dispatchable nature requires immediate production when the resource is available. Conversely, hydroelectric power is a dispatchable renewable energy source, which introduces a different dynamic to the analysis as it can balance total production.

The results are presented in the sections below. The results include five regression tables, one for each specific country combination with NO2 (NO2-DK1, NO2-DE, NO2-NL, NO2-UK), along with a consolidated pooled regression model for NO2 and abroad. The pooled model aggregates all countries with NO2 under a collective unit, employing dummy variables to determine the individual impact of each country on the price difference in relation to NO2. Model 1 in each regression table is dedicated to analyzing the influence of weather conditions on the price difference between the countries. Model 2 in each regression table studies the impact of renewable energy production on the price difference for each combination. The analytical approach to studying weather and production in two different models is to address the uncertainty that increased weather not necessarily indicates that the resource is directly converted into electricity. This is why we have included model 2, which focuses on capturing the actual production's impact on price difference. Including both weather and production models is done to reinforce the effect of weather on the price difference, through whether it has a similar effect as production on the price difference. Our focus is therefore mostly the weather variables, but is substantiated by the production variables.

5.2.1 NO2

Based on hydro power's effect on price difference in Norway, we do not expect wind and precipitation in NO2 to have a direct impact on the price difference. However, looking at the production variables in all regressions presented below, it is clear that over the years, hydro production and wind production in NO2 have a significant effect on price differences. In all regressions, wind production in NO2 indicates a highly significant negative relationship with the price difference, denoting that an increase in wind energy production in NO2 is strongly correlated with a decrease in price in Norway. Hydro production in NO2 also shows a significant negative effect on price differences, highlighting the role of hydro as a flexible and dispatchable source of energy that can be utilized to balance the market and reduce price differences. This reflects the effect of increasing the supply of a lower-cost energy source, which is expected to decrease local prices and consequently price differences with other markets. Further, we will now look at each combination of interconnectors abroad and subsequently the impact weather and production have on price differences.

5.2.2 Results: NO2 - DK1

The results from regression model 1 align with these expectations. A key observation is that the daily mean wind speed in DK1 is the only statistically significant weather coefficient. This implies that an increase in daily mean wind speed positively influences the price difference between the two areas. Using supply and demand theory, an increase in available wind resources will lead to increased electricity production of wind, and consequently lower prices in DK1, further increasing the price difference. Consequently, the findings align with theoretical predictions.

In model 2, all production coefficients for DK1 exhibit statistical significance, corresponding to the expectations. The electricity production in DK1 has a positive impact on the price difference, indicating that an increase in production further results in decreased prices in DK1 and hence increased price difference. This outcome is coherent with the principles of supply and demand theory as well, where increased production is likely to result in reduced prices locally and increased price differences between the regions.

For season dummies all months except for April are statistically significant, indicating that seasons affect the price difference. With negative signs, the coefficients reduce price differences in both weather and production models relative to January.

Table 5.2: NO2 - DK1

	Dependent variable:	
	Price_diff_NO2_DK1	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−0.051	
	(0.442)	
Daily_Precipitation_Amount_NO2	−0.027	
	(0.097)	
Daily_Mean_Windspeed_DK1	7.088***	
	(0.586)	
Daily_Sunshine_Duration_DK1	0.138	
	(0.207)	
Hydro_NO2		−0.330***
		(0.00002)
Wind_NO2		−0.472***
		(0.0001)
Solar_DK1		0.293***
		(0.0003)
Wind_DK1		0.469***
		(0.00004)
D_Feb	−12.713***	−10.518***
	(3.403)	(3.034)
D_March	−19.651***	−14.847***
	(3.424)	(3.041)
D_April	−4.834	−6.297*
	(3.597)	(3.299)
D_May	−10.014***	−20.027***
	(3.519)	(3.411)
D_June	−20.263***	−38.165***
	(3.633)	(3.755)
D_July	−18.655***	−39.258***
	(3.446)	(3.548)
D_Aug	−16.568***	−36.177***
	(3.476)	(3.516)
D_Sept	−10.187***	−30.296***
	(3.693)	(3.595)
D_Oct	−14.716***	−29.374***
	(3.609)	(3.365)
D_Nov	−34.208***	−31.677***
	(3.634)	(3.260)
D_Des	−7.871**	−4.922
	(3.608)	(3.256)
Constant	−24.558***	39.810***
	(3.528)	(4.868)
Observations	1,329	1,340
R^2	0.254	0.414
Adjusted R^2	0.245	0.408
Residual Std. Error	26.045 (df = 1313)	23.162 (df = 1324)
F Statistic	29.745*** (df = 15; 1313)	62.461*** (df = 15; 1324)
Note:		*p<0.1; **p<0.05; ***p<0.01

5.2.3 Results: NO2 – DE

In regression model 1, the daily mean wind speed in DE is statistically significant, suggesting a positive influence on the price difference between NO2 and DE. This effect seems reasonable, as increased accessibility to a resource typically leads to heightened production, subsequently lowering local prices. Further, as wind constitutes a large portion of energy production, the results seem reasonable with wind as the only significant weather variable in DE.

In model 2, all production related variables display statistical significance. Wind in DE has a positive impact on the price difference between NO2 and DE, indicating that an increase in production of wind further reduces prices in DE, and hence increases the price difference. This aligns with the supply and demand theory. Solar in DE is on the other hand negative. This is not expected as we would expect more solar production to have the same effect as an increase in wind production. It could for example be due to solar production not being as production effective as wind, but this would need to be further researched.

For season dummies there is less consistency in which months are significant. Apart from April, the significant coefficients are negative and reduce price differences in both weather and production models relative to January.

Table 5.3: NO2 - DE

	Dependent variable:	
	Price_diff_NO2_DE	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−0.096	
	(0.575)	
Daily_Precipitation_Amount_NO2	0.369**	
	(0.160)	
Daily_Mean_Windspeed_DE	5.357***	
	(0.584)	
Daily_Sunshine_Duration_DE	−0.141	
	(0.315)	
Hydro_NO2		−0.343***
		(0.00004)
Wind_NO2		−1.230***
		(0.0001)
Solar_DE		−0.010***
		(0.00001)
Wind_DE		0.016***
		(0.00000)
D_Feb	−3.193	0.075
	(5.367)	(4.759)
D_March	−12.398**	−1.736
	(5.359)	(5.096)
D_April	10.357*	15.284***
	(5.597)	(5.543)
D_May	1.465	0.694
	(5.387)	(6.148)
D_June	−6.283	−9.051
	(5.838)	(6.802)
D_July	−19.712***	−27.112***
	(5.490)	(6.437)
D_Aug	−3.625	−13.454**
	(5.677)	(6.088)
D_Sept	7.810	−3.508
	(5.936)	(6.342)
D_Oct	−17.332***	−33.275***
	(5.924)	(5.673)
D_Nov	−56.054***	−50.550***
	(5.932)	(5.174)
D_Des	−6.907	−1.894
	(5.331)	(4.644)
Constant	−39.611***	29.187***
	(5.785)	(8.844)
Observations	969	997
R^2	0.233	0.422
Adjusted R^2	0.220	0.413
Residual Std. Error	35.354 (df = 953)	30.596 (df = 981)
F Statistic	19.252*** (df = 15; 953)	47.787*** (df = 15; 981)
Note:		*p<0.1; **p<0.05; ***p<0.01

5.2.4 Results: NO2 – NL

In regression model 1, the daily mean wind speed in the Netherlands is statistically significant, indicating a positive effect on the price difference. This is the same effect we have observed in previous regressions. Concerning production variables in model 2, we see that solar and wind are positive statistically significant as well, implying a positive impact on the price difference.

For season dummies there is less consistency in which months are significant. Five summer months are positive, and three winter months are negative in model 1, and in model 2 all months for July to December are negative relative to January.

Table 5.4: NO2 - NL

	Dependent variable:	
	Price_diff_NO2_NL	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−1.645***	
	(0.594)	
Daily_Precipitation_Amount_NO2	0.467***	
	(0.166)	
Daily_Mean_Windspeed_NL	4.195***	
	(0.999)	
Daily_Sunshine_Duration_NL	0.337	
	(0.326)	
Hydro_NO2		−0.314***
		(0.00004)
Wind_NO2		−1.322***
		(0.0002)
Solar_NL		1.238***
		(0.0005)
Wind_NL		0.031***
		(0.00001)
D_Feb	−0.079	3.623
	(5.833)	(5.616)
D_March	−7.911	−8.414
	(5.841)	(5.706)
D_April	16.666***	3.243
	(5.987)	(6.124)
D_May	27.328***	6.872
	(6.032)	(6.405)
D_June	21.183***	−9.070
	(6.195)	(6.980)
D_July	10.599*	−18.975***
	(5.920)	(6.614)
D_Aug	14.261**	−14.204**
	(5.961)	(6.564)
D_Sept	10.170	−15.225**
	(6.382)	(6.693)
D_Oct	−10.116*	−22.798***
	(6.138)	(6.105)
D_Nov	−24.590***	−22.928***
	(6.204)	(5.969)
D_Des	−19.923***	−12.415**
	(6.101)	(5.916)
Constant	−47.790***	14.352
	(6.377)	(9.044)
Observations	1,329	1,340
R^2	0.118	0.174
Adjusted R^2	0.108	0.165
Residual Std. Error	44.205 (df = 1313)	42.814 (df = 1324)
F Statistic	11.739*** (df = 15; 1313)	18.585*** (df = 15; 1324)
Note:		*p<0.1; **p<0.05; ***p<0.01

5.2.5 Results: NO2 – UK

In regression model 1, the daily mean wind speed in the UK is statistically significant. An increase in daily mean wind speed is associated with an increase in the price difference. With wind constituting approximately 24.19% of the power generation mix, the results align with the expectations (Our World in Data, 2023).

