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A Comparative Analysis of Price Drivers of Day-Ahead Electricity Prices in EPEX and Nord Pool

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Problem Description

European electricity markets have in recent years become more integrated across borders, with the purpose of achieving more stable and flexible electricity markets. More interconnected markets are beneficial for producers and consumers, as the electricity can be utilized more efficiently.

This master's thesis will analyze and compare the fundamental factors driving the electricity prices in Nord Pool and EPEX. The planned interconnection, the NordLink cable, between Norway and Germany motivates the investigation of the price dynamics of these two markets and how they can utilize each others differences. Market participants require a thorough understanding of the price dynamics in order to maximize the benefits of the future interconnection. For instance, our thesis will contribute to the investment and production planning for power producers. It examines how the spot price drivers in these two markets differ and how the market dynamics might compliment each other after the integration. Thus, the producers are given insight on how the interconnection will alter the price dynamics, consequently becoming better equipped to make optimal decisions.

Preface

This master's thesis is the final work of our Master of Science degree in Industrial Economics and Technology Management at the Norwegian University of Science and Technology (NTNU). It was written during the spring of 2016.

We would like to thank our supervisor professor Sjur Westgaard, at the Department of Industrial Economics and Technology Management, for inspiration and excellent guidance during the fulfilment of our master's thesis. Professor Westgaard has shown great interest in our work and provided time and resources to make our master's thesis as good as possible. We would also like to express our gratitude to co-supervisor, PhD Candidate Lars Ivar Hagfors at the Department of Industrial Economics and Technology Management, for his invaluable input, constructive criticism and unrestricted availability for questions during this process.

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Abstract

European energy markets have undergone, and will continue to undergo, large changes in coming years, as the share of renewable energy power production increases and markets become more interconnected. We analyze the fundamental drivers behind electricity spot prices in Nord Pool and the German European Power Exchange (EPEX), and compare the price formation dynamics in these two markets. The comparison is motivated by the NordLink cable which will connect Germany and Norway in 2020. It will exploit the different market characteristics, and is expected to reduce the price spread and improve utilization of renewable energy sources. Our thesis increases the understanding of the market mechanisms, which is required by market participants in order to adapt to the future changes.

A linear quantile regression is used to estimate quantiles spanning the entire price distribution. Separate regression models are estimated for each trading period to capture highly varying intraday properties of the electricity prices. We examine the price formation dynamics across the entire distribution, and how it differs between Nord Pool and EPEX. The results show that the fundamental variables impact the two markets differently and non-linearly throughout the trading day. Autoregressive effects are most influential in Nord Pool, together with demand and supply in the highest quantile. Overall, most variables have a low price impact; this is likely due to the large amount of flexible and stable hydro power which cancels out fluctuations in other parameters. EPEX has a higher number of important price drivers across the price distribution. Demand is the primary price determinant, while fossil fuel prices, autoregressive effects, and wind power production also notably impact the price formation. The energy mix characteristics are the likely reason for these differences, as EPEX is much more inflexible due to large-scale thermal production and intermittent renewable energy. Clearly, market participants can utilize the different characteristics and mutually benefit from the upcoming connection.

Sammendrag

Europeiske energimarkeder har gjennomgått og vil fortsette å gå gjennom store endringer i kommende år, med en økende andel fornybar energi og større integrasjon av kraftmarkeder. Vi analyserer de fundamentale driverne bak elektrisitetspriser i Nord Pool og den tyske kraftbørsen (EPEX), og sammenligner dynamikken bak prisformasjonen i disse to markedene. Sammenligningen er motivert av NordLink-kabelen som skal koble sammen Tyskland og Norge i 2020. Den vil utnytte de ulike markedkarakteristikkene, og forventes å redusere prisforskjellen og bedre utnyttelsen av fornybare energikilder. Vår masteroppgave øker forståelsen av markedsmekanismene som kreves av markedsaktører for å kunne tilpasse seg fremtidige endringer.

En lineær kvantil regresjon har blitt brukt til å estimere kvantiler som dekker hele prisdistribusjonen. Separate regresjonsmodeller er estimert for hver enkelt time for å fange opp svært varierende intradag-egenskaper til strømprisene. Vi undersøker prisformasjons-dynamikken i hele distribusjonen, og hvordan den er forskjellig i Nord Pool og EPEX. Resultatene viser at variablene påvirker de to markedene ulikt og ikke-lineært gjennom handelsdagen. Autoregressive effekter har størst påvirkning i Nord Pool, sammen med tilbud og etterspørsel i den høyeste kvantilen. Samlet sett har de fleste variablene liten påvirkning på prisen; dette skyldes trolig den store mengden fleksibel og stabil vannkraft som jevner ut svingninger i de andre parametrene. EPEX har et større antall viktige prisdrivere på tvers av prisdistribusjonen. Etterspørsel er den viktigste prisdeterminanten, mens prisene på fossile energikilder, autoregressive effekter og produksjon fra vindkraft også har merkbar påvirkning på prisformasjonen. Forskjellene i energikildene brukt i strømproduksjonen er den sannsynlige forklaringen bak disse forskjellene, fordi EPEX er mye mindre fleksibel grunnet storskala termisk produksjon og uregelmessig fornybarproduksjon. Markedsaktørene kan åpenbart utnytte de ulike karakteristikkene og ha gjensidig nytte av den kommende forbindelsen.

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Chapter 1

Introduction

The two day-ahead electricity markets, Nord Pool and EPEX, are to be connected for the first time in 2020 when the 1400 MW NordLink cable between Norway and Germany starts operating. In this context it is relevant to study how the electricity day-ahead price formation compares between the quite stable Nord Pool spot market - encompassing the Nordic and Baltic states - and the more volatile German spot market, EPEX. The Nordic power production is strongly dominated by hydro power, a highly flexible and relatively predictable energy source. Germany's power production is dominated by large-scale inflexible thermal energy, such as nuclear and coal, with a fairly large and swiftly growing share of intermittent wind and photovoltaic power.

Connecting two markets with complimentary characteristics is expected to be beneficial for market participants on both sides. For instance, when EPEX wind production is very high, the excess energy can be exported to Nord Pool to cover demand, hence storing hydro power for later (Mauritzen (2013)). Oppositely, when wind production is low in Germany, Nordic hydro producers can increase production and export to EPEX, preventing prices from spiking. Overall, the interconnection is expected to reduce the price spread between the two markets. A thorough understanding of the present market situation and how it will be impacted by the changes is important for many market participants, as the interconnection is likely to impact the price dynamics. A thorough understanding is vital for; among others, transmission system operators (TSOs) administering the grid and ensuring security of supply, power producers considering future developments, and investors seeking new opportunities in these markets.

The purpose of our analysis is to study how the different exogenous variables, e.g., demand, wind power, and fuel prices, impact the price formation. The price dynamics will be compared based on fundamental variables, with the purpose of understanding the similarities and the differences between the two markets. We will model the spot price distribution in both EPEX and Nord Pool using a linear quantile regression. Linear quantile regression is sufficiently powerful to facilitate a comparative study, as our purpose is not to forecast prices or examine which model provides the best results methodologically, but to compare the dynamics. Each trading period is modeled separately to assess how the impact varies throughout the trading day. Low, intermediate, and high quantiles of the price distributions are modeled to capture the non-linear impact of each fundamental variable.

In order to meet the European climate and environmental targets, large increases in renewable energy and improved interconnections are forthcoming. Germany, for instance, aims at eliminating nuclear power production within 2022, and requires large increases in new energy capacity. The changes introduced are slowly modifying the fundamental structure of the market. However, the impact on the overall market dynamics are unlikely to change drastically in relatively near future. Our analysis is therefore relevant for assessing and comparing the market dynamics of EPEX and Nord Pool. According to Statnett, the main grid operator in Norway, the NordLink cable is found to be profitable and to have positive impacts on security of supply and intermittency issues caused by renewable energy (Statnett (2013)). Our thesis aims at analyzing and comparing the market dynamics in EPEX and Nord Pool, thus providing a tool for market participants to better adapt to the upcoming changes. Both markets have been analyzed separately (Hagfors et al. (2016b), Paraschiv et al. (2014), Huisman et al. (2013), Huisman et al. (2015), and Nguyen (2015)), but a comparative analysis of the price drivers as presented here does not, according to our knowledge, exist in literature.

Our results clearly show that the price formation dynamics in EPEX and Nord Pool are different, and that the fundamental variables have highly non-linear effects in various quantiles and time of day. With its less flexible energy mix, EPEX has a high number of relevant price drivers. The most influential parameters are the balance between production and consumption, followed by fuel prices and autoregressive effects. Wind and volatility mainly impact the tails of the price distribution. The price formation dynamics in Nord Pool are dominated by autoregressive effects, while other parameters tend to be influential only in the tails. The sensitivities of fossil fuel prices and wind power production are lower than in EPEX, which is reasonable considering the differences in energy mix. The flexible hydro production balances fluctuations in other parameters, thus limiting the price impact when prices are in the normal range.

The remainder of the thesis is structured as follows. In Chapter 2 an overview of existing literature on use of fundamental models on electricity prices and previous market comparisons is presented. Next, Chapter 3 presents market descriptions of the German EPEX market and Nord Pool, a comparison of energy mixes, and a discussion on expected future changes. Chapter 4 discusses choice of data and its statistical properties, and includes an analysis of correlations between EPEX and Nord Pool. Linear quantile regression and modeling choices are presented in Chapter 5. The impact of each fundamental variable is analyzed and compared in Chapter 6; the price drivers are examined throughout the entire trading day and price distribution. Finally, the conclusion of the comparative analysis is presented in Chapter 7, as well as recommendations for further work.

Chapter 2

Literature Review

Our thesis can be placed in the context of two main research areas: (i) fundamental modeling of electricity prices, and (ii) interactions and comparisons between different electricity markets. Understanding the electricity price formation and modelling it with high accuracy has been a popular topic in the literature for years. Identifying the drivers behind electricity prices and their individual impact is required to be able to understand the relationship between fundamental variables, such as demand and supply, and consequently prices.

The literature regarding fundamental modeling of electricity prices in various markets is extensive. Nogales et al. (2002) develop a dynamic regression model and a transfer function model, using demand as the single explanatory variable, for accurate price forecasts in the Spanish and the Californian electricity market. The results show that the models greatly contribute to developing bidding strategies for market participants. Torro (2007) further develops the time series modeling with an ARIMAX model using temperature, precipitation, reservoir levels, and the spread between future and spot prices to model weekly futures prices at the Nord Pool market. The forecasting power of the estimated model is found to be highly useful for agents dealing with weekly future contracts. Karakatsani and Bunn (2008) critique Nogales et al. (2002), among others, for limiting forecasting models to autoregressive effects and few explanatory variables. Thus, the models are not appropriate for modeling complicated markets. To achieve good day-ahead forecasting performance for electricity spot prices in the British market, they apply a time-varying parameter regression model and a regime-switching model. Karakatsani and Bunn (2008) include the explanatory variables; demand, demand slope and curvature, demand volatility, margin, lag 1 margin, scarcity, learning (three past price values), price volatility, spread, seasonality, trend, diurnal, and weekly effects. They conclude that the best predictive performance is obtained from models involving market fundamentals, nonlinearity, and time-varying coefficients.

Chen (2009) compliments the research of Karakatsani and Bunn (2008) by studying the nonlinear relationship between the electricity price and its fundamental drivers in the British market. By using fuel price, demand, carbon price, and reserve margin as variables, he investigates how these factors impact the spot price non-linearly and the intraday variation of the impacts. Acknowledging the limitations of regime-switching models, Chen (2009) develops a structural finite mixture regression (SFMR) model, a more flexible version of regime-switching. Its forecasting performance outperforms regime-switching models and linear regression models. The results also demonstrate that prices in different trading periods within a day are driven by different fundamental factors. Chen and Bunn (2010) confirm these results using a logistic smooth transition regression (LSTR) model, a special type of regime-switching model, on the British market. A critique of the model is that it is not yielding good results on complicated markets.

Intraday properties of fundamental spot price drivers are also investigated by Hagfors et al. (2016a). They apply fundamental quantile regression models for each trading period in the British market. Explanatory variables used are the prices of gas, coal and carbon emissions, lagged spot price, demand, and margin forecasts. They show that the sensitivities to fundamental factors varies across quantiles and time of day. Bunn et al. (2016) expand this research by including price volatility as an additional explanatory variable, and include GARCH properties in the quantile regression models on the British market. They confirm that the price coefficients vary considerably across the price distribution.

Literature covering quantile regression models in Nord Pool is scarce. Nguyen (2015) studies how fundamental factors affect various quantiles of the spot price distribution in Nord Pool. Only trading period 4 and 11 are analyzed, and the results show that the regression coefficients change across quantiles for both periods. Lundby and Uppheim (2011) use quantile regression for Value at Risk (VaR) forecasting of the spot price in Nord Pool. They compare the forecasting performances to an exponentially weighted quantile regression (EWQR) model and an extended conditional autoregressive (CaViaR) model. They find that the extended CAViaR model outperforms the other models. Other methods have been applied to model the Nord Pool spot price. Weron et al. (2004) apply a mean reverting jump diffusion model to capture the main characteristics of the spot price. Vehviläinen and Pyykkönen (2005) treat fundamental drivers as stochastic factors to model the impact on the spot price, by presenting a model suited for mid-term analysis. The model is a combination of three models of consumption, generation and marginal water value, and performs better for long-term forecasts than short-term forecasts. Fuglerud et al. (2012) continue the mid-term modeling and add a model for exchange. Their model provides realistic forecasts of the spot price and its distribution.