In model 2, both wind and solar power exhibit statistical significance. The observed relationship indicates that increased production from wind power sources correlates with an increase in the price difference, while increased solar production has a converse effect, reducing the price difference. This pattern for solar production appears to be odd based on expectations from supply and demand theory, which typically states that heightened production leads to a decrease in price. This is the same as solar in DE.

For season dummies there is less consistency in which months are significant. Five summer months are positive, and three winter months are negative in model 1, and in model 2 all months are negative relative to January.

Table 5.5: NO2 - UK

	Dependent variable:	
	Price_diff_NO2_UK	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−1.599** (0.709)	
Daily_Precipitation_Amount_NO2	0.413** (0.197)	
Daily_Mean_Windspeed_UK	2.700*** (0.647)	
Daily_Sunshine_Duration_UK	−0.421 (0.400)	
Hydro_NO2		−0.438*** (0.00004)
Wind_NO2		−1.535*** (0.0002)
Solar_UK		−0.002*** (0.0001)
Wind_UK		0.026*** (0.00001)
D_Feb	−12.455* (6.907)	−11.955* (6.282)
D_March	−8.433 (6.920)	−4.180 (6.438)
D_April	27.711*** (6.969)	8.608 (7.327)
D_May	23.577*** (7.024)	−3.288 (7.878)
D_June	17.630** (7.250)	−18.295** (8.532)
D_July	5.543 (6.948)	−31.630*** (8.007)
D_Aug	20.015*** (7.132)	−16.078** (7.994)
D_Sept	44.903*** (8.308)	−1.769 (9.013)
D_Oct	−19.263*** (6.728)	−40.462*** (6.536)
D_Nov	−46.977*** (6.833)	−44.510*** (6.113)
D_Des	−3.444 (6.766)	2.107 (6.115)
Constant	−34.966*** (7.929)	43.863*** (10.511)
Observations	689	701
R^2	0.241	0.378
Adjusted R^2	0.224	0.364
Residual Std. Error	37.267 (df = 673)	33.701 (df = 685)
F Statistic	14.230*** (df = 15; 673)	27.762*** (df = 15; 685)
Note:		*p<0.1; **p<0.05; ***p<0.01

5.2.6 Pooled regression

To further substantiate our findings, we find it relevant to do a pooled regression to understand the collective effect weather in the countries that have interconnectors to Norway have on price differences. Looking at the weather variables abroad, the impact of wind speed on price difference is significantly positive, implying that increased wind speed in the countries abroad is associated with an increase in the price difference. Sunshine duration abroad does not exhibit a statistically significant relationship with the price difference, which could be due to the lesser share of solar production in today's energy landscape abroad.

Wind production abroad has a positive significant effect on the price difference between NO2 and abroad. This indicates that when wind production increases abroad, the price difference with Norway increases, likely due to the reduction in prices in local markets abroad as they utilize more wind power. Solar production abroad is negatively associated with price differences but with a smaller coefficient. This suggests that while solar energy contributes to price dynamics, its influence is less substantial, possibly due to its smaller share in the energy mix or the less substantial effect of solar variations on overall market prices.

The influence of the interconnectors NordLink and North Sea Link that opened in the period between 2020 and 2023, is expected to level prices across markets by increasing supply flexibility and reducing bottlenecks. Relative to the base period before NordLink was opened, the post-NordLink period is associated with a significant decrease in price difference in model 1 but is not significant in model 2. However, the post-North Sea Link dummy is significantly negatively correlated with price differences in model 2 but is not significant in model 1. This inconsistency suggests that the anticipated market integration effects might be influenced by various factors not captured in the model. It could also be due to problems with capacity in the opening of NSL, and that NordLink quite early started increasing the capacity in the trial period.

For season dummies there is less consistency in which months are significant. Two summer months are positive, and five winter months are negative in model 1, and in model 2 all months for July to December are negative relative to January.

For the country specific variables, both in models 1 and 2, where DK1 serves as the baseline, the coefficients for DE, NL, and UK are all significantly negative. This indicates that the effect of the country Germany, the Netherlands, or the UK is associated with a lower price difference compared to DK1. This aligns with our expectations, as Denmark is the country that Norway exports most power to, the other countries should have a lower effect on price difference relative to DK1. The size of these coefficients is substantial, suggesting notable differences in the effect on price differences among these countries.

Table 5.6: NO2 - Abroad

	Dependent variable:	
	Price_diff_NO2_Abroad	
	(1)	(2)
Wind_NO2	-0.490^{*}	
	(0.291)	
Precipitation_NO2	0.273^{***}	
	(0.078)	
Wind_abroad	4.339^{***}	
	(0.342)	
Sunshine_abroad	-0.153	
	(0.156)	
Wind_prod_NO2		-0.831^{***}
		(0.0001)
Hydro_NO2		-0.431^{***}
		(0.00002)
Wind_prod_abroad		0.013^{***}
		(0.00000)
Solar_prod_abroad		-0.001^{***}
		(0.00000)
D_DE	-14.001^{***}	-24.863^{***}
	(1.693)	(3.516)
D_NL	-24.877^{***}	-28.537^{***}
	(1.467)	(1.357)
D_UK	-25.762^{***}	-21.731^{***}
	(1.983)	(1.826)
D_Feb	-6.168^{**}	-3.378
	(2.719)	(2.533)
D_March	-11.634^{***}	-9.144^{***}
	(2.721)	(2.490)
D_April	12.128^{***}	1.687
	(2.802)	(2.566)
D_May	10.902^{***}	-9.524^{***}
	(2.772)	(2.664)
D_June	2.714	-26.879^{***}
	(2.891)	(2.862)
D_July	-4.887^{*}	-36.322^{***}
	(2.753)	(2.840)
D_Aug	2.381	-28.728^{***}
	(2.798)	(2.810)
D_Sept	7.695^{**}	-25.931^{***}
	(3.006)	(3.078)
D_Oct	-16.474^{***}	-34.963^{***}
	(2.864)	(2.773)
D_Nov	-39.303^{***}	-36.318^{***}
	(2.896)	(2.693)
D_Des	-10.603^{***}	-5.820^{**}

	(2.791)	(2.605)
D_Post_NordLink	−4.014**	−0.664
	(1.996)	(1.860)
D_Post_NSL	−1.151	−9.335***
	(1.732)	(1.655)
Constant	−19.407***	74.446***
	(3.307)	(3.996)
Observations	4,316	4,378
R^2	0.189	0.294
Adjusted R^2	0.186	0.291
Residual Std. Error	37.387 (df = 4295)	34.890 (df = 4357)
F Statistic	50.154*** (df = 20; 4295)	90.913*** (df = 20; 4357)
Note:		*p<0.1; **p<0.05; ***p<0.01

6 Discussion

To our knowledge there have not been similar studies analyzing and focusing on the effect weather and production have on bottlenecks. Therefore we gained interest in analyzing and discussing our findings and how they can affect climate policies and contribute to supporting climate change, as well as the transmission of electricity in this discussion. Our main focus is the impact of the green transition and increased share of renewable energy influencing the bottlenecks between the Norwegian electricity market (NO2), through interconnectors towards other price areas in Europe.

As outlined in the market description, many countries have already begun to increase the share of renewables in their power production mix, signaling an active progression towards a greener production and economy. Gianfreda et al. (2016) argues that the nature of intermittent energy sources tends to counteract price convergence (increased price difference), primarily due to the growing usage of intermittent energy sources in today‘s electricity markets. Our findings substantiate this, indicating a significant positive correlation between wind and price difference. The impact of wind in each country abroad is found to be statistically significant (apart from NO2 where hydropower balances production) suggesting that wind power substantially influences price difference between Norway and abroad. An increase in average mean wind speed abroad correlates with an increase in wind production, leading to a decrease in electricity prices within the area it occurs abroad, further leading to an increase in price difference. This is shown in our data, supporting our findings that wind coefficients both for weather and production are positively significant. The argument of Gianfreda et al. (2016), aligns with our results as an increasing portion of wind power correlates with an increase in price difference from abroad towards NO2.