Huisman et al. (2013) and Huisman et al. (2015) investigate how the increase of low marginal cost renewable energy supply impacts the electricity prices in Nord Pool. As the marginal costs of hydro production vary according to reservoir levels, the price impact of different levels is of particular interest. Both papers conclude that higher reservoir levels lead to lower electricity prices and Huisman et al. (2015) show how the impact of supply and demand variables on the prices differ as reservoir levels changes. Paraschiv et al. (2014) continue the examination of renewable energy sources (wind and photovoltaic) on electricity prices by studying the EEX day-ahead prices in Germany. Using a state space model, they find that renewable energy increases the extreme price fluctuations, and that the price sensitivity differs for each variable in each trading period. These results are confirmed and their work is extended by Hagfors et al. (2016b). Hagfors et al. (2016b) run quantile regression models to investigate the influence from fundamental drivers, especially the impact of wind and photovoltaic power, on the EEX day-ahead electricity price distribution.

Frondel et al. (2010) and Paraschiv et al. (2014) find that feed-in tariffs increase the electricity price, thus penalizing the consumers, and suggest to reduce the tariffs once the renewable energy targets are met. Sensfus et al. (2008) also examine the presumed high consumer costs by considering the merit-order effect of increasing low marginal cost renewable energy in Germany. Applying an agent-based simulation platform, they find that the volume of the merit-order effect exceeds the net support paid by the consumers. Therefore, the literature is conflicted regarding the economic impact of renewable energy sources.

Nicolosi and Fürsch (2009) study the consequences for the conventional generation capacity mix in Germany, considering the growing share of renewable energy. They find that more intermittent energy increases the volatility of the residual demand; thus, a higher peak load plant share is required. The higher residual demand volatility in turn increases the volatility of the electricity price. Ketterer (2014) also examines the impact of wind on the German electricity prices. Using a GARCH model, the level and volatility of the electricity price are investigated. The results show that the price level is reduced due to the wind power generation, while the volatility increases. The increased price volatility is reduced by regulatory changes introduced by the German government. Thus Ketterer (2014) states that regulation and policy may facilitate better integration of renewable energy sources.

Literature comparing the design, bidding process, or transmission management of electricity markets exists (Imran and Kockar (2014), Ela et al. (2014), and de Menezes and Houllier (2016)). However, literature comparing fundamental electricity drivers of different electricity markets as comprehensively as our thesis does not, to our knowledge, exist. Our work is an extension of both Hagfors et al. (2016b) and Nguyen (2015); the whole spot price distribution in both EPEX and Nord Pool is studied, and a comprehensive analysis of all fundamental variables is performed. Thus, this master's thesis contributes to the research on fundamental electricity drivers in both Nord Pool and EPEX, and provides a detailed analysis and comparison of the intraday price dynamics across the entire spot price distribution.

Chapter 3

Market Description and Analysis

3.1 Electricity Markets

EPEX and Nord Pool are similar in the sense that both are transparent, liberalized and competitive electricity spot markets, and have an increasing share of renewable energy sources. The introduction of near zero marginal cost renewable power, in the form of wind and photovoltaic power, has changed the merit order curve, which is a ranking of available energy sources based on ascending price per MWh. When producing, renewable energy substitutes the traditional base load technologies, which results in lower power prices, as cheaper plants become the price setters. This has been observed in Germany in later years; the prices have even become negative when high levels of wind power generation coincide with low demand (Paraschiv et al. (2014)).

Renewable energy poses a challenge to power markets, as the intermittency strongly impacts traditional producers and increases the need for flexible capacity to ensure security of supply (Kilic and Baute (2014) and Forrest and MacGill (2013)). According to a report by Adapt Consulting AS (2014), the energy mix changes require system dimensioning that accounts for variable production, in addition to expected load. Although the prognoses for renewable energy production are increasingly accurate, intermittency remains a challenge that requires flexible reserves with good ramping-rates. An example of an energy source fulfilling these requirements are hydro reservoirs, such as those found in Norway and Sweden.

3.1.1 EPEX

The bidding process in EPEX consists of bids and offers for each trading period within 12:00 the day before delivery. A trading period is defined as one hour, e.g., trading period 1 is from 00:00-01:00. All market participants receive the market-clearing price, which is found at the intersection of the demand and supply for each trading period.

The expansion of renewable production has been strongly incentivized by the German government. This has resulted in wind and photovoltaic power production increasing rapidly, reaching 19.2% of total power production in 2015, as seen in Table 3.1. The most significant regulatory change to achieve this was the Renewable Energy Act (EEG) from 2000, which guaranteed producers of renewable energy a minimum compensation per produced kWh. The latest significant regulatory change, the Equalization Mechanism Ordinance (AusglMechV), entirely changed the market mechanisms of trading renewable energy. It obliged TSOs to sell EEG-electricity on the day-ahead market, starting 1st of January 2010.

The overall target of the EEG is to achieve 35% renewable energy production in 2035, and 80% in 2050 (Gullberg et al. (2014)). In addition, the German government has decided that nuclear energy is to be phased out within 2022, while transitioning to a low-carbon energy system. Consequently, continued encouragement to develop renewable energy is necessary to cover the German energy demand. The cost of the transition to renewable energy is carried by consumers through the EEG levy; producers are compensated through feed-in tariffs. The subsidies have certainly been efficient in increasing renewable capacity, however, Frondel et al. (2010) argue that the introduction of renewable has not been cost-effective. The average spot prices have been reduced due to the increased renewable capacity (Hagfors et al. (2016b), Schneider and Schneider (2010), and Paraschiv et al. (2014)), but Fanone et al. (2013) argue that the feed-in tariffs exceed the reduction in power prices, causing a negative net effect for consumers.

As discussed in Paraschiv et al. (2014), the weak transmission grid between the high-demand southern part of Germany and the north, where the majority share of wind power is generated, is a particular challenge. This causes congestions in the power system, as well as sub-optimal utilization of the renewable resources. The issue may be alleviated by improving the transmission grid in Germany, or by developing stronger connections to surrounding areas, e.g., Netherlands, Switzerland, Denmark, or Norway.

3.1.2 Nord Pool

Nord Pool Spot AS is the largest power exchange in Europe: Elspot is the market for trading day-ahead electricity, and Elbas is the intraday market. Nord Pool is divided into bidding areas with different area prices resulting from transmission constraints between the regions. With no constraints, the price would be equal in all areas; this is the system price, a theoretical price ignoring internal transmission constraints. Market participants submit bids and offers within 12:00 the day before delivery, and the market is settled shortly after. A trading period is a specific hour, just as in EPEX, and all market participants receive the market clearing price.

Nord Pool has a large share of hydro, as shown in Table 3.1. The largest part of the hydro reservoirs are found in Norway and Sweden. Wind power production has steadily increased in recent years, and has reached a share of 8.9% in 2015 (Table 3.1). Denmark is currently the largest producer of non-hydro renewable energy, due to wind power production. Increased renewable energy production in Norway and Sweden is facilitated through a joint market for tradable green electricity certificates introduced in 2012. The aim is to ensure 26.4 TWh of new renewable production within 2020. Producers of clean, renewable energy are issued certificates which are sold to market participants. These participants are required to buy these in proportion to their electricity sales. If failing to buy sufficient certificates, a penalty is charged. In this way an additional income for renewable producers is ensured. The price is not fixed, but determined in the open market. As in Germany, consumers ultimately carry the costs through a premium per consumed kWh.

3.2 Energy Mix Comparison

Nord Pool and EPEX are fundamentally different markets; Nord Pool is mainly based on stable and flexible hydro, while Germany relies heavily on less flexible thermal energy and intermittent renewable energy. The different market structures are highlighted by the share of total renewable energy; Nord Pool has 70.8%, which exceeds the 29.9% found in EPEX. These differences in energy mixes are likely to have a large impact on the price formation and intraday price patterns.

The share of hydro power production varies according to water inflow each year, but constitutes approximately 60% of power production in Nord Pool (Statnett (2013)). As a consequence, the share of fossil and nuclear power in the Nord Pool energy mix is only 28.9%, and is drastically lower than the 65.9% found in EPEX. The higher share of large-scale thermal energy in Germany partially explains the higher number of negative price occurrences. The costs of shutting down/reducing thermal power production exceed the losses of operating at low/negative prices which typically occur with high levels of low-cost renewable production. According to Keles et al. (2011), utilities are willing to accept -€120/MWh or lower to get rid of excess electricity produced, as energy storage is not a viable option with current technologies. Hydro power producers in Nord Pool can more easily adjust the production to handle variability in the power in-feed from renewable energy sources, preventing the prices from fluctuating excessively and becoming extremely high or low. The variable cost of hydro is the opportunity cost of producing today versus delaying production, when the price expectation may be higher or lower. Increasing production is thus only beneficial to hydro producers if the price today exceeds the

Table 3.1: Energy mix (2015). Source: EPEX (Energiebilanzen (2015)), Nord Pool (Data provided by ENTSO-E (2015)). Total renewables includes hydro, wind, PV, biomass, and incineration.

	Fossil	Nuclear	Wind	PV	Hydro	Other	Total renewables
EPEX	51.8%	14.1%	13.3%	5.9%	3.0%	11.8%	29.9%
Nord Pool	10.5%	18.4%	8.9%	0.2%	55.9 %	6.1%	70.8%

expected income at a later time.

Intermittency caused by renewable energy can be absorbed by hydro reservoirs, as discussed by Mauritzen (2013), Green and Vasilakos (2010), and Gullberg et al. (2014). The reservoirs can be utilized as batteries by using renewable energy when it is very cheap to pump water back into the reservoirs. Thus, they can literally operate as batteries, allowing for storing significant amounts of energy for use when it is scarce. Hydro reservoirs can also function as batteries by producing less when cheap renewable energy is available, for example from strong winds. The electricity is thus stored for later when sufficient energy from other sources is less available. Li (2015) shows that the growth of wind power in Nord Pool has lowered the spot price volatility, because of the interaction with hydro resources and strong transmission lines. In contrast, Ketterer (2014) showed the increase in wind power has increased price volatility in EPEX. Conclusively, recent developments in Nord Pool and Germany have impacted the volatility of day-ahead prices differently. The phasing out of stable nuclear power plants in Germany is likely to further increase the price volatility, as the share of intermittent renewable energy increases.

Clearly, flexibility is valuable in systems with a large share of intermittent renewable energy. However, sufficient transfer capacity between the areas with large intermittent production and hydro-rich areas is necessary to alleviate the adverse impacts from intermittency. Price differences will be reduced, and consumers will ultimately be provided with cheaper, cleaner energy.

3.3 Future Developments

The energy mix is expected to change further in near future in both markets, particularly EPEX. Germany is transitioning towards less large-scale nuclear and carbon-emitting coal energy, while expanding renewable energy production. The Nordic countries are also focused on increasing the amount of wind energy, thus moving towards an even lower-carbon system.

To accommodate the ambitious goals set by Germany, it is necessary to develop more renewable energy plants while handling the variability issues arising. Security of supply is ensured by having sufficient flexible reserves, which can be addressed through different measures. As discussed by Gullberg et al. (2014)) and Jacobsen and Zvingilaite (2010), there are several options to achieve this; installing more peak load plant capacity, enhance energy storage, or improve interconnections between areas. Strong interconnections promote more stable prices and an increasingly competitive market that further limits opportunities to exercise market power when supply is scarce (Li (2015)).

The 1400 MW NordLink cable is expected to facilitate better use of resources on both sides, as improved transmission reduces adverse effects of renewable energy production (Jacobsen and Zvingilaite (2010)); particularly if enabling utilization of the characteristics of different markets. Security of supply will be improved, while utilization of renewable energy production is enhanced as predictability improves. Market participants will benefit from importing/exporting by exploiting the price spread between Nord Pool and EPEX. When EPEX prices exceed those in Nord Pool, Nordic producers export. If EPEX prices are lower, the Nordics import cheap power and conserve hydro power for later. In dry years, the interconnection is likely to improve the handling of energy shortages and lead to lower consumer prices in Nord Pool. Overall, according to Statnett (2013), Norwegian prices are expected to increase with €5/MWh in 2020 and €4/MWh in 2025, thus consumers will face higher prices. For EPEX, an interconnection improves load balancing and reduces volatility thus lower extreme price occurrences, as well as expanding the power trading market. However, to fully utilize the benefits, the transmission grid between north and south Germany must be strengthened. The transmission capacity of 1400 MW is unlikely to equalize the prices in Nord Pool and EPEX; Statnett (2013) claims there will be congestions and relatively large price differences most of the time.

In addition to the NordLink cable under construction, a cable from Norway to the UK, the 1400 MW NSN cable, is planned to be finished in 2021. The UK market differs greatly from Nord Pool, and a cable is likely to have similar benefits as the connection between Norway and Germany. The development of strong interconnections is an important step in achieving a more connected, low-carbon European power system, and in meeting environmental targets set by European countries.

Chapter 4

Data Analysis

4.1 Choice of Data

4.1.1 Choice of Price Data

We analyse hourly day-ahead spot prices in the German EPEX and in Nord Pool between 4th of January 2010 and 31st of May 2014. Significant regulatory changes were effective in Germany from early 2010, as discussed in Section 3.1.1, which limits our data to post-2010. The regulatory changes altered the market mechanisms and reduced the volatility of electricity prices as a consequence, as shown by Ketterer (2014). As discussed in Section 3.2, the energy mix has changed in recent years, primarily in the form of more wind and photovoltaic power, and an ongoing reduction of nuclear power in Germany. We therefore consider data pre-2010 to not be representative for the current state of these day-ahead electricity markets for comparative purposes.