However, the impact of solar energy on price differences is less significant compared to wind energy. This could be attributed to smaller fluctuations from solar production and its relatively minor presence in the current energy mix abroad. Additionally, the limited development of solar energy infrastructure might contribute to its limited effect on price differences. However, solar technology is still evolving. This is shown in our production model measuring actual solar energy generation, indicating a small impact of solar power on price differences. This suggests that the current solar energy infrastructure is not yet at a level where it can convert solar energy as effectively as wind energy infrastructure does for wind. It still indicates that solar energy has a significant effect on price difference, and must be taken into consideration when increasing the use of intermittent renewable energy.

As seen in our regression model and descriptive statistics, increased use of intermittent renewable energy abroad affects price differences between areas and hence the occurrence of bottlenecks. The surge in renewable energy production not only strains the grid but also affects electricity market dynamics. When the grid reaches its capacity limits due to intermittent renewable energy surges, supply and demand imbalances arise. These imbalances cause prices to diverge between regions. It is therefore obvious that a large hurdle to achieving the UN Sustainability Goal number 7: Affordable and clean energy, is modernizing the transmission grid to accommodate electrification and renewable energy generation. Investing in transmission system technology that expands the capacity to transfer energy from areas with favorable conditions for renewable energy development to major load centers and that bridge regional divides in energy distribution is crucial to meeting these goals (Hitachi Energy, 2021). While the path to decarbonization of society involves substantial financial commitments and presents various challenges, the long term benefits, spanning economic growth, social advancement, and improved health outcomes are significant. Key to this transition is the strategic planning and investment in the transmission infrastructure, to have efficient energy flow. An example is if the development of wind production increases in areas where there often is a surplus of electricity production it will not help the green transition if there is not enough capacity in the power grid to transmit the electricity to other areas with a deficit of power production. This will therefore only lead to further increases in price differences and bottlenecks. Strategical investments, when aligned with renewable energy initiatives, can significantly contribute to job creation, economic prosperity, and overall societal advancement (Hitachi Energy, 2021).

Further, limited capacity in the power grid can contribute to a slower development of green investments. If we want to increase green development, the challenge for new establishments is the limited capacity in the grid (NVE-RME, 2023). However, it is important to understand that if we want this development, we must also be open to the idea that the expansion of the power grid is necessary to provide energy for green development. It is very clear in our data, as seen in figure 3.1, that bottleneck issues have become more prominent along with the focus on more green development and more green production through intermittent renewables in recent years. Therefore, we can understand our findings as there is a significant need to expand grid capacity near the production of intermittent energy sources because it seems that this is where the most significant bottlenecks occur. Addressing bottleneck issues through the expansion of the grid is crucial to reduce such problems effectively. Price areas are connected through cables, and the price difference depends on the production patterns of these areas and transmission capacity. Investing in the expansion of areas with low capacity can be economically beneficial for the local society. By strategically enhancing infrastructure in these areas, it can reduce bottleneck problems and contribute to a more balanced and efficient energy market.

7 Conclusion

This thesis highlights the importance of dispatchable energy sources and robust power grids to better navigate the complexities of a renewable energy dominated future. This also leads to a need for optimizing available resource use across interconnected electricity markets. Addressing our hypothesis on how the green transition with increasing use of renewable energy, affects bottlenecks between NO2 and international interconnectors, our findings provide relevant insights. We observe that the integration of intermittent renewables like wind significantly affects price differences, substantiating the need for strategic grid enhancements and improvements to reduce bottleneck occurrence.

Our data analysis indicates a significant effect of wind on price differences. This supports our hypothesis that intermittent renewables also significantly impact bottlenecks through price differences. The expansion of intermittent renewable production has a significant influence on price differences, explaining the pronounced effect of wind, which constitutes a significant share of production in countries abroad. In contrast, solar production does not account for a large share of power production and does therefore not show the same effect on price differences. Our analysis suggests that wind, being extensively developed, has a significant effect and that further expansion of intermittent renewable energy could lead to more price differences and hence more bottlenecks. Therefore, it's crucial to also develop dispatchable power sources to balance intermittent energy sources, especially for countries aiming to contribute to the green transition as the intermittent energy sources are part of the solution.

The potential of dispatchable renewable sources, such as hydroelectric power, offers a mitigating effect against fluctuations in power. This highlights the importance of a balanced energy mix, combining both intermittent and dispatchable sources, to navigate the path of the green transition. Developing more production sources that can balance energy strategically will benefit the power grid. The green transition, including the development of technology and potential energy storage solutions, helps to balance price differences, as seen in Norway's hydroelectric production. Innovation and new development are important factors for the green transition to positively impact reducing price differences and the number of bottlenecks.

The increasing reliance on wind and solar power, together with hydroelectricity flexibility, points to a future where energy trade is guided not just by immediate demand and supply but also by strategic considerations of resources and optimal utilization. If Europe wants to reach the UN Sustainability Goals and EU's target to be climate-neutral by 2050, it can be more beneficial to for example invest in infrastructure in areas where the total dynamics of power is exchanged most beneficially. For example, with much hydro production in Norway, it could be more beneficial to build more wind power in the Netherlands, rather than in Norway as we already have a surplus most of the year and therefore export electricity. This is extremely difficult to manage between countries, and to a large degree affected by politics, but we encourage new research to further explore this subject matter to find what is beneficial for society and the climate.

Our study suggests that for a successful transition, investments in both renewable energy sources and grid infrastructure are imperative to ensure reliability and economic efficiency in the energy market. Further research should also therefore investigate the role of energy storage technologies in reducing the challenges caused by intermittent renewable sources. This includes examining how different storage technologies, like battery storage or pumped hydro storage, can help balance the grid and reduce bottlenecks. Extending the research to include a wider range of geographical price areas, especially those with different renewable energy portfolios and grid infrastructures, could also provide valuable insights into how diverse energy mixes impact grid stability and electricity pricing. In addition, future studies should also explore how advancements in renewable energy technologies, grid infrastructure, and energy management systems can facilitate the transition to a more sustainable and efficient energy system.