Electricity prices differ considerably from those of financial assets because they are seasonal, exhibit volatility clustering and mean-reversion, as well as occasional observations of extremely high/low prices. Unlike most financial asset prices, electricity day-ahead prices are often stationary, as confirmed by the results of an augmented Dickey Fuller (ADF) test with 7 lags. Based on test statistics shown in Table 4.1, both price series are stationary at 1% significance level. The Ljung-Box Q-statistics with 7 lags included are shown in Table 4.2, and confirm the expectation of auto-correlation in the day-ahead spot prices. Each trading period has its own unique set of fundamental price drivers, as confirmed by Chen and Bunn (2010). Hence each trading period is treated as a separate time series in the modeling, yielding 1609 data points for every period. This is done to capture the different intraday characteristics exhibited by electricity prices, and to facilitate a comparison of price drivers in two fundamentally different markets throughout the trading day.

Table 4.1: ADF test statistics for spot prices. The critical values at 1% significance level is -3.43 for the intercept-only test, and -3.96 for the intercept - and trend test.

Price series	EPEX Spot	Nord Pool Spot
ADF (7) (intercept)	-36.27	-16.17
ADF (7) (intercept and trend)	-38.34	-19.40

Table 4.2: Ljung-Box statistics for spot prices and the series of first differences of prices. Includes both lag 1 and lag 7.

Price series	EPEX Spot	Nord Pool Spot
Ljung-Box (1) (price)	32989	36382
Ljung-Box (1) (first difference)	4236	3344.4
Ljung-Box (7) (price)	103715	205520
Ljung-Box (7) (first difference)	9482	7457

4.1.2 Choice of Fundamental Variables

The fundamental variables chosen to model the spot price in EPEX are given in Table A.3, and variables used to model the Nord Pool spot price are given in Table A.4. Fuel and CO_2 prices are equal in both markets, as these commodities are traded on common Northern European markets. The first and seventh lag of the spot prices are used to capture recent trends and weekly patterns commonly observed in power markets; typically, electricity prices tend to be lower during weekends. Volatility is considered a relevant variable to explain the price formation, as it is well known that electricity prices exhibit volatility clustering and correspondingly erratic behavior. Volatility is, for both markets, computed from an exponentially weighted moving average on the residuals of a seven-lag OLS-regression. The lambda used is 0.94, a value we consider a good approximation to smoothly capture recent market movements. The demand forecast for EPEX is modeled according to the approach described in Paraschiv et al. (2014). Each trading period is modeled separately while accounting for time of year and weekday, so that the demand variable captures the intraday seasonality pattern of electricity prices. Demand data used in Nord Pool is based on realized load, not forecasts. This is mainly related to data availability, as demand forecast data for Nord Pool was unavailable until November 2011. Based on results presented in Table 4.3, the characteristics of forecasted and realized demand are nearly identical in years 2013/14; the descriptive statistics are very similar, and the correlation is 0.996. Only excess kurtosis somewhat differs, as it is slightly less for the forecast, implying its distribution is a bit flatter than the realized demand. The correlations with the spot price in this period are nearly perfectly equal; 0.419 with realized demand, and 0.414 with forecasted demand. This supports that realized demand is interchangeable with forecasted demand for the Nord Pool market. Forecasts for wind, photovoltaic and power plant availability (PPA) are available for Germany, while similar data is not available for the entire sample period for Nord

Table 4.3: Descriptive statistics of realized and forecasted demand in Nord Pool. Due to data availability we use values for 2013-14. Source: Nord Pool

	Mean	Std. Error	Median	Excess Kurtosis	Skew	Range	Min	Max
Demand	45803	68.38	44750	-0.56	0.34	44498	27275	71773
Forecast	45964	68.55	44952	-0.60	0.33	44322	27766	72088

Table 4.4: Descriptive statistics of realized and forecasted supply in Nord Pool. Due to data availability we use values for 2013-14. Source: Nord Pool

	Mean	Std. Error	Median	Excess Kurtosis	Skew	Range	Min	Max
Production	45849	9721.94	44584	-0.49	0.36	49973	24120	74093
Forecast	45064	9676.34	43842	-0.47	0.38	46169	25170	71339

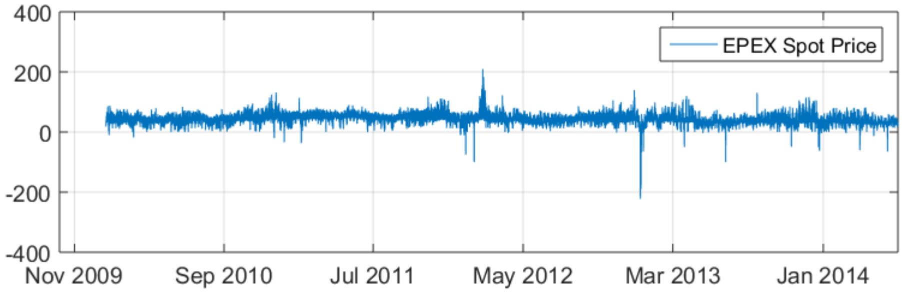
Pool. Note that the PPA forecast is based voluntary submission by producers and is therefore not complete; however, a large majority of relevant companies report their forecasts and the data is thus a good approximation for the entire market (Paraschiv et al. (2014)). In Nord Pool, we choose to use realized total production as the supply variable, due to data availability. As seen in Table 4.4, the descriptive statistics of forecasted and realized supply are very similar, and the correlation between the series is 0.994. Photovoltaic power is not a relevant variable in Nord Pool. For wind we use true wind production, as forecasts are unavailable for the modeled time period. Given a high correlation of 0.969 between forecasted and realized wind production, we assume this approximation is reasonable. Electricity certificate prices and hydro reservoir levels are only included in the models used for the Nord Pool spot price, as these variables are only found in this market.

4.2 Descriptive Statistics of Prices

The descriptive statistics of the spot prices are presented in Table 4.5. We first note that Nord Pool has the highest maximum price of €300.03/MWh compared with €210/MWh in EPEX, but that the German prices have a larger price range due to negative prices - implying thicker tails. Although the Nord Pool price range is shifted to the right, the mean price is €1.90 lower than in EPEX, implying that very high prices in Nord Pool are less frequent. The median in EPEX slightly exceeds the mean, also indicating there is a higher chance of observing prices in the upper tail. This is somewhat contradicted by the negative skewness of -1.02, as it implies a higher probability of observing prices in the lower end of the distribution. Statistically, the Nord Pool spot price mainly differs from the EPEX price in that the skewness is positive, and that the mean exceeds the median. The implication is that the probability of observing prices in the upper part of the distribution is higher in Nord Pool. Further, it implies that EPEX prices are more likely to be extremely high or low, which is supported by a higher mean and thicker

Table 4.5: Descriptive statistics of EPEX and Nord Pool spot prices.

	EPEX Spot	Nord Pool Spot
Mean	42.94	41.04
Median	43.07	38.61
Maximum	210.00	300.03
Minimum	-221.99	1.38
Standard Deviation	15.52	15.85
Skew	-1.02	1.72
Excess Kurtosis	16.44	12.91
Jarque-Bera	441492	287786



(a) Overview of EPEX spot price over time.

(b) Overview of Nord Pool spot price over time.

Figure 4.1: Plots of both price series over time.

left tail. The high positive excess kurtosis, large standard deviation and high Jarque-Bera test-statistic confirm that the price distributions are highly non-normal and thick-tailed in both markets. Further, we note that both price series clearly exhibit occasional spikes and volatility clustering, as seen in Figure 4.1.

The characteristics of estimated volatility of both price series are presented in Tables A.1 and A.2. The average volatility in EPEX is €8.63/MWh, more than twice as high as in Nord Pool (€3.76/MWh), and likely to increase even further as discussed in Section 3.2. This strengthens the implication that the tails of the EPEX prices are thicker compared with Nord Pool.

The correlations between day-ahead price and its own lags are shown in Table 4.6 for both markets. The correlations in Nord Pool are much higher, but the weekday-effect (lag 7) is stronger in EPEX relative to the other correlations. The correlation with the seventh lag exceeds the correlation with the other lagged prices, except the first lag. The high correlations in Nord Pool are supported by the lower volatility, as it indicates that prices are likely to be similar

Table 4.6: Auto-correlation between prices in EPEX and Nord Pool.

	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7
EPEX Spot Price	0.69	0.52	0.48	0.46	0.47	0.58	0.68
Nord Pool Spot Price	0.92	0.86	0.83	0.82	0.81	0.83	0.84

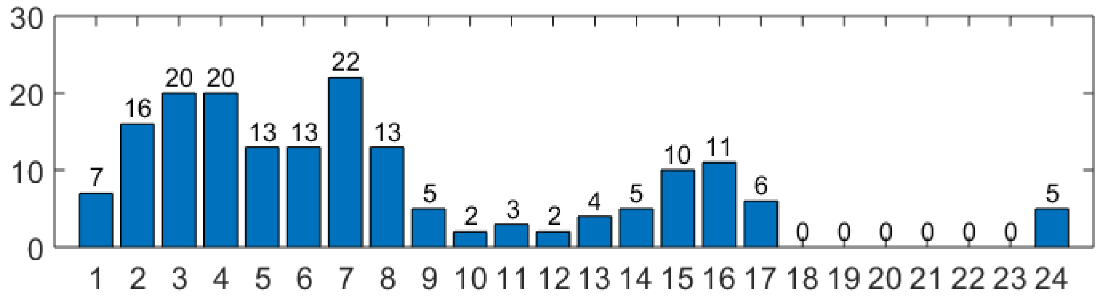


Figure 4.2: Distribution of negative prices per trading period in German EPEX.

on a day-to-day basis. Further, high correlation is supported by the lower price range in Nord Pool.

From the price plots in Figure 4.1, we note that the Nord Pool price is always positive, unlike in Germany where there are negative price observations. As seen from Figure 4.2, most negative prices occur during night. Further, from Figure A.2 we note that negative EPEX prices tend to occur when wind power production is at its highest - Paraschiv et al. (2014) and Hagfors et al. (2016b) show this happens mainly during night. The minimum and average negative prices during night are much more extreme than those observed during day, when average demand is higher (Figure A.1), as seen in Table 4.7.

Table 4.7: Overview of characteristics of negative prices in German EPEX.

Trading period	Number of Negative Prices	Average Negative Price	Minimum Price
1	7	-35.5	-149.9
2	16	-30.5	-200.0
3	20	-34.8	-222.0
4	20	-38.8	-221.9
5	13	-46.6	-199.9
6	13	-38.7	-199.0
7	22	-30.4	-199.9
8	13	-22.2	-156.9
9	5	-1.4	-6.0
10	2	-1.4	-2.8
11	3	-1.9	-5.7
12	2	-4.2	-8.3
13	4	-2.7	-9.9
14	5	-19.8	-59.5
15	10	-24.6	-100.0
16	11	-17.6	-100.0
17	6	-15.3	-46.9
24	5	-30.4	-91.0

4.3 Descriptive Statistics of Fundamental Variables

Descriptive statistics of all variables are presented in Tables A.1 (EPEX) and A.2 (Nord Pool), and the correlations between variables are found in Table A.5 (EPEX) and A.6 (Nord Pool). We first note that demand in EPEX varies notably more than PPA, as the range and standard deviation is less for the latter. In Nord Pool, demand and supply have quite similar statistical properties. The range is slightly shifted towards higher values for supply, indicating excess supply is more likely than very high demand. Demand and supply parameters are slightly positively skewed in Nord Pool, indicating higher levels are slightly more likely to occur - the opposite is true for EPEX. The more volatile EPEX demand/supply relationship supports the higher volatility of German electricity spot prices as previously discussed. Excess kurtosis is negative in both markets; the distributions are quite flat with relatively thin tails, meaning these variables mostly are stable.

The correlation between demand and supply is very high (0.97) in Nord Pool, as seen in Table A.6. A plausible explanation for this is the low elasticity of demand - and thus required supply. The supply side in Nord Pool is dominated by flexible hydro power, so that supply is able to adjust to demand; hence, high demand is followed by higher supply levels. Correlation between demand and PPA in Germany is much lower at 0.34, indicating that high demand levels are less likely to coincide with high levels of supply. This may be caused by the incompleteness of the PPA variable itself, as previously discussed. Another plausible explanation is that intermittent renewable energy strongly affects the balance between supply and demand by either increasing or decreasing supply relative to demand.

It is also very interesting to look at the relationship between the standard deviation of demand and PPA/supply in EPEX/Nord Pool; for Nord Pool, the standard deviation is approximately the same for demand and supply. In EPEX, however, demand varies much more than PPA, even though the mean values are similar. This may be due to the extensive share of large scale thermal energy in EPEX. Large-scale thermal plants are unable to vary the output swiftly due to physical and financial constraints, resulting in very low volatility of supply relative to demand. The relatively high correlation of 0.66 between demand and spot prices in EPEX confirms that high prices are more likely when demand is high, and oppositely for low demand. This correlation is lower in Nord Pool at 0.45, which may be explained by fewer situations where scarcity pricing is necessary due to available and relatively low cost supply in cases of high demand.

Wind is negatively correlated with the spot prices in both markets, as anticipated, as wind is expected to lower day-ahead prices. The correlation is more negative in EPEX, which corresponds well with the higher share of wind in EPEX (Table 3.1). The correlations between CO_2, gas, and oil are all quite high - not surprising, as these commodities are closely linked. CO_2 has a relatively high, positive correlation with coal, while the correlation with gas is negative.

The high correlations strongly imply that multicollinearity is present, a phenomenon which adversely affects the modeling; this issue is further discussed in Chapters 5 and 6.

Overall, the correlations indicate that the markets behave quite similarly in some aspects; demand, coal, and environmental costs are positively correlated with the spot price, as expected. Not surprisingly, hydro reservoir levels and wind power production are negatively correlated with the day-ahead prices. One would expect high fuel prices to contribute to higher electricity prices, but we note negative correlation between spot prices and gas/oil price, particularly in Nord Pool. When prices are low, hydro producers may choose to wait due to low prices, as the expected value of future production is higher. This increases the need for utilizing thermal peak load plants to balance load, even though the fuel prices are high. This may explain the negative correlation. Oppositely, if the electricity price is high, the hydro producers choose to ramp up production, thus preventing thermal peak load plants to operate even though fuel prices may be low.

4.4 Correlation of Variables Across Markets

The correlations between hourly spot prices in EPEX and Nord Pool are shown in Figure 4.3, and correlations between corresponding variables are shown in Table 4.8. Considering how the spot prices and fundamental variables compare is relevant for understanding the market dynamics. We first note that the spot price correlation varies between 0.30 to 0.53, with the highest correlations in peak load periods. Thus, prices are more similar across the markets when demand is at its highest (Figure A.1). During night, in off-peak periods, the correlations are lower. Generally, the correlations are not very high, implying the interconnection will be operated at full transfer capacity a large share of the time due to the price spread (Statnett (2013)). The weak correlation of 0.27 between the volatility series suggests that volatile periods are unlikely to coincide, and that extreme prices are unlikely to occur simultaneously, hence increasing the stabilization benefits of connecting the markets.

Interestingly, demand, supply, and wind power exhibit much stronger correlations across markets than the spot prices and volatilities. This implies similar consumption and production patterns that result in different price impacts due to the different market structures and pro-

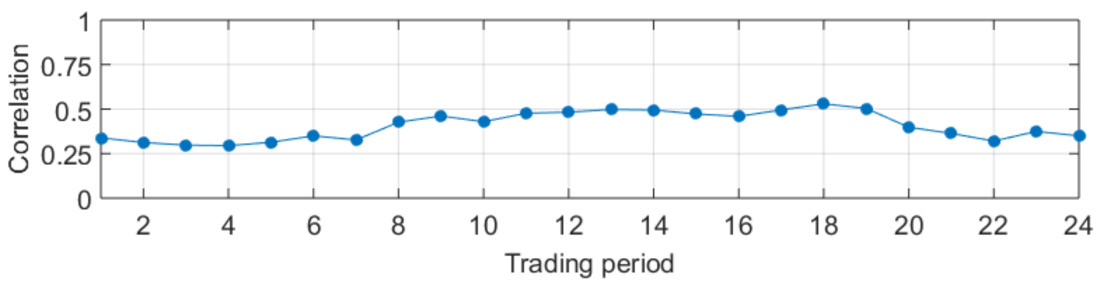


Figure 4.3: Correlations between hourly spot prices in EPEX and Nord Pool.

Table 4.8: Correlations between comparable variables in EPEX and Nord Pool. We assume the EPEX PPA corresponds to supply in Nord Pool.

Demand	Wind	Supply	Volatility
0.67	0.67	0.65	0.27

duction technologies (Table 3.1). However, as noted, the price correlations are at their highest when peak demand typically occurs and peak load plants are more likely to be required in both markets. EPEX has a large share of thermal power, which is harder to adjust according to fluctuations in the load. Nord Pool production is easily adjusted to match demand, as discussed in the previous section. This is in line with the higher price volatility in EPEX, and the less flexible production. For these reasons the correlation between the resulting spot prices do not reflect the high correlations of the other fundamental variables. The high correlation of wind power production reduces the benefits of interconnecting the markets, as more similar levels of renewable production make it harder to reduce the adverse impacts of excessively high or low renewable production.

Chapter 5

Methodology

5.1 Linear Quantile Regression

Quantile regression, which was first introduced by Koenker and Basset Jr. (1978), estimates the conditional relationship between the dependent variable and the independent variables for different quantiles. The residuals are assumed to be identically and independently distributed. Further, an advantage of this method is that there are no assumptions regarding the distribution due to the semi parametric form of the model. Thus, the quantile regression handles the unique behaviour of the electricity spot price and its time-varying volatility. Quantile regression permits an investigation of the entire distribution, thus providing a very detailed picture of how fundamental factors affect the electricity price. This allows for empirically estimating a unique conditional quantile model for most quantiles; exceptions are extremely high or low quantiles, due to few empirical observations. However, this is hardly an obstacle for modeling electricity day-ahead prices with the purpose of examining price drivers across the distribution. When prices are at levels which are observed extremely rarely, it is likely to be an extraordinary situation. For instance, the breakdown of a large power plant causes a strong reduction in supply, hence increasing the spot price. No econometric model can accurately predict the price in these situations based on fundamental variables, as such outliers cannot be captured by variations in variables that typically govern electricity day-ahead prices. Quantile regression therefore has a sufficiently fine resolution of tail estimates to provide a basis for discussing the factors driving the prices across the distribution.

We will have different linear quantile regression models for Nord Pool and EPEX due to different fundamental variables. For Nord Pool the regression model is given by:

$$\begin{aligned} Q_q(\ln P_{i,t}) = \alpha_i^q &+ \beta_{i,1}^q \ln P_{i,t-1} + \beta_{i,2}^q \ln P_{i,t-7} + \beta_{i,3}^q \ln DEMAND_{i,t} + \beta_{i,4}^q \ln SUPPLY_{i,t} \\ &+ \beta_{i,5}^q \ln WIND_{i,t} + \beta_{i,6}^q \ln RES.LEVELS_t + \beta_{i,7}^q \ln GAS_{t-1} + \beta_{i,8}^q \ln OIL_{t-1} \\ &+ \beta_{i,9}^q \ln COAL_{t-1} + \beta_{i,10}^q \ln CO_{2\,t-1} + \beta_{i,11}^q \ln EL.CERT_{t-1} + \beta_{i,12}^q \ln VOLATILITY_{i,t} \end{aligned}$$

while the regression model for EPEX will be:

$$\begin{aligned} Q_q(\ln P_{i,t}) = {} & \alpha_i^q + \beta_{i,1}^q \ln P_{i,t-1} + \beta_{i,2}^q \ln P_{i,t-7} + \beta_{i,3}^q \ln EX.DEMAND_{i,t} + \beta_{i,4}^q \ln EX.WIND_{i,t} \\ & + \beta_{i,5}^q \ln EX.PV_{i,t} + \beta_{i,6}^q \ln EX.PPA_t + \beta_{i,7}^q \ln COAL_{t-1} + \beta_{i,8}^q \ln GAS_{t-1} + \beta_{i,9}^q \ln OIL_{t-1} \\ & + \beta_{i,10}^q \ln CO_{2\,t-1} + \beta_{i,11}^q \ln VOLATILITY_{i,t} \end{aligned}$$

where $q \in [0,1]$ is the 5%, 25%, 50%, 75% and 95% quantile. The spot price of each day, $\ln P_{i,t}$, is the dependent variable on $\mathbf{X}_{i,t}$, which is the k-dimensional vector of explanatory variables, where i represents the 24 time periods throughout the day, and t represents the trading day. The constant for each quantile q is represented by α_i^q and the regression coefficients are represented by $\boldsymbol{\beta}_i^q$. α_i^q and $\boldsymbol{\beta}_i^q$ are found by the following optimization

$$\min_{\alpha_i^q, \boldsymbol{\beta}_i^q} \sum_{t=1}^{T} (q - \mathbf{1}_{\ln P_{i,t} \leq \alpha_i^q + \mathbf{X}_{i,t}\boldsymbol{\beta}_i^q})(\ln P_{i,t} - (\alpha_i^q + \mathbf{X}_{i,t}\boldsymbol{\beta}_i^q)),$$

where

$$\mathbf{1}_{\ln P_{i,t} \leq \alpha_i^q + \mathbf{X}_{i,t}\boldsymbol{\beta}_i^q} = \begin{cases} 1, & \text{if } \ln P_{i,t} \leq \alpha_i^q + \mathbf{X}_{i,t}\boldsymbol{\beta}_i^q, \\ 0, & \text{otherwise.} \end{cases}$$

Thus the models can be rewritten as:

$$Q_q(\ln P_{i,t} | \mathbf{X}_{i,t}) = \alpha_i^q + \mathbf{X}_{i,t}\boldsymbol{\beta}_i^q,$$

with the respective vector of explanatory variables for each market. The *sqreg* command in STATA has been used to estimate the quantile regression models. The *sqreg* command estimates the quantiles for a given hour simultaneously, and standard errors are obtained by bootstrapping. Bootstrapping is a statistical resampling technique used to determine the confidence intervals for any statistic. An advantage of bootstrapping is that it has no assumptions regarding the distribution of neither the dependent variables nor the error term.

5.2 Transformation of Negative Prices

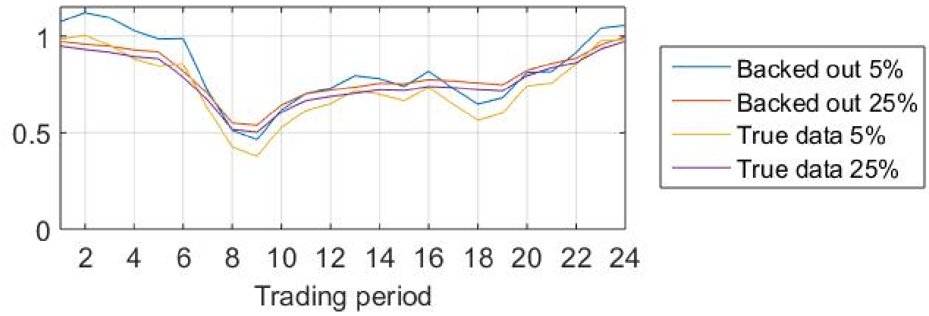
Use of logarithmic price series has the benefit of yielding coefficients that can be interpreted as elasticities. For the German EPEX prices, this is not straightforward, as there are negative price observations for most of the trading periods (Table 4.7). To account for negative prices and facilitate a logarithmic transformation, an option is to truncate the negative prices by setting them to a low positive value. This is corresponding to the approach taken by Forrest and MacGill (2013) when modeling the Australian NEM; prices below \$1/MWh were considered extremely low and outliers, and were set to \$1/MWh, yielding a logarithm of zero. The benefit of this approach is that the price series become more or less directly comparable, and trading periods with no negative prices are not affected, i.e., trading period 18-23. However, estimating lower quantiles in trading periods with a higher number of negative price occurrences is problematic. The results will be highly distorted if very low prices are treated as outliers. Some trading periods have up to 20 negative prices, approximately 1.5% of total observations (Table 4.7). Particularly the trading periods in the middle of the night have very low average negative prices; truncating these hours may cause a substantial loss of information. Thus, another option to handle negative prices is to shift all the prices, such that all values become positive and can be logarithmically transformed. This approach achieves less distortion in lower quantiles, but complicates the interpretation of the estimated coefficients as they cannot be interpreted as elasticities.

To minimize the adverse effects, we choose to use both methods according to which quantiles are being modeled. Upper quantiles for EPEX will not be noticeably impacted by truncating the lowest prices to a low positive value. Lower quantiles, on the other hand, will be distorted as a large amount of the data points would be artificially removed. Therefore, it is more reasonable to shift this data. With this reasoning, quantiles up to and including 25% are modeled using shifted EPEX prices. €223.37/MWh is added to each data point, ensuring the lowest EPEX price equals the lowest Nord Pool spot price of €1.38/MWh (Table 4.5). Quantiles above 25% are modeled using truncated data, minimizing the adverse effects. The data is truncated such that prices below €1/MWh are set to €1/MWh. We choose to not use prices below €1/MWh to avoid negative logarithmic prices - the logarithm of 1 is 0, while it is -2.303 for 0.1. The Nord Pool prices have not been altered, as there are no negative prices in the series.

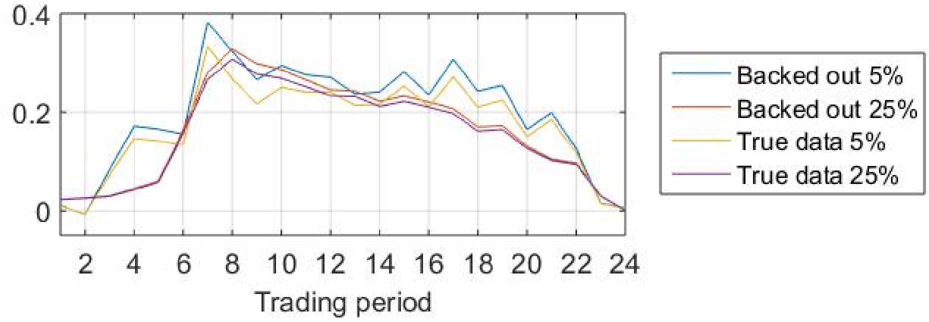
5.3 Transformation of Coefficient Estimates from Shifted Data

Directly interpreting the coefficients as elasticities from the lower quantile regressions in EPEX is not possible, nor are the estimates comparable with the higher quantiles. Therefore, to achieve comparable quantile curves, elasticity estimates for EPEX for quantiles 5% and 25% are backed out from the shifted coefficient estimates. First, the average value of each input variable is calculated for each trading period. A spot price estimate is computed from these average values and the coefficients estimated from shifted data, before incrementing a specific variable by +1% and calculating a new price estimate. The percentage change for the price estimates is taken as the elasticity of that specific variable; all variables and both quantile 5% and 25% in EPEX are handled in this manner.