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Appendices

A Correlation matrix

Figure A.1: Correlation Matrix Denmark Weather

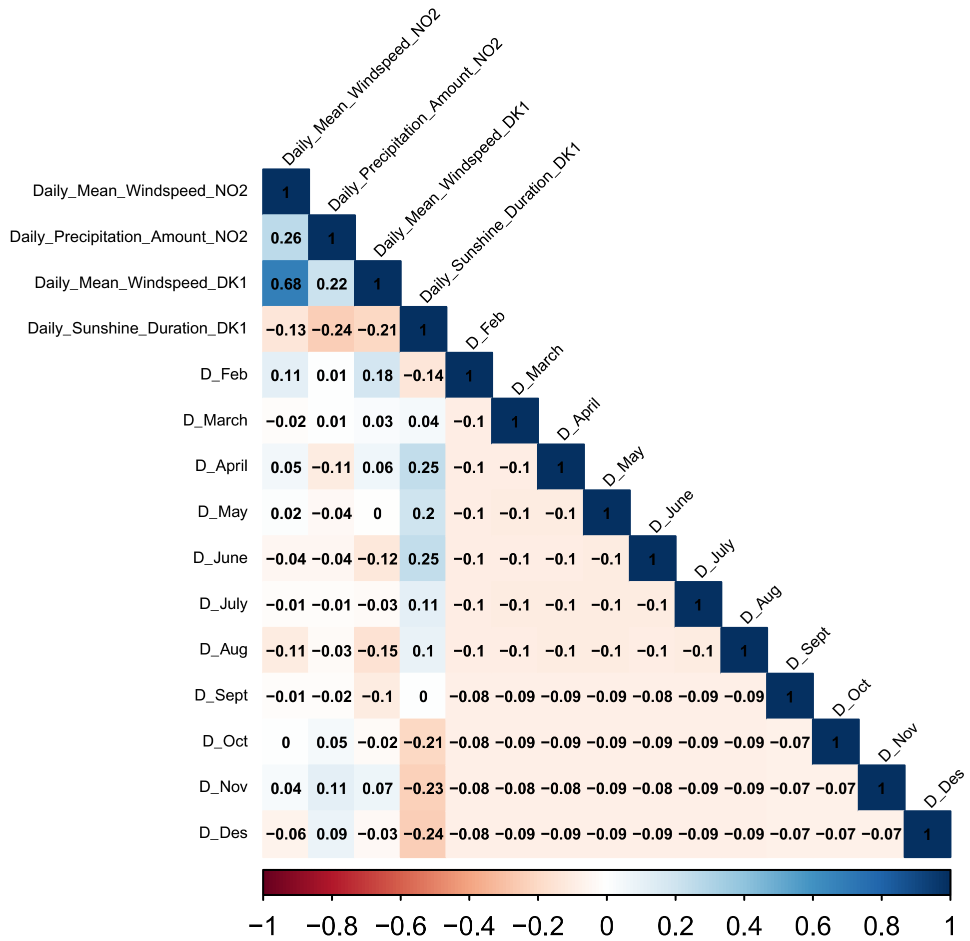


Figure A.2: Correlation Matrix Denmark Production

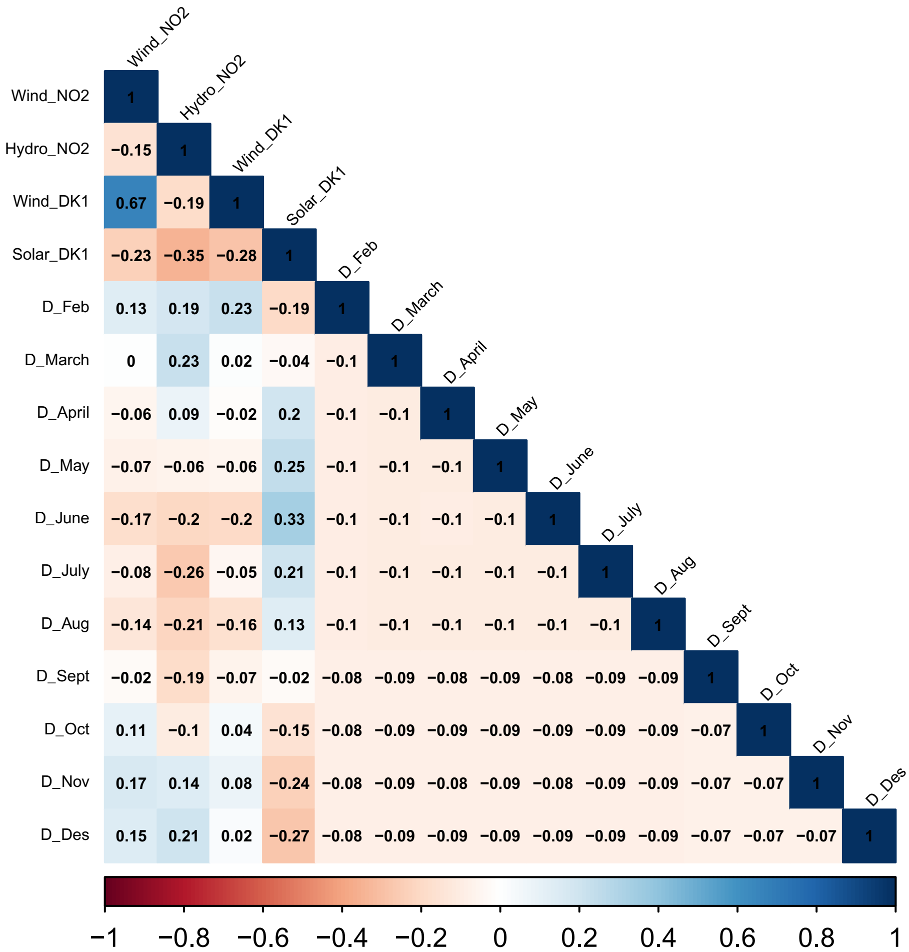


Figure A.3: Correlation Matrix Germany Weather

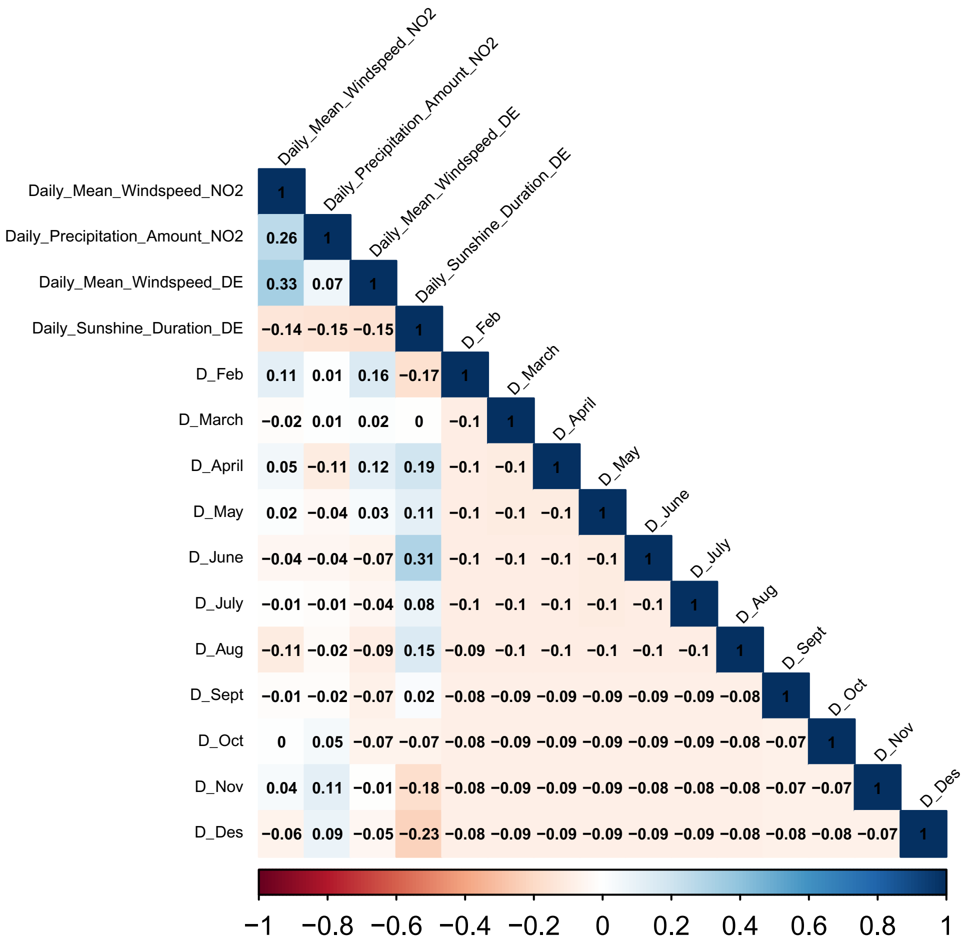


Figure A.4: Correlation Matrix Germany Production

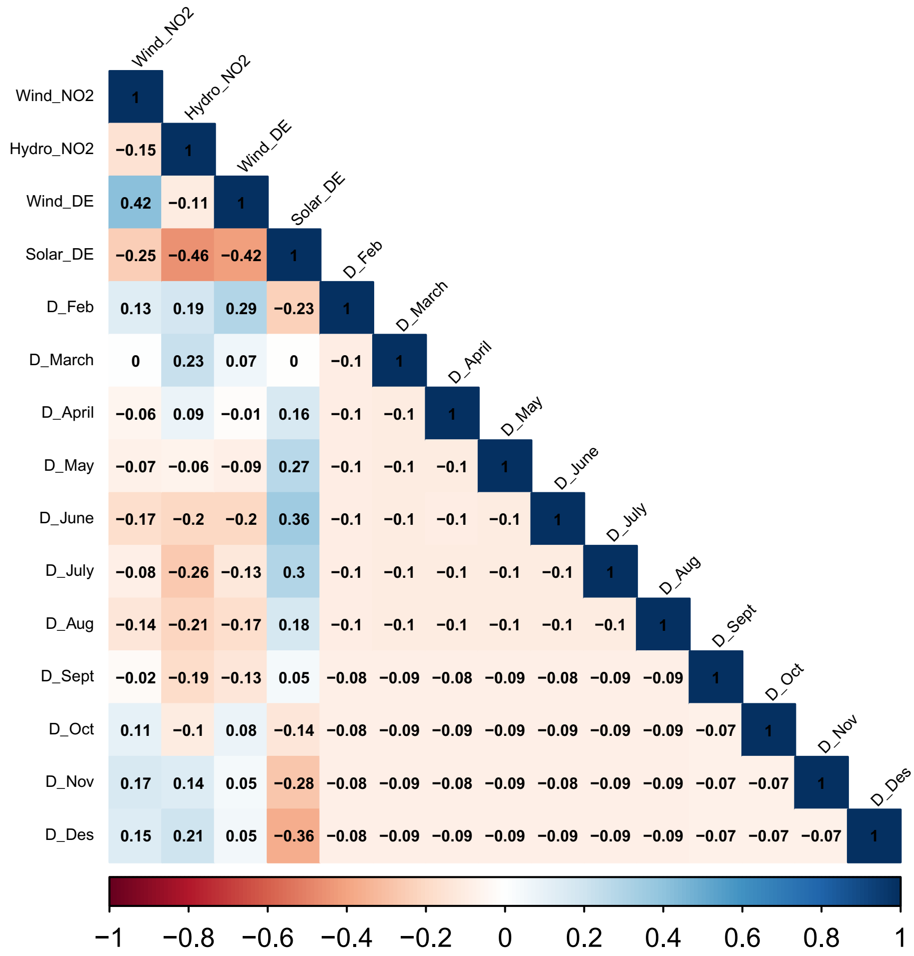


Figure A.5: Correlation Matrix Netherland Weather

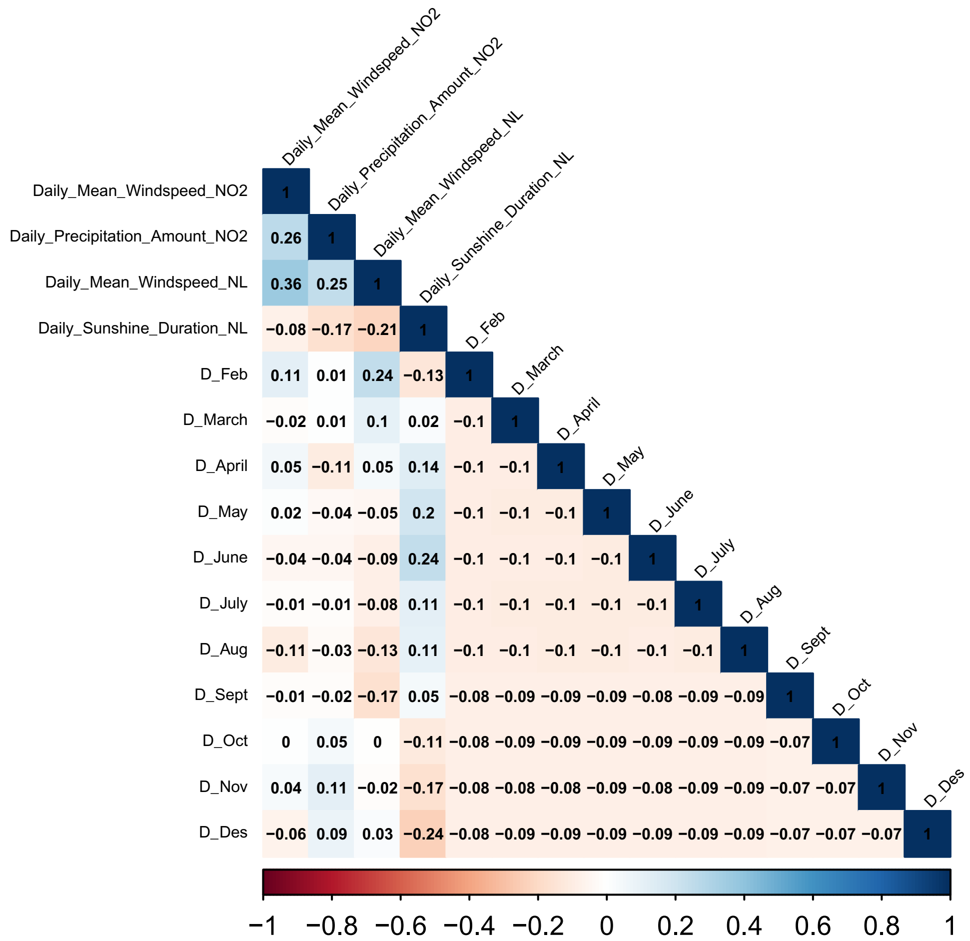