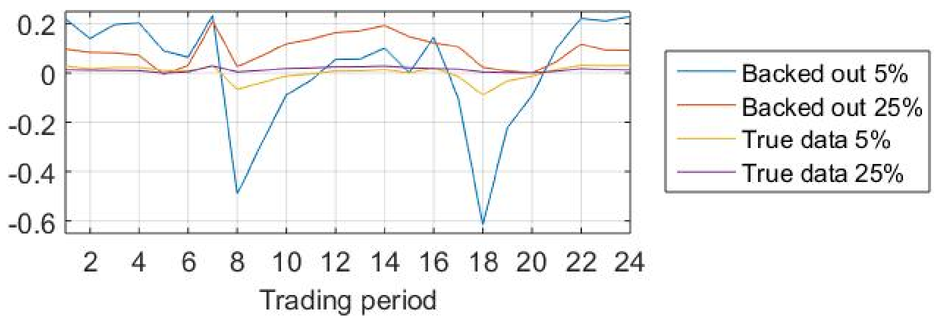
To ensure that the backed out approach yields adequate results, the approach was applied on the Nord Pool price data for comparison. A selection of the results is shown in Figure 5.1. It is assumed that these results are transferable to the EPEX data set, and that it behaves similarly. The results of the comparison are encouraging. The degree of similarity is high, particularly



(a) Lag 1.



(b) Lag 7.



(c) Supply.

Figure 5.1: Backed out and true coefficient estimates of lag 1, lag 7, and supply in Nord Pool.

when the significances are high, such as for the first and seventh lag (Figures 5.1a and 5.1b). The backed out elasticities tend to deviate noticeably primarily when the significances are low, such as for supply shown in Figure 5.1c. The backed out elasticities tend to be shifted on the y-axis relative to the true estimates. Further, we note that the quantile curves obtained from true data are slightly smoother, especially for the 5% quantile. Based on these results, we argue that backed out EPEX elasticities based on average values of input data provides an adequate foundation for a comparative analysis.

5.4 Transformation of Explanatory Variables

To facilitate a comparison of the coefficient estimates of explanatory variables, the input variables must be on logarithmic form. All parameters other than EPEX spot prices and photovoltaic forecasts are always larger than zero and logarithmically transformable. The photovoltaic forecasts series naturally include a large number of zero forecasts, thus we chose to set all values below 1 MWh to the value of 1, achieving a minimum logarithmic value of zero. There were 988 data points with forecasted production above 0 and below 1 MWh. It is reasonable to assume that solar in-feed below 1 MWh is practically zero production. All other variables were positive and directly transformed to logarithmic values for both markets. To obtain daily hydro reservoir estimates from weekly data, linear interpolation was used, assuming that the hydro usage is approximately linear within a single week.

5.5 Multicollinearity

As noted in Section 4.3 and observed from Tables A.5 and A.6, the correlations between gas, oil, and CO_2 prices are very high - all are above 0.64. These variables are highly linearly correlated, and should not be simultaneously included in the modeling to ensure the results are properly interpretable. To account for this, we remove the correlated variables when estimating the impact of each variable. For instance, when estimating the quantile curves of gas price in EPEX and Nord Pool, regressions excluding oil and CO_2 prices are estimated to capture the impact of the gas price. Further, the correlation between coal and CO_2 is quite high at 0.56. Testing indicated that the model results were less robust when both were included simultaneously; thus, quantile curves for coal are modeled excluding CO_2, and opposite when estimating CO_2 curves.

When discussing all the other variables, all variables are used in the regressions. This is not detrimental to the analysis, as it focuses on how the estimated coefficients - and thus the impact on price formation - varies throughout the trading day. In these cases the values of the linearly correlated variables do not matter.

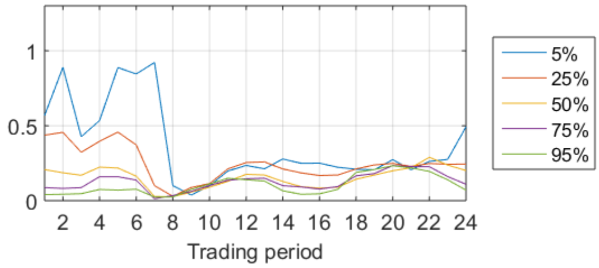
Chapter 6

Results and Discussion

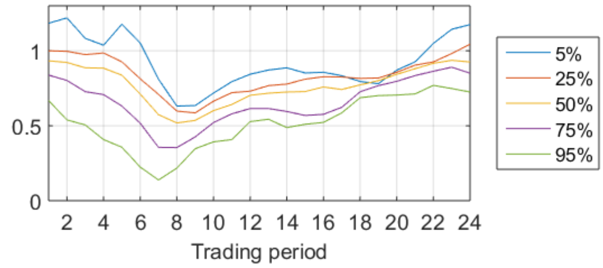
6.1 Quantile Regression Results

The results for each fundamental variable will be separately discussed and compared in the following sections. Photovoltaic forecasts, hydro reservoir levels, and prices of green electricity certificates are only present in one of the markets, and cannot be compared across markets. However, the impact of these variables is evaluated to obtain a more complete analysis of the price drivers in each market. To examine the drivers throughout the entire price distribution, results for quantiles 5%, 25%, 50%, 75%, and 95% are presented. The models used to estimate coefficients for analysing the linearly correlated prices of oil, gas, CO_2 and coal differ from the other models, as discussed in Section 5.5. This was required to enable an analysis of the price formation dynamics resulting from each variable, as the results otherwise are non-robust and harder to interpret. When analyzing the results, consideration of the significance of each variable is necessary, thus the p-values from the regression results are presented and evaluated. The p-values are easy to interpret and compare across quantiles and markets, and are therefore chosen to represent the significance of the variables.

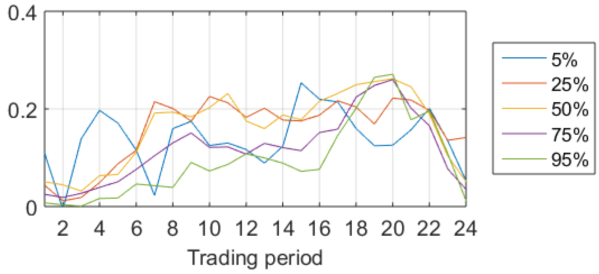
As discussed in Section 5.2, the 5% and 25% quantile regressions for EPEX are estimated on shifted price data. The elasticities for these two quantiles have been backed out from the regression results, using the approach described in Section 5.3. This is done to achieve comparable elasticities for all estimated quantiles. Thus, when analyzing the results, it is important to keep in mind that the three upper quantile curves in EPEX are more robust. The Nord Pool elasticities are all estimated on unaltered data, thus all quantiles are equally robust and comparable.



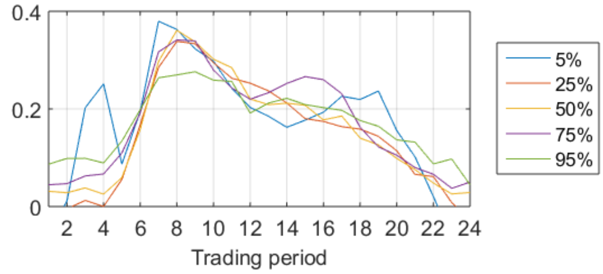
(a) Lag 1, EPEX.



(b) Lag 1, Nord Pool.



(c) Lag 7, EPEX.



(d) Lag 7, Nord Pool.

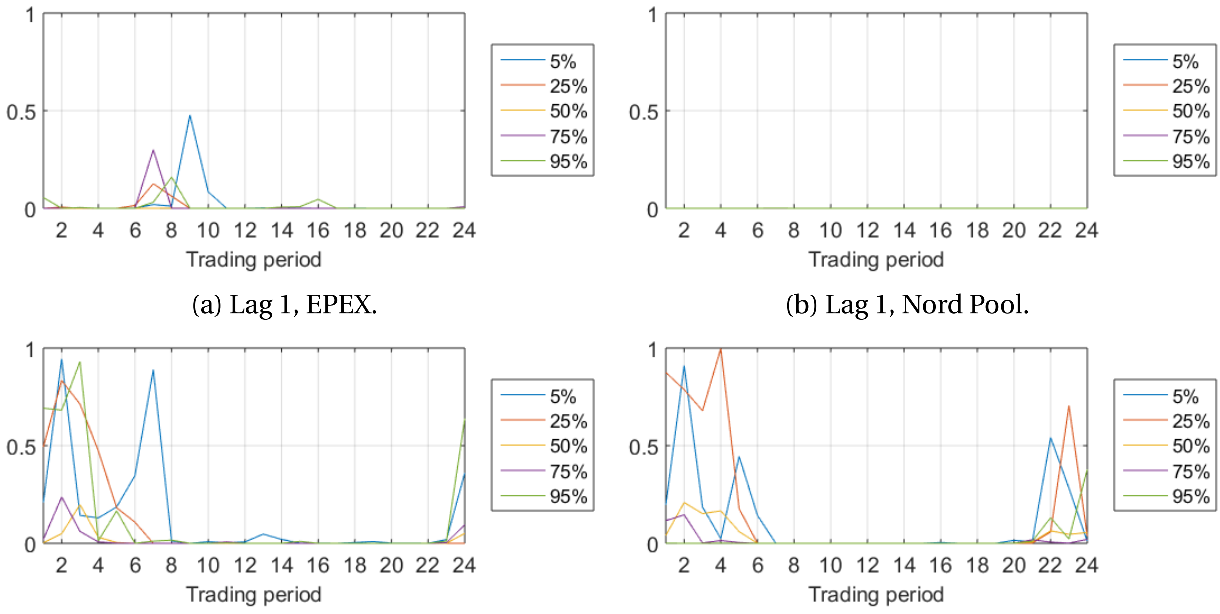
Figure 6.1: Coefficient estimates of lag 1 and lag 7 throughout the trading day.

6.2 Lagged Prices

The coefficient estimates of the first and seventh lagged prices are presented in Figure 6.1. The significances of both lags are shown in Figure 6.2; lag 1 is practically always significant, with few exceptions in EPEX. The estimated coefficients for lag 1 tend to be highest during night, and lowest in the late morning for both markets and all quantiles. In contrast, the elasticities of the seventh lag are low during night compared to day, particularly in Nord Pool. The results imply that yesterday's price is a more important price driver in trading periods with predictable low average demand, as shown in Figure A.1, relative to higher-demand trading periods.

The coefficient magnitudes of lag 1 are mostly larger than those of lag 7 in Nord Pool. The highest lag 1 coefficient is 1.22% in trading period 2, compared with 0.38% for lag 7 in trading period 7, both in quantile 5% in Nord Pool. This corresponds well with the discussion in Section 4.2, where the auto-correlation between spot price and lag 1 (0.92) is found to be noticeably higher than the correlation between spot price and lag 7 (0.84). Further, we note from 6.1a and 6.1b that the coefficient magnitudes of lag 1 decrease with higher quantiles, implying that other factors drive very high prices in both markets. In EPEX, this is particularly evident in the early morning; however, note that the 5% and 25% elasticities are backed out from shifted data and may be exaggerated. The seventh lag tends to be most influential when people and industry are more active, thus capturing the difference between a working day and a weekend.

Lag 1 and lag 7 in EPEX have relatively similar impacts on the spot price throughout the trading day, with some exceptions during night when the impact of the first lag is higher. This



(a) Lag 1, EPEX. (b) Lag 1, Nord Pool.

(c) Lag 7, EPEX. (d) Lag 7, Nord Pool.

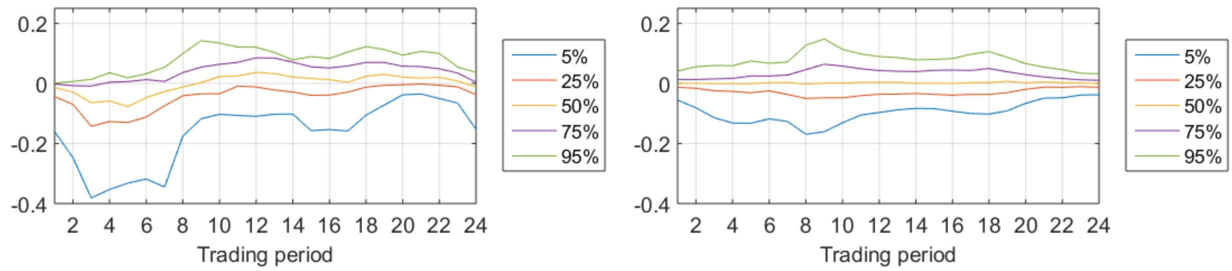
Figure 6.2: Significance of lag 1 and lag 7 coefficients throughout the trading day.

is as expected, since the correlations with the spot price for both variables are close to equal (Table 4.6). Therefore, the day-ahead and the weekday-effect have approximately the same influence in EPEX. Oppositely, the lag 1 magnitudes are larger than those of lag 7 in Nord Pool, thus the day-ahead effect is more pronounced relative to the weekday effect. These results show that the weekly consumption patterns are relatively more important to the price formation in EPEX than in Nord Pool. The higher volatility exhibited by the EPEX spot prices, as discussed in Section 4.2, likely explains the lesser importance of price lags as price drivers. Nord Pool prices are generally much more stable, and it is thus reasonable that the price of the next trading day are more similar to recent prices.

6.3 Price Volatility

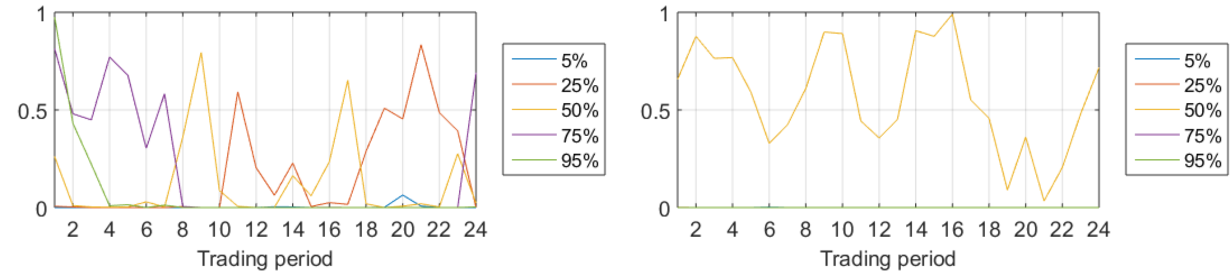
From the discussion in Section 4.2 we know that the price range and price volatility in EPEX is much higher than in Nord Pool, suggesting the tails of the price distribution in EPEX are thicker. From the significances shown in Figure 6.4 we observe that volatility in Nord Pool is significant in all quantiles except 50%. In EPEX, the 25% and 50% quantiles are the least significant quantiles. The tails are highly significant throughout the trading day, except quantile 95% during night. This confirms that volatility is a more important driver in the tails of the price distributions. Considering that electricity prices exhibit volatility clustering, it is not unanticipated that high volatility further increases high prices or reduces already low prices.

The coefficients for both markets are shown in Figure 6.3. In general, the quantile curves are quite similarly shaped in each market, with similar positive magnitudes in the two highest



(a) EPEX. (b) Nord Pool.

Figure 6.3: Coefficient estimates of price volatility throughout the trading day.

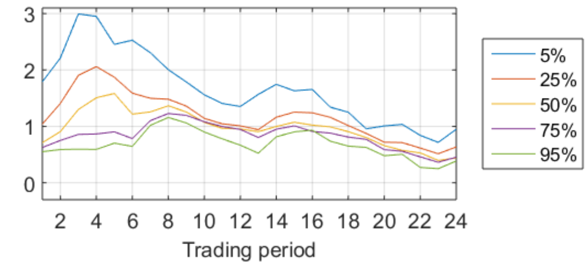


(a) EPEX. (b) Nord Pool.

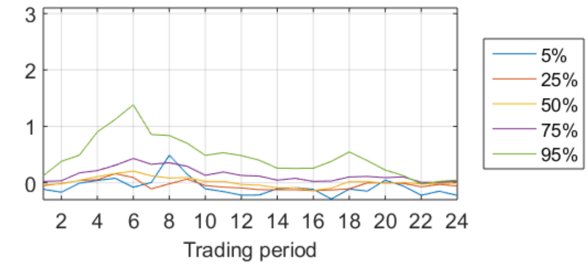
Figure 6.4: Significance of price volatility coefficients throughout the trading day.

quantiles. These volatility curves closely follow the average daily demand (Figure A.1); there are small peaks around noon and early evening, and the magnitudes are lowest during night. This implies that price volatility is closely related to demand when prices are high. The elasticities are at their highest in quantile 95% in trading period 9 in both markets; 0.14% in EPEX, and 0.15% in Nord Pool. Although significant, the volatility is not the primary price driver behind high prices, as the elasticities are low.

The price impact of volatility is negative in the low quantiles for both markets, where the magnitudes of the lowest quantile are noticeably larger in EPEX than in Nord Pool. This suggests that the price reducing impact is at its strongest when unpredictable wind production leads to negative prices in EPEX. The 50% quantile also has significant negative coefficients in EPEX during night, implying that when prices are on expected levels and average demand is low, higher volatility tends to decrease spot prices. The negative price impact of volatility in Nord Pool is quite similar throughout the trading day, but slightly stronger during day. The 5% is notably lower than the 25% quantile, confirming that volatility is most influential in the tails in both markets.

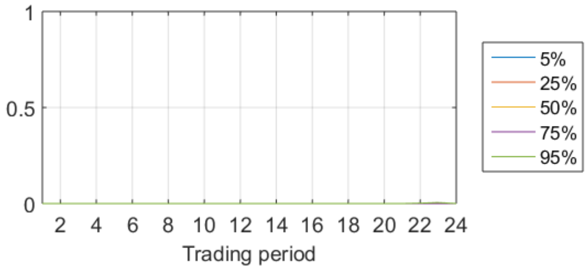


(a) EPEX.

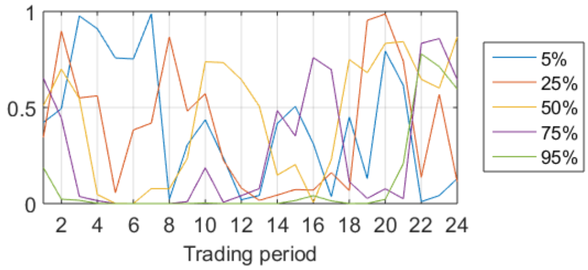


(b) Nord Pool.

Figure 6.5: Coefficient estimates of demand throughout the trading day.



(a) EPEX.



(b) Nord Pool.

Figure 6.6: Significance of demand coefficients throughout the trading day.

6.4 Demand

The coefficient estimates of demand are shown in Figure 6.5, and significances are depicted in Figure 6.6, and we initially note that demand is always influential in EPEX. The significances vary greatly in Nord Pool, and are only notably high for the 95% quantile. These results are supported by the correlations between spot prices and demand discussed in Section 4.4; the correlation in EPEX of 0.66 by far exceeds that of 0.45 in Nord Pool. Further, Nord Pool is a less volatile market; the large amount of hydro provides flexibility in the power system, as discussed in Section 3.2. Therefore, fluctuations in demand are only influential in parts of the spot price distribution.

As discussed in the previous section, the upper quantile volatility coefficient curves follow the average demand curves. Thus, the dynamics behind the highest prices are closely related to both average demand levels and price volatility in both markets. As expected from the significances and correlations, the magnitudes of demand coefficients in EPEX, shown in Figure 6.5a, exceed those of Nord Pool, confirming demand is a more important price driver for all quantiles in EPEX. The influence of demand is at its highest during very early morning and late afternoon in both markets, but the Nord Pool elasticities tend to peak 2-3 trading periods after those in EPEX.

A major difference between the two markets is that the coefficient magnitudes decrease with higher quantiles in EPEX, while they increase with higher quantiles in Nord Pool. The 5% quantile coefficients in EPEX are notably higher than the other quantiles, with a peak value of 2.99% in trading period 3. The highest Nord Pool elasticity is 1.38%, found in trading period 6 quantile 95%. The demand elasticities for both markets are at their highest when average demand is fairly low, as seen from Figure A.1; thus, changes in demand are most influential in off-peak periods. This may be due to market participants not anticipating changes in lower-demand trading periods, so that unexpected changes induce higher price impact than otherwise expected.

The importance of demand in higher quantiles in Nord Pool can be explained by several factors. The flexibility provided by the hydro reservoirs enables demand fluctuations to be covered without utilizing more expensive peak-load plants. However, when demand is very high, more expensive peak load plants will be switched on and become price setters, thus increasing the spot price. Although Nord Pool is a highly competitive market with many producers, situations with power scarcity may allow producers with available capacity to exercise market power and set prices above the marginal cost, further increasing prices in the highest quantiles.

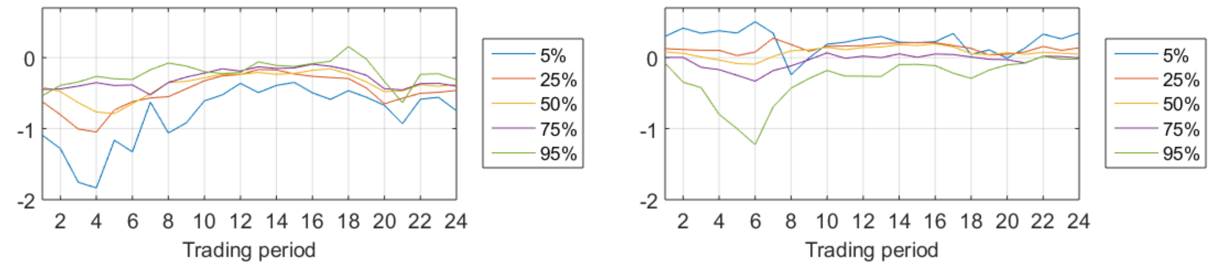
6.5 Supply Parameters

Here we present the estimated coefficients and the significances of the different supply parameters. Note that hydro reservoir levels and photovoltaic production are only present in Nord Pool and EPEX, respectively, hence cannot be compared.

6.5.1 PPA/Supply

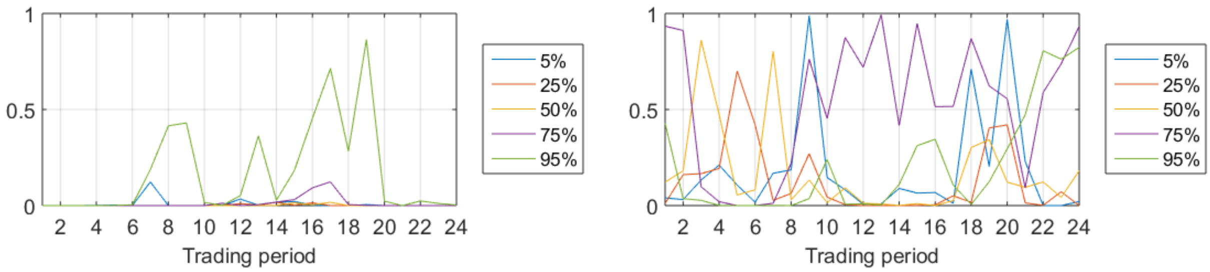
The estimated coefficients for the supply parameter in EPEX and Nord Pool are presented in Figure 6.7, and the significances are found in Figure 6.8. Note that the variables used to represent supply in EPEX and Nord Pool are differently defined, as discussed in Section 4.1.2. The supply parameter is more significant in EPEX than in Nord Pool, likely due to the differences in energy mixes discussed in Section 3.2, as most German producers have limited ability to adjust the production if desired.

As expected, PPA coefficients are negative, confirming that increasing supply reduces the spot price. The coefficients magnitudes in EPEX decrease with higher quantiles, hence PPA is most influential when prices are either in the low or expected range. PPA tends to be most influential in off-peak periods, and the lowest elasticity of -1.83% is found in quantile 5% in trading period 4. Inflexible large scale thermal load is typically used to cover most of the demand in these trading periods, and a relatively strong price-reducing impact is anticipated as production cannot be swiftly and cost-efficiently adjusted following load fluctuations. The lesser importance of PPA in upper quantiles indicates that increasing expected supply levels are unable



(a) EPEX. (b) Nord Pool.

Figure 6.7: Coefficient estimates of PPA/supply throughout the trading day.



(a) EPEX. (b) Nord Pool.

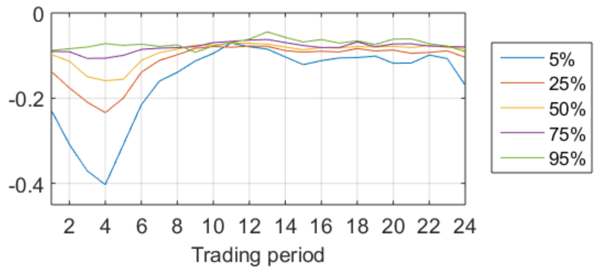
Figure 6.8: Significance of PPA/supply coefficients throughout the trading day.

to entirely prevent spot prices from reaching very high levels, as these prices are likely to have other primary determinants.

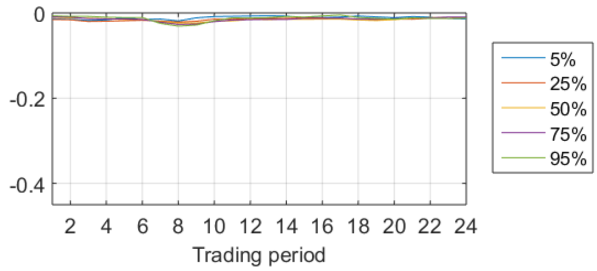
Nearly all elasticities in Nord Pool are negative, with few exceptions for the three lowest quantiles. There are some positive and significant estimates in the 5% quantile, particularly during night and early morning. The coefficients are mostly insignificant for all quantiles, except the 95% quantile during the first half of the day and 5% during night/noon. This implies that supply in Nord Pool is most influential in the tails of the price distribution. The highest negative elasticity of -1.12% is found for the 95% quantile in trading period 6. Supply is generally found to have a price-dampening effect in Nord Pool for upper quantiles, particularly for off-peak periods (Figure A.1b). Unlike EPEX, the supply elasticities become more negative with higher quantiles, strongly implying that supply is more price-dampening for higher prices. This may be due to the flexibility offered by hydro reservoirs, as production can be swiftly ramped up when spot prices and profits are higher - consequently increasing the market supply and lowering the spot price.