Figure A.6: Correlation Matrix Netherland Production

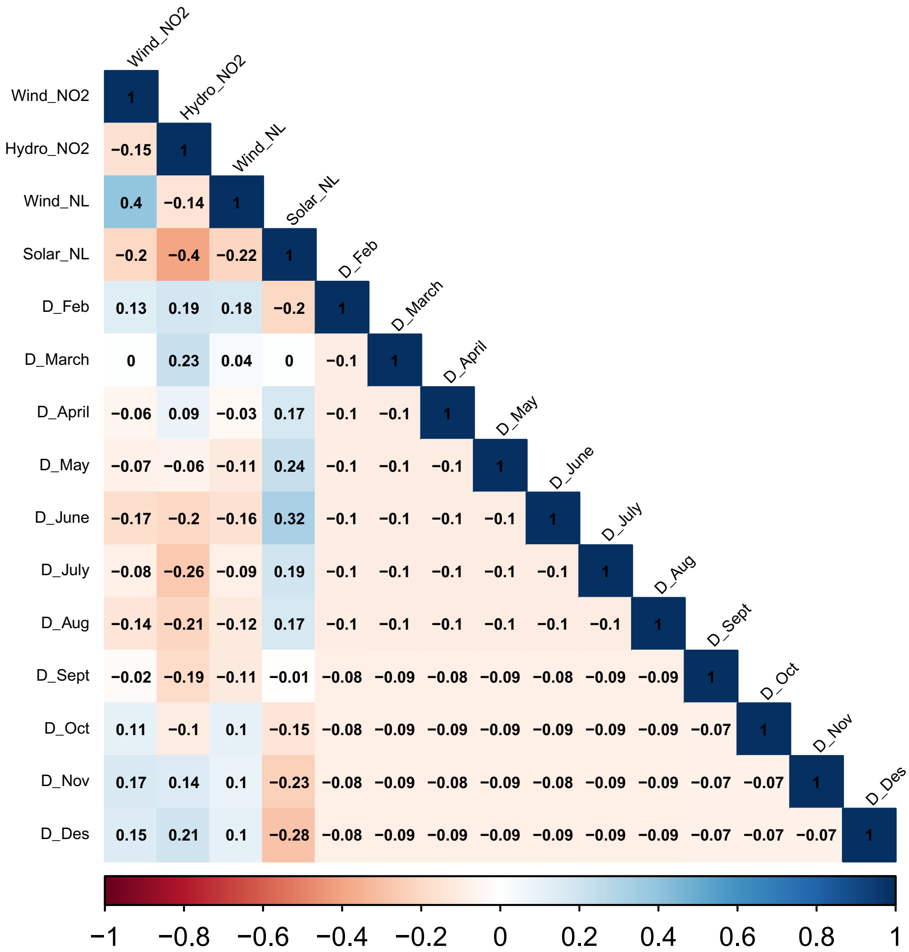


Figure A.7: Correlation Matrix United Kingdom Weather

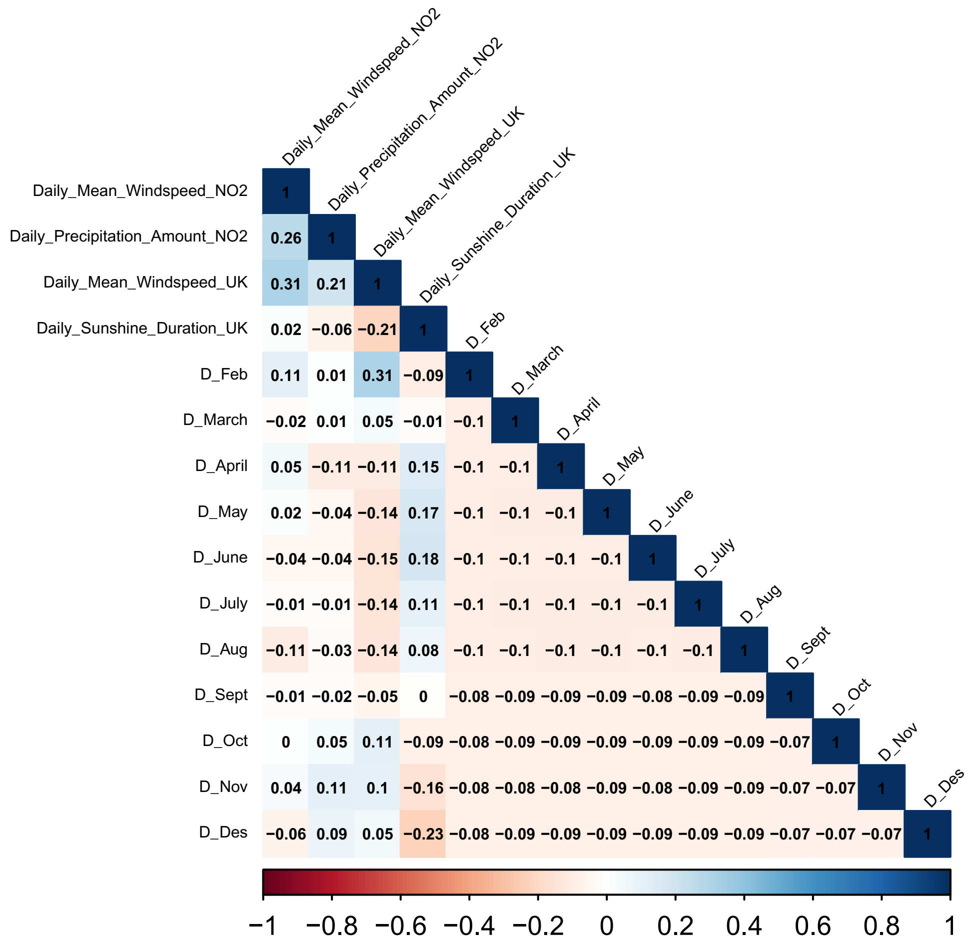


Figure A.8: Correlation Matrix United Kingdom Production

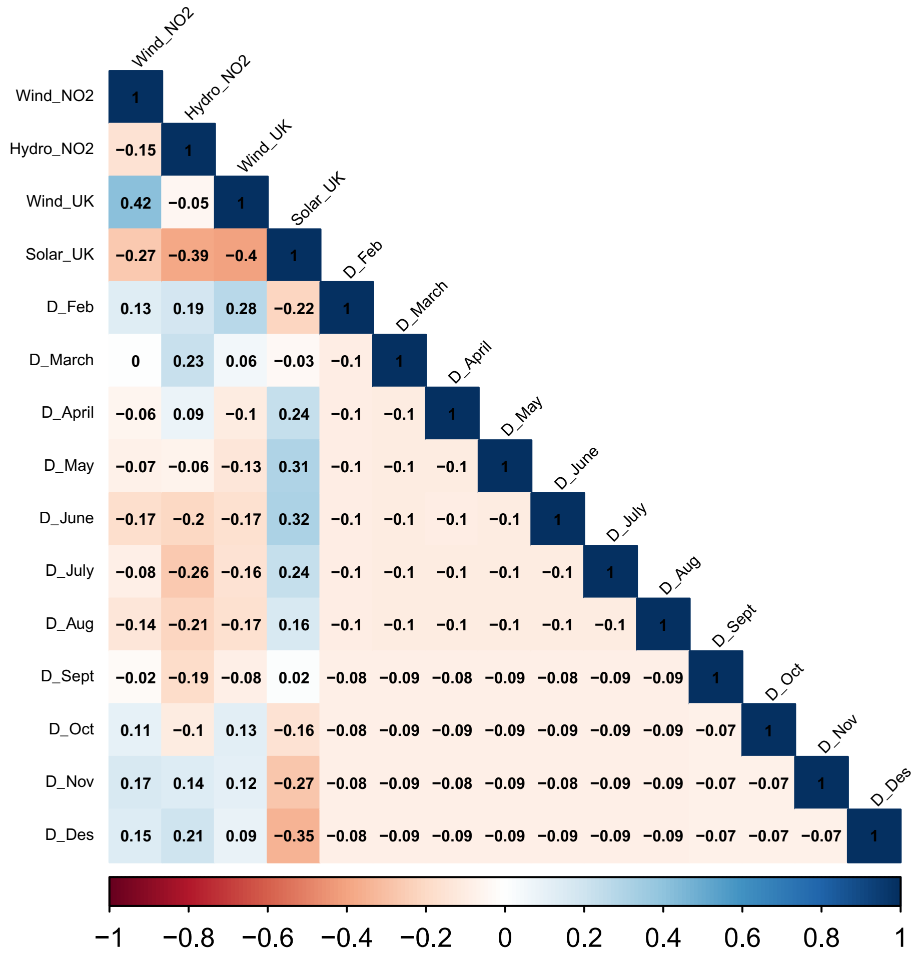


Figure A.9: Correlation Matrix Pooled CountriesKingdom Weather

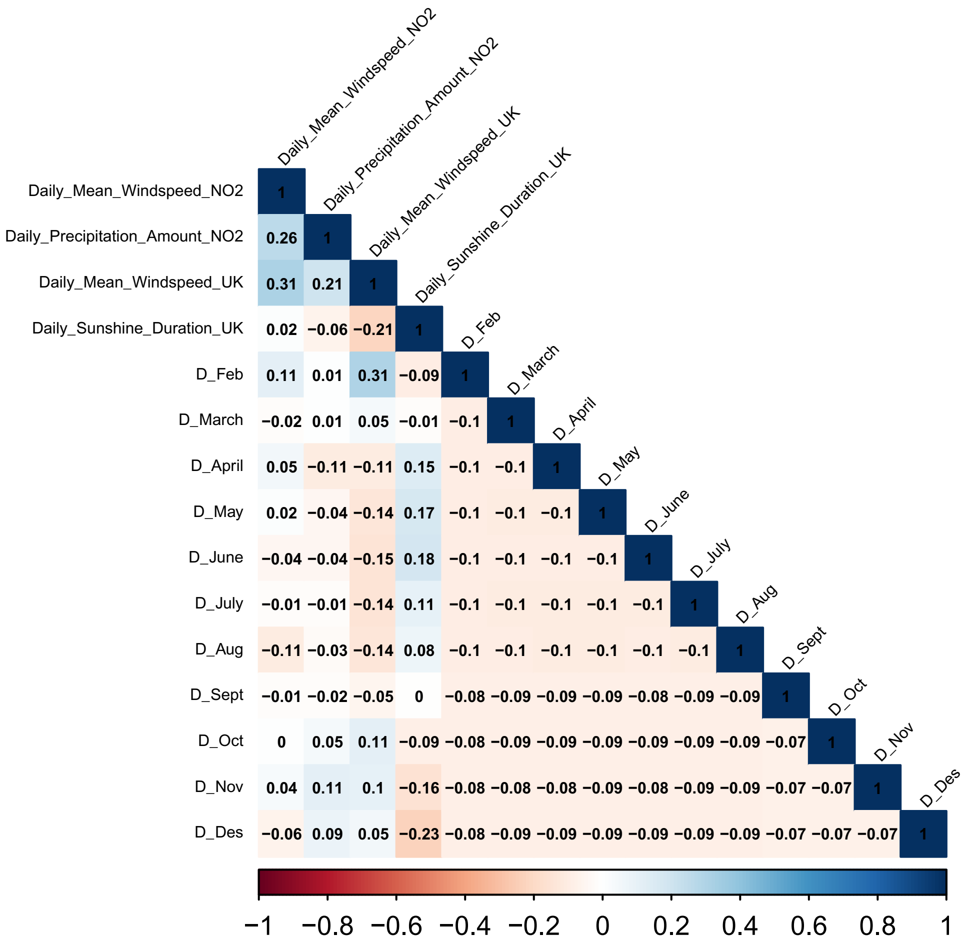
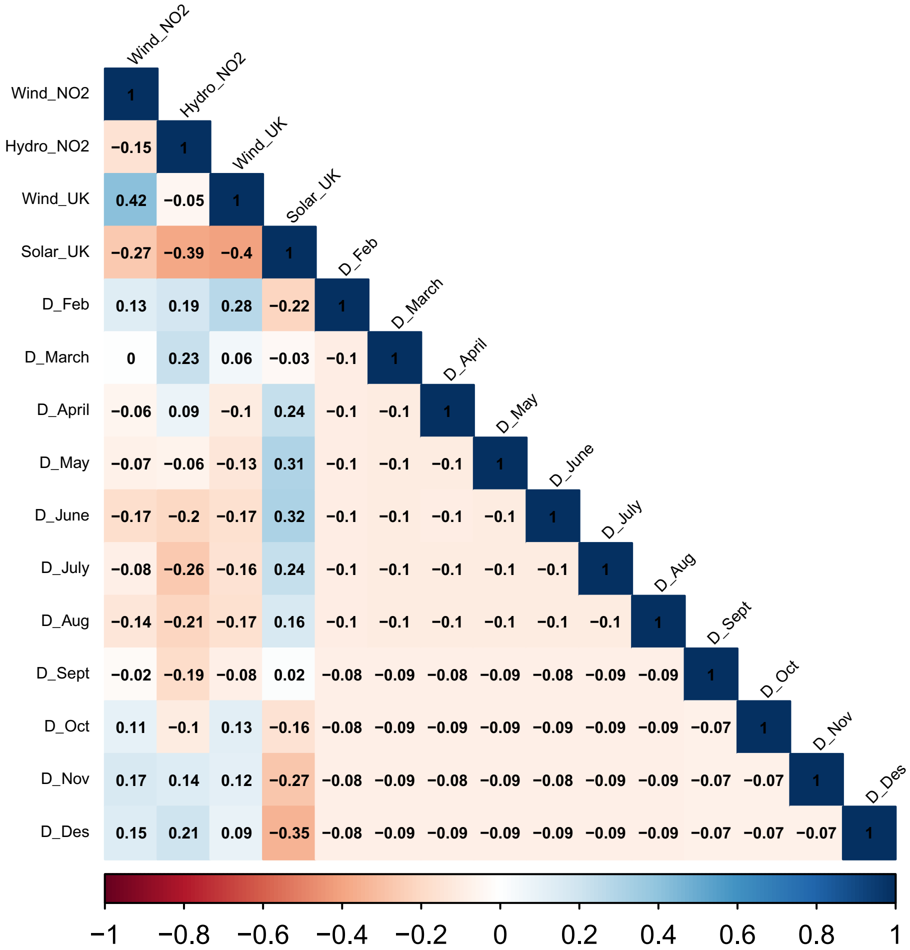


Figure A.10: Correlation Matrix United Kingdom Production



B Robustness

After ensuring that the models appear to be valid, it is desirable to investigate whether the model appears robust. The results of the robustness testing are presented in the tables below, consisting of five regressions with adjustments to the price difference values. In the regressions, we examine how the extreme levels in the spot price affect the main analysis, by filtering the data so that the most extreme values are set to the 80th percentile upward and the 20th percentile downward, and then running the regressions again. In other words, performing a winsorizing where we normalize the extreme values.