6.5.2 Wind Power Production

The coefficients for wind power production for all quantiles are shown in Figure 6.9. Unsurprisingly, the estimated coefficients are negative. Consequently wind reduces electricity spot prices, as the introduction of low marginal cost wind power substitutes more expensive power

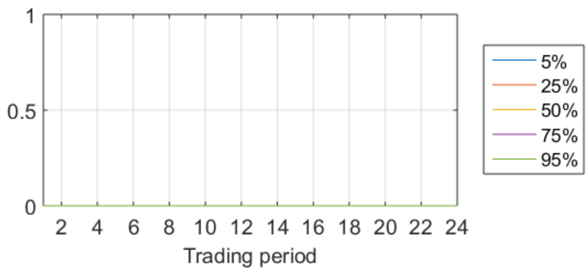


(a) EPEX.

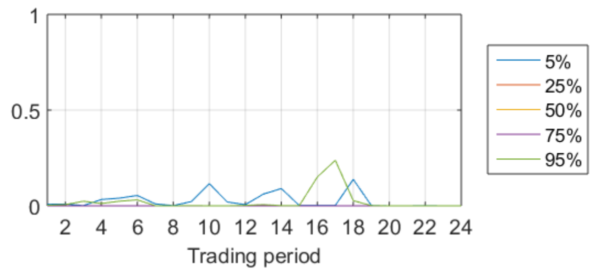


(b) Nord Pool.

Figure 6.9: Coefficient estimates of wind power production throughout the trading day.



(a) EPEX.



(b) Nord Pool.

Figure 6.10: Significance of wind power production coefficients throughout the trading day.

plants. The magnitudes of the coefficients are noticeably higher in EPEX than Nord Pool, which is reasonable considering the larger share of wind power in EPEX than in Nord Pool; 13.3% compared with 8.9% (Table 3.1). This is further supported by the more negative correlation between wind power and spot price in EPEX, as discussed in Section 4.3.

As seen from the significance plots in Figure 6.10, wind is practically always significant in both markets. Exceptions are some trading periods in the 5% and 95% quantiles in Nord Pool. However, the elasticities in Nord Pool are very low for all quantiles, hence wind is not a dominant price driver. In EPEX, the influence of wind is at its highest during night and early morning, when the average demand is at its lowest and wind likely constitutes a large share of the production. The elasticities decrease in magnitude towards higher quantiles, confirming that wind is most influential in the lower tail. This is further supported by Figure A.2, from which it is clear that low spot prices tend to occur when wind power production is high. Overall, wind is an important electricity price driver in EPEX, and is particularly important in the formation of low spot prices.

6.5.3 Photovoltaic Power Production

The estimated coefficients of photovoltaic production forecast in EPEX are given in Figure 6.11, and the corresponding significances are presented in Figure 6.12. Note that only results for trading periods 7-21 are shown, as the photovoltaic production is negligible for the other periods

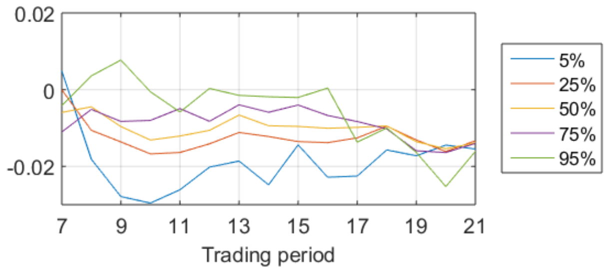


Figure 6.11: Coefficient estimates of photovoltaic power production.

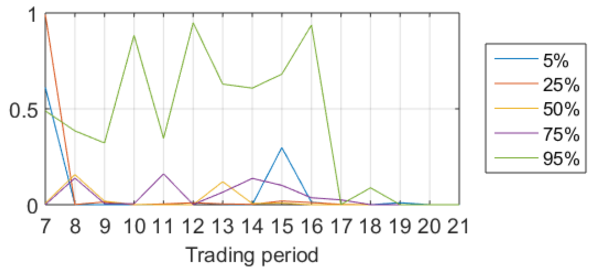


Figure 6.12: Significance of photovoltaic power production.

(Figure A.3). The significances vary; the 95% quantile is least significant in most trading periods, followed by 75%. Photovoltaic production is generally most significant during day when the sun is at its highest.

As expected, the coefficient estimates are negative; consequently, increasing photovoltaic production reduces the EPEX spot prices. The coefficient magnitudes increase with lower quantiles; the strongest price-dampening effect of photovoltaic production is -0.030% in quantile 5% in trading period 10. When the 95% quantile is significant in the early evening, a sensitivity of -0.025% in trading period 20 is the highest. These results imply that photovoltaic production is most influential in the lower tail, similar to wind power production. However, the coefficient estimate magnitudes for wind are noticeably larger than for photovoltaic production, hence the latter is a less important price determinant. This is supported by the different shares in the energy mix (Table 3.1); the share of photovoltaic power is 5.9%, while wind is 13.3%.

6.5.4 Hydro Reservoir Levels

The first observation for the hydro reservoir levels variable in Nord Pool are the varying significances throughout the distribution, shown in Figure 6.14. The estimated coefficients are given in Figure 6.13, and we note that an increase in hydro reservoir levels has a price-reducing impact for the higher quantiles in Nord Pool. Higher reservoir levels reduce the benefit of postponing production and increase the risk of spillovers, hence producers are willing to increase production and the highest spot prices are reduced. The significant and positive coefficients for the 5% quantile during night are unanticipated. A possible explanation is that increased water inflow stimulates power export when Nord Pool prices are low, thus decreasing local supply and causing higher prices. Further, it may be due to bidding behaviour and strategic production planning. These results are similar to those of the supply parameter, where the lowest quantile also had significant positive coefficients during night.

The two highest quantiles are most significant during night; the highest price impact in the upper tail is an elasticity of -0.094% in trading period 7 for the 95% quantile. The insignificance of the upper quantiles during daytime implies that an increase in hydro reservoir levels is insufficient to prevent high spot prices in these trading periods. This may be due to already utilizing

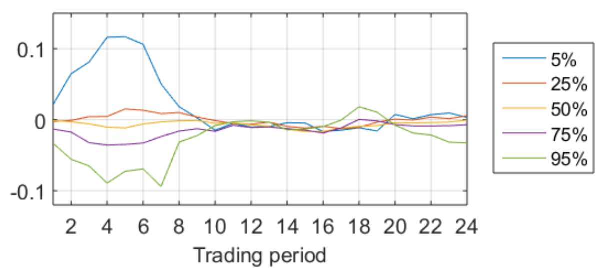


Figure 6.13: Coefficient estimates of hydro reservoir levels.

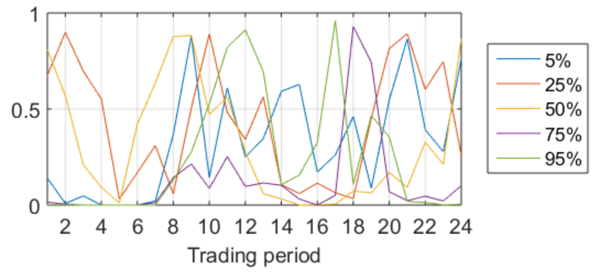


Figure 6.14: Significance of hydro reservoir levels.

maximum production capacity, or due to increasing exports in high-demand trading periods, thus not reducing the Nord Pool spot price. The 5% quantile is also most significant during night, and has its highest elasticity of 0.12% in trading period 5. As for the supply parameter, the overall result is that hydro reservoir levels are most influential in the tails of the price distribution during night. This is in accordance with the 50% quantile having insignificant low coefficients, implying the price expectation is not severely impacted by reservoir levels.

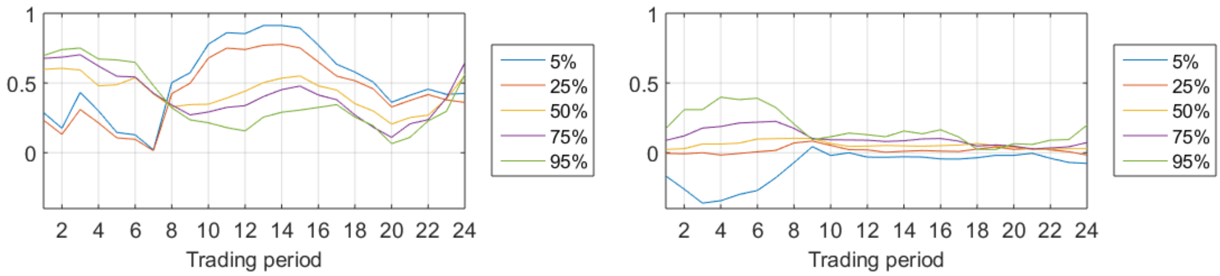
6.6 Fuel Prices

The results for the different fuel parameters are presented here. Note that each model for coal, oil and gas is estimated excluding the highly correlated variables, to isolate the impact of each respective fundamental variable.

6.6.1 Coal

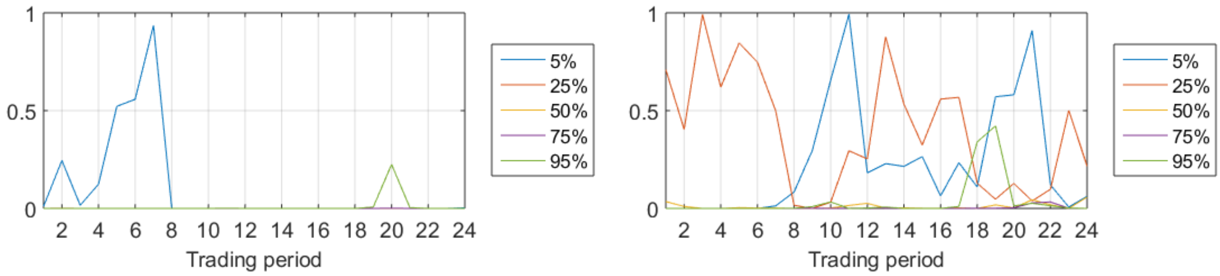
As depicted in Figure 6.16, coal prices are highly significant in EPEX, and less significant in the lower tail in Nord Pool. From Figure 6.15, we note that the estimated coefficients are positive when significant in both markets, confirming that higher coal prices increase the electricity prices. An exception is found in the 5% quantile in Nord Pool, where the elasticities during night are negative and significant. The coal price coefficients in EPEX are noticeably higher than those in Nord Pool, indicating coal price is a more important driver behind electricity prices in Germany. This is according to expectations due to the higher share of coal in the German power system, as discussed in Section 3.2.

In EPEX, the coal price is most influential in the upper quantiles during night, as it is often the price setter in these trading periods. During day the dynamics are different in EPEX; the lower tail coefficients are most influential. High demand levels cannot be covered by base load alone, yielding coal less relevant in the highest quantiles during day. Base load covers a larger share of demand when electricity prices are close to or below expected levels, as the results indicate. Thus, coal is an important determinant behind lower prices in trading periods when demand is at medium to high levels (Figure A.1).



(a) EPEX. (b) Nord Pool.

Figure 6.15: Coefficient estimates of coal prices throughout the trading day.



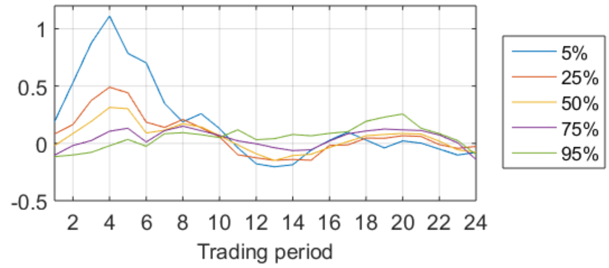
(a) EPEX. (b) Nord Pool.

Figure 6.16: Significance of coal price coefficients throughout the trading day.

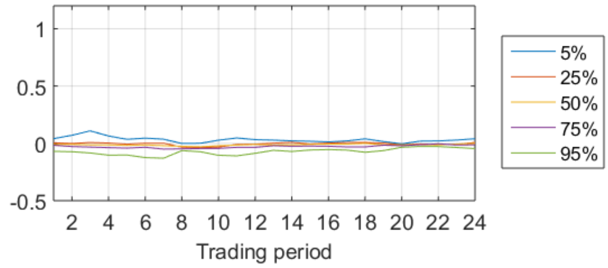
The two lowest quantile curves in EPEX are quite similar magnitude-wise, and peak during day; note that the 5% quantile is mostly insignificant during night and early morning. This strongly indicates that spot prices in the lowest quantiles are driven by other factors - such as wind power. In Nord Pool, the lower quantiles are mostly insignificant, implying that coal is not an important driver behind low prices. An exception is the 5% quantile during night, when coefficient values are negative. This is unanticipated, but may be due to higher coal prices shifting production towards lower marginal-cost technologies, such as large-scale nuclear or hydro production. The upper quantiles are more significant, and have positive coefficients which increase with higher quantiles. Like in EPEX, the coal price coefficient magnitudes for Nord Pool are at their highest during night in the 95% quantile. At those times when hydro is less able to meet demand, for instance during dry years, coal price becomes more important and leads to higher nightly spot prices.