In the graphs below, you can see the distribution of the price difference between NO2 and the various countries and the outliers that are replaced and normalized through winsorizing. Furthermore, you can see regression tables that show the new regression outputs after trimming the data set. From the tables, we can see that the outputs are not very different from the original regressions, and for this reason, the data foundation is considered reasonable.

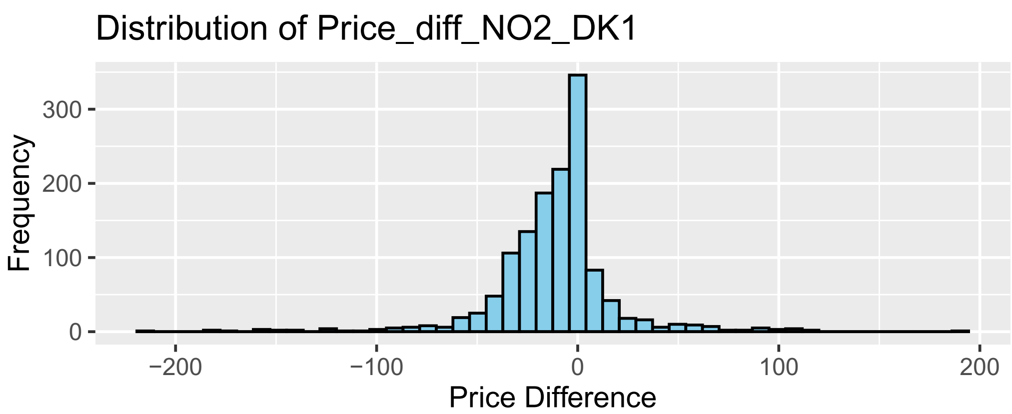


Figure B.1: Price difference distribution NO2 - DK1

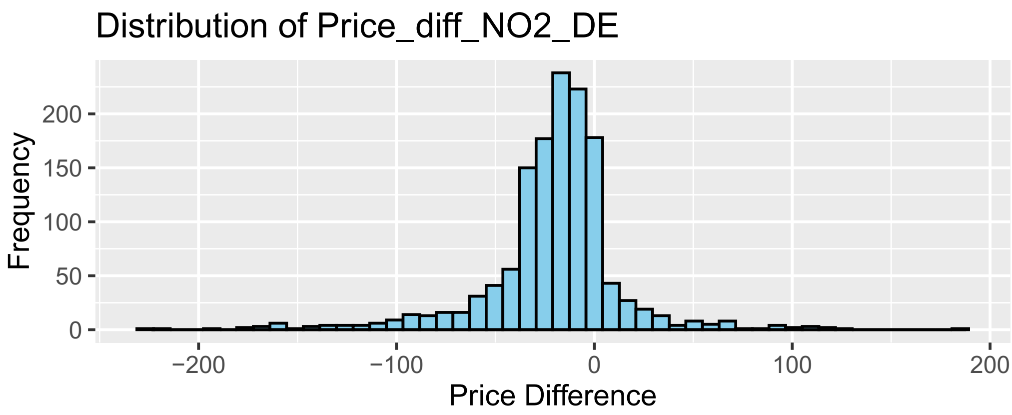


Figure B.2: Price difference distribution NO2 - DE

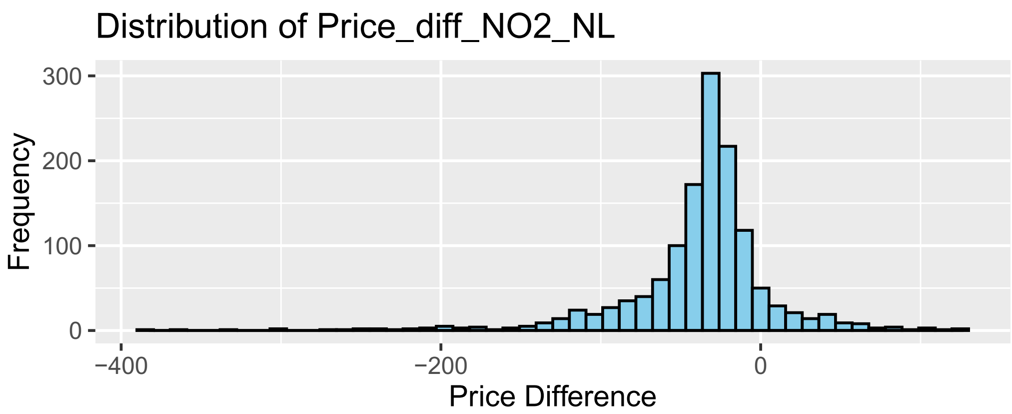


Figure B.3: Price difference distribution NO2 - NL

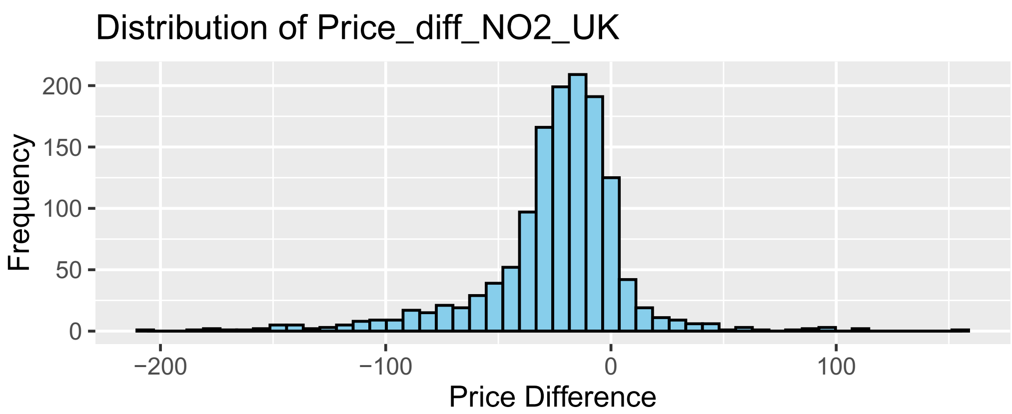


Figure B.4: Price difference distribution NO2 - UK

Table B.1: NO2 - DK1

	Dependent variable:	
	Price_diff_NO2_DK1	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−0.127	
	(0.157)	
Daily_Precipitation_Amount_NO2	0.023	
	(0.034)	
Daily_Mean_Windspeed_DK1	3.123***	
	(0.208)	
Daily_Sunshine_Duration_DK1	0.029	
	(0.073)	
Hydro_NO2		−0.112***
		(0.00001)
Wind_NO2		−0.224***
		(0.00004)
Solar_DK1		0.385***
		(0.0001)
Wind_DK1		0.235***
		(0.00001)
D_Feb	−4.549***	−4.061***
	(1.208)	(1.035)
D_March	−6.184***	−5.229***
	(1.215)	(1.038)
D_April	−3.421***	−4.985***
	(1.277)	(1.126)
D_May	−3.809***	−8.390***
	(1.249)	(1.164)
D_June	−11.320***	−18.689***
	(1.289)	(1.281)
D_July	−10.613***	−18.788***
	(1.223)	(1.211)
D_Aug	−10.519***	−18.014***
	(1.234)	(1.199)
D_Sept	−8.479***	−15.806***
	(1.311)	(1.227)
D_Oct	−5.993***	−11.010***
	(1.281)	(1.148)
D_Nov	−12.727***	−11.195***
	(1.289)	(1.112)
D_Des	−5.373***	−3.708***
	(1.280)	(1.111)
Constant	−15.445***	5.799***
	(1.252)	(1.661)
Observations	1,329	1,340
R^2	0.366	0.535
Adjusted R^2	0.359	0.530
Residual Std. Error	9.242 (df = 1313)	7.902 (df = 1324)
F Statistic	50.519*** (df = 15; 1313)	101.704*** (df = 15; 1324)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.2: NO2 - DE

	Dependent variable:	
	Price_diff_NO2_DE	
	(1)	(2)
Daily_Mean_Windspeed_NO2	−0.310	
	(0.192)	
Daily_Precipitation_Amount_NO2	0.101*	
	(0.053)	
Daily_Mean_Windspeed_DE	1.699***	
	(0.195)	
Daily_Sunshine_Duration_DE	0.034	
	(0.105)	
Hydro_NO2		−0.116***
		(0.00001)
Wind_NO2		−0.503***
		(0.00005)
Solar_DE		−0.003***
		(0.00000)
Wind_DE		0.005***
		(0.00000)
D_Feb	−2.023	−0.697
	(1.790)	(1.575)
D_March	−2.813	0.634
	(1.788)	(1.687)
D_April	2.024	3.741**
	(1.867)	(1.834)
D_May	−0.716	−0.961
	(1.797)	(2.035)
D_June	−5.499***	−6.269***
	(1.948)	(2.251)
D_July	−10.954***	−13.131***
	(1.832)	(2.130)
D_Aug	−5.197***	−8.728***
	(1.894)	(2.015)
D_Sept	−2.299	−6.018***
	(1.980)	(2.099)
D_Oct	−6.759***	−11.810***
	(1.976)	(1.877)
D_Nov	−17.739***	−15.684***
	(1.979)	(1.712)
D_Des	−4.307**	−2.378
	(1.778)	(1.537)
Constant	−19.381***	2.786
	(1.930)	(2.927)
Observations	969	997
R^2	0.218	0.423
Adjusted R^2	0.206	0.414
Residual Std. Error	11.795 (df = 953)	10.126 (df = 981)
F Statistic	17.748*** (df = 15; 953)	47.893*** (df = 15; 981)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.3: NO2 - NL

	Dependent variable:	
	Price_diff_NO2_NL	
	(1)	(2)
Daily_Mean_Windspeed_NO2	-0.654^{***}	
	(0.193)	
Daily_Precipitation_Amount_NO2	0.130^{**}	
	(0.054)	
Daily_Mean_Windspeed_NL	1.768^{***}	
	(0.325)	
Daily_Sunshine_Duration_NL	0.191^{*}	
	(0.106)	
Hydro_NO2		-0.074^{***}
		(0.00001)
Wind_NO2		-0.513^{***}
		(0.0001)
Solar_NL		0.616^{***}
		(0.0002)
Wind_NL		0.013^{***}
		(0.00000)
D_Feb	-3.545^{*}	-2.117
	(1.897)	(1.840)
D_March	-2.643	-3.436^{*}
	(1.900)	(1.869)
D_April	5.770^{***}	0.977
	(1.948)	(2.006)
D_May	7.065^{***}	0.360
	(1.962)	(2.098)
D_June	7.159^{***}	-2.517
	(2.015)	(2.287)
D_July	-0.938	-9.923^{***}
	(1.926)	(2.167)
D_Aug	-1.499	-10.172^{***}
	(1.939)	(2.150)
D_Sept	-1.784	-9.190^{***}
	(2.076)	(2.193)
D_Oct	-5.083^{**}	-8.123^{***}
	(1.997)	(2.000)
D_Nov	-12.168^{***}	-11.249^{***}
	(2.018)	(1.955)
D_Des	-7.812^{***}	-5.359^{***}
	(1.985)	(1.938)
Constant	-35.603^{***}	-18.760^{***}
	(2.074)	(2.963)
Observations	1,329	1,340
R^2	0.154	0.197
Adjusted R^2	0.144	0.188
Residual Std. Error	14.379 (df = 1313)	14.026 (df = 1324)
F Statistic	15.894^{***} (df = 15; 1313)	21.663^{***} (df = 15; 1324)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.4: NO2 - UK

	Dependent variable:	
	Price_diff_NO2_UK	
	(1)	(2)
Daily_Mean_Windspeed_NO2	-0.812^{***}	
	(0.236)	
Daily_Precipitation_Amount_NO2	0.112^{*}	
	(0.066)	
Daily_Mean_Windspeed_UK	0.774^{***}	
	(0.216)	
Daily_Sunshine_Duration_UK	-0.255^{*}	
	(0.133)	
Hydro_NO2		-0.144^{***}
		(0.00001)
Wind_NO2		-0.587^{***}
		(0.0001)
Solar_UK		-0.022^{***}
		(0.00002)
Wind_UK		0.007^{***}
		(0.00000)
D_Feb	-7.208^{***}	-6.888^{***}
	(2.302)	(2.110)
D_March	1.234	3.264
	(2.307)	(2.163)
D_April	11.190^{***}	5.616^{**}
	(2.323)	(2.462)
D_May	10.148^{***}	2.550
	(2.341)	(2.647)
D_June	9.392^{***}	-1.682
	(2.417)	(2.866)
D_July	3.540	-7.802^{***}
	(2.316)	(2.690)
D_Aug	5.113^{**}	-6.392^{**}
	(2.377)	(2.686)
D_Sept	14.099^{***}	-0.663
	(2.769)	(3.028)
D_Oct	-4.419^{**}	-10.934^{***}
	(2.243)	(2.196)
D_Nov	-12.145^{***}	-11.053^{***}
	(2.277)	(2.054)
D_Des	1.673	3.563^{*}
	(2.255)	(2.055)
Constant	-21.947^{***}	3.442
	(2.643)	(3.531)
Observations	689	701
R^2	0.232	0.363
Adjusted R^2	0.215	0.349
Residual Std. Error	12.422 (df = 673)	11.322 (df = 685)
F Statistic	13.548^{***} (df = 15; 673)	26.050^{***} (df = 15; 685)
Note:		*p<0.1; **p<0.05; ***p<0.01

Table B.5: NO2 - Abroad

	Dependent variable:	
	Price_diff_NO2_Abroad	
	(1)	(2)
Wind_NO2	−0.243**	
	(0.099)	
Precipitation_NO2	0.090***	
	(0.026)	
Wind_abroad	1.565***	
	(0.116)	
Sunshine_abroad	−0.062	
	(0.053)	
Wind_prod_NO2		−0.322***
		(0.00003)
Hydro_NO2		−0.140***
		(0.00001)
Wind_prod_abroad		0.004***
		(0.00000)
Solar_prod_abroad		−0.001***
		(0.00000)
D_DE1	−7.766***	−10.205***
	(0.575)	(1.209)
D_NL1	−22.071***	−23.253***
	(0.498)	(0.467)
D_UK1	−14.024***	−12.196***
	(0.674)	(0.628)
D_Feb	−3.817***	−2.709***
	(0.924)	(0.871)
D_March	−2.657***	−2.115**
	(0.925)	(0.856)
D_April	3.730***	0.117
	(0.952)	(0.883)
D_May	3.098***	−3.777***
	(0.942)	(0.916)
D_June	−0.554	−10.655***
	(0.983)	(0.984)
D_July	−4.978***	−15.426***
	(0.936)	(0.977)
D_Aug	−3.807***	−14.373***
	(0.951)	(0.967)
D_Sept	−1.904*	−13.124***
	(1.022)	(1.059)
D_Oct	−6.344***	−12.308***
	(0.973)	(0.954)
D_Nov	−14.000***	−12.757***
	(0.984)	(0.926)
D_Des	−4.798***	−3.230***

	(0.948)	(0.896)
D_Post_NordLink	−1.089	0.099
	(0.678)	(0.640)
D_Post_NSL	0.013	-2.444^{***}
	(0.589)	(0.569)
Constant	-12.355^{***}	18.690^{***}
	(1.124)	(1.375)
Observations	4,316	4,378
R^2	0.408	0.471
Adjusted R^2	0.406	0.468
Residual Std. Error	12.706 (df = 4295)	12.001 (df = 4357)
F Statistic	148.216^{***} (df = 20; 4295)	193.753^{***} (df = 20; 4357)
Note:		*p<0.1; **p<0.05; ***p<0.01

C Limitations

C.1 Using daily observations

A limitation we want to address on our master thesis is that we use daily observations rather than hourly observations. We are aware that aggregating data to daily observations rather than remaining on an hourly basis might exclude some information. We therefore conducted a comparison of daily and hourly spot prices with another thesis. The hourly spot price data shows higher deviation in the value of spot prices, which the daily data does not have the same spikes and lows. We are aware that this is a limitation of our analysis. However, the general trends in the data are similar and we believe the daily observations will provide us with sufficiently reliable data, giving us the possibility to find general and interesting correlations in the data.

C.2 Not including hydro run-of-river

Even though there are several factors that affect spot price, we have decided to look at the affect of intermittent renewable energy that is present in the areas abroad and in NO2 that we are interested in looking at. There are several more energy sources we could have analyzed, but due to the limited timeframe for our research and availability of data, we have had to be realistic of how many factors we could investigate. Hydro run-of-river is an intermittent renewable energy that would be interesting to look at, but since it is not present or very little production of it in the relevant areas abroad, we chose to omit the variable. We understand that it is a limitation of our thesis that we only have hydro for NO2, and wind and solar production abroad, but we made the decision du to which intermittent renewable energy sources were most prominent in each area. We believe this choice gives us representative variables to understand the affect weather and intermittent energy production has on bottlenecks, as those energy sources are most prominent.