6.6.2 Gas

The gas price coefficients for all trading periods and quantiles are presented in Figure 6.17, with significances shown in Figure 6.18. The significances vary throughout the trading day and tend to increase with higher quantiles, particularly in Nord Pool. Gas is slightly more significant in EPEX, which is reasonable considering the larger share of thermal energy and lack of flexible

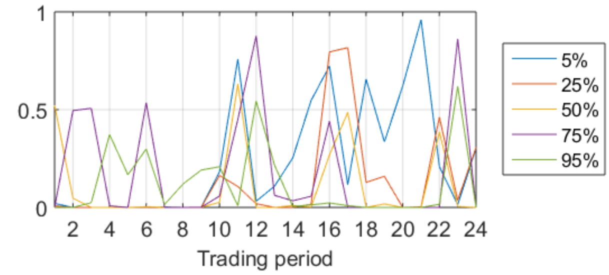


(a) EPEX.

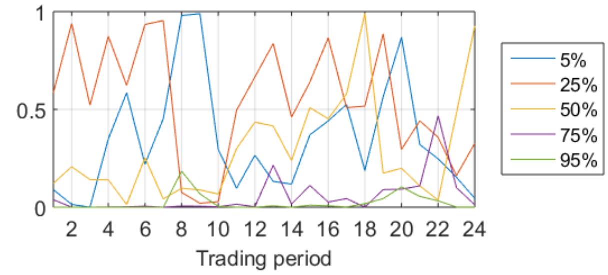


(b) Nord Pool.

Figure 6.17: Coefficient estimates of gas price throughout the trading day.



(a) EPEX.



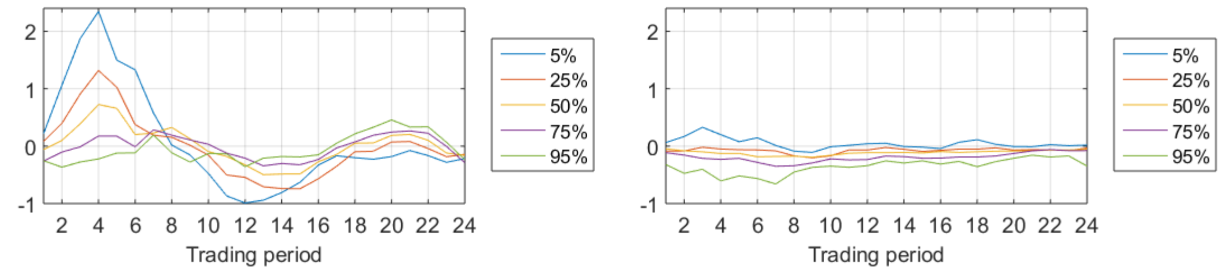
(b) Nord Pool.

Figure 6.18: Significance of gas price coefficients throughout the trading day.

hydro to cover peak load.

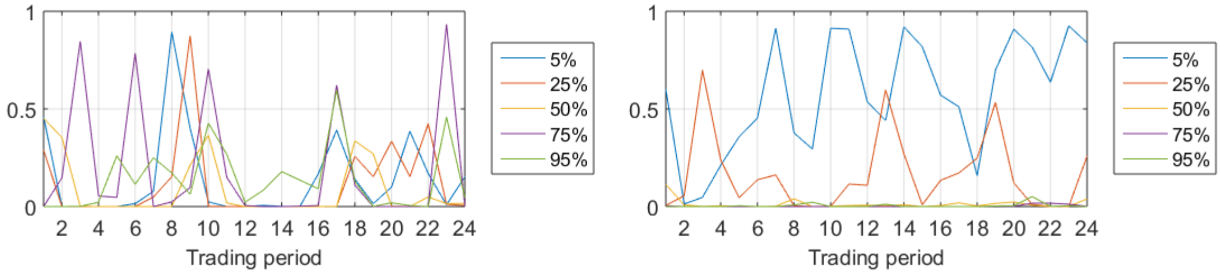
The upper quantiles are the most significant in Nord Pool, and have low negative elasticities, as was indicated by the negative correlation between gas and spot price discussed in Section 4.3. A possible explanation is that high spot prices and expensive gas motivates hydro producers to meet load, resulting in lower electricity prices. However, the coefficient magnitudes are negligible, hence gas is not an important price driver in Nord Pool. In EPEX, the impact of gas price varies across different quantiles. The 5% and 25% quantiles are significant during night, with high positive magnitudes for the 5% quantile. The 5% quantile elasticity peaks at 1.11% in trading period 4. The high coefficient values for low quantiles during night are unexpected, as gas is not commonly used to cover load during off-peak hours when prices are low. The explanation may be that a sudden drop in low marginal cost wind power production necessitates the use of gas, thus increasing the price. These results may be further exacerbated due to using backed out elasticities, as discussed in Section 5.3.

Interestingly, the coefficients become negative and significant for the three lowest quantiles in EPEX in the middle of the day, simultaneously as photovoltaic average production levels peak (Figure A.3). The negative coefficients are possibly due to substitution; low marginal cost photovoltaic power replaces more expensive peak load plants, and spot prices are lowered. Oppositely, the 95% quantile has significant and positive coefficients in these trading periods. This is likely due to gas covering demand when low marginal cost photovoltaic production is lack-



(a) EPEX. (b) Nord Pool.

Figure 6.19: Coefficient estimates of oil price throughout the trading day.



(a) EPEX. (b) Nord Pool.

Figure 6.20: Significance of oil price coefficients throughout the trading day.

ing, thus increasing the upper tail prices. Gas price coefficients are positive and significant for quantiles 75% and 95% in the early evening when demand is at its highest (Figure A.1a), as anticipated. Large scale thermal plants and renewable energy sources are unable to cover peak demand, and gas power plants are used, consequently increasing the prices. This effect increases with higher quantiles, as the 95% quantile estimates are well above those of the 75% quantile.

6.6.3 Oil

The coefficient estimates for the oil price are given in Figure 6.19, with corresponding significances given in Figure 6.20. In Nord Pool, quantile 5% is insignificant throughout the trading day, closely followed by the 25% quantile. The insignificance illustrates that when prices are already low, oil does not affect the price formation, which is expected as oil-fueled plants are used mainly to cover peak demand. The significance of the remaining quantiles in Nord Pool is unexpected as the share of oil in this market is negligible. The significances in EPEX vary greatly, but are highest for all quantiles in the middle of the day and in the evening for the two highest quantiles.

In Nord Pool, the quantile estimates are negative and particularly low during morning for the 95% quantile; the elasticity is -0.66% in trading period 7. The negative coefficient estimates decrease towards zero for lower quantiles. However the negative coefficients are unexpected, as for the gas price discussed previously. A possible explanation is that high electricity prices during night motivate hydro producers to ramp up production to cover demand, thus lowering the highest prices and reducing the need for fossil fueled peak load plants. Overall, the sensitivities to oil price are very low, thus oil is not an important price driver in Nord Pool.

The highest elasticities in EPEX are found in quantiles 5% and 95%. Similar to the gas price, the 5% quantile has a strong positive impact during night; this may be due to a sudden lack of wind power necessitating the use of peak load plants to meet demand. According to Paraschiv et al. (2014), oil is rarely used for power production in Germany and is primarily related to coal transportation. This may explain the positive price impact in off-peak periods, when coal dominates the power production. In the afternoon, all quantiles but 95% are significant and negative. As for gas, this is likely related to cheaper low marginal cost photovoltaic power substituting the peak load plants. The results found in the peak periods are according to expectations; the two highest quantiles have a notably positive elasticities, as oil is more likely to be the price setter.

6.7 Environmental Costs

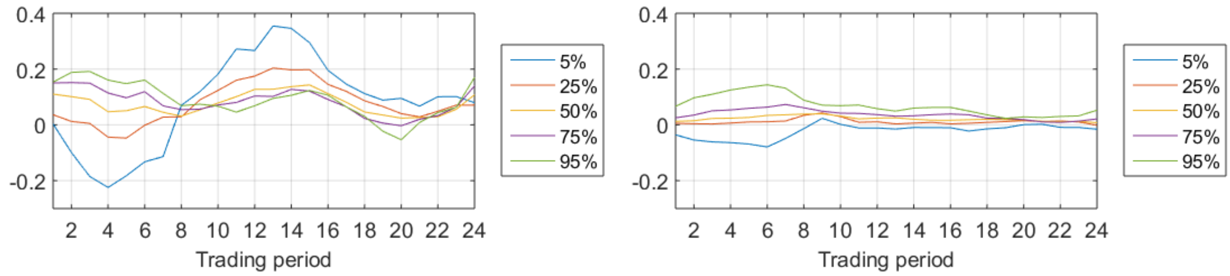
The results for the environmental costs, CO_2 emission costs in both Nord Pool and EPEX, and electricity certificate prices (only in Nord Pool) are presented here. Note that due to multicollinearity, CO_2 is estimated without prices of coal, gas and oil included.

6.7.1 CO_2

When assessing the sensitivities to the cost of CO_2 presented in Figure 6.21, it is important to note that this cost is primarily related to coal, as it emits the largest amounts of CO_2. Hence, it is as expected that the estimated quantile curves for CO_2 are similarly shaped to those of coal. This is also true for the significance curves shown in Figure 6.22. Note that the CO_2 quantiles have the opposite shape compared to gas/oil curves, as expensive carbon allowances shift some production from coal to gas/oil which emit less CO_2.

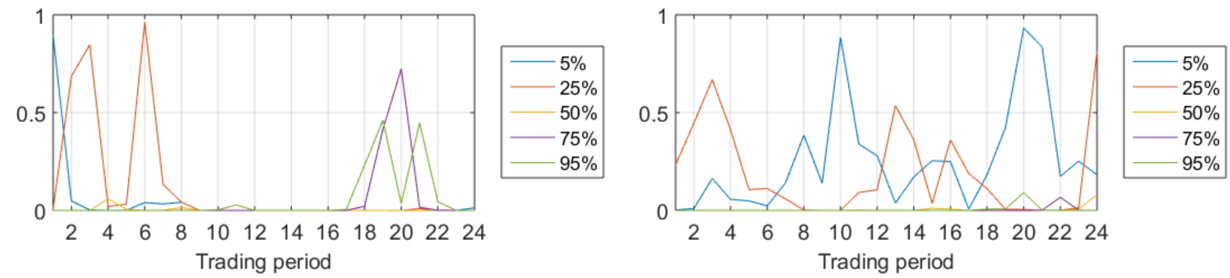
The lower quantile CO_2 elasticities are highest during day in EPEX, as for the coal price. During night, the highest quantile curve has the largest positive coefficients, while the lowest quantile is most negative. Further note that the magnitudes of CO_2 elasticities are less than those of coal. This implies that the cost of carbon amplifies the price impact of coal throughout the price distribution. Keep in mind that the 5% quantile elasticities in EPEX are backed out as described in Section 5.3, thus the high magnitudes may be exaggerated. Considering that a 1% increment in the CO_2-price is less in absolute value than a similar change in the coal price, we conclude the sensitivity to carbon emission costs is low in EPEX.

Low coefficient values in Nord Pool are as anticipated, considering the low share of fossil



(a) EPEX. (b) Nord Pool.

Figure 6.21: Coefficient estimates of CO_2 price throughout the trading day.



(a) EPEX. (b) Nord Pool.

Figure 6.22: Significance of CO_2 price coefficients throughout the trading day.

fuels. However, as seen in Figure 6.22b, the coefficients are mostly significant except quantiles 5% and 25%. From Figure 6.21b we conclude there is a small positive sensitivity to emission costs. The CO_2 price is most influential in the 95% quantile, with coefficients nearly as high as those in EPEX during night. The implication is that fossil fuels are used primarily when prices are high for each trading period. This is further confirmed by the low significance of the lower quantile curves. Carbon emission costs are not a main price driver in Nord Pool, but rather accentuate the impact of fossil fuels, particularly coal. The cost of CO_2 is notably more influential in EPEX due to the considerably larger share of thermal energy.

6.7.2 Electricity Certificates

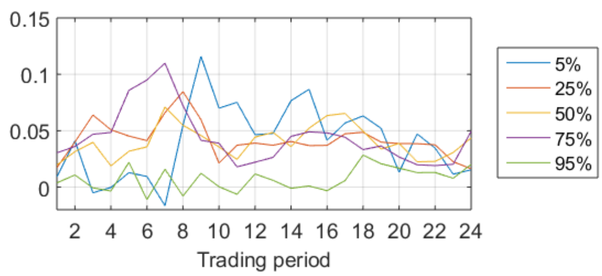


Figure 6.23: Coefficient estimates of electricity certificate prices.

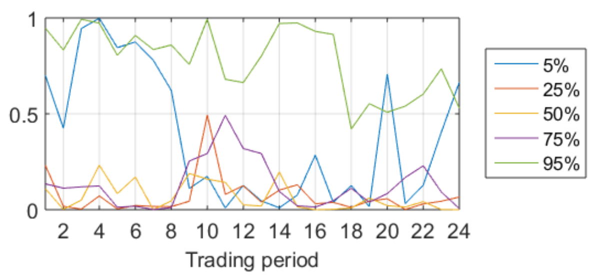


Figure 6.24: Significance of electricity certificate prices.

The electricity certificate price coefficients and significances in Nord Pool are presented in Figures 6.23 and 6.24. Firstly, we note that the coefficient magnitudes are low and positive, and mostly insignificant in the tails of the price distribution. The 75% quantile is also mostly insignificant, except in the morning/afternoon hours. Thus, certificate prices are not important when prices are very high or low. This is as expected, as extreme prices are likely to be determined by other factors than environmental subsidies.

The 50% quantile is the most significant, followed by 25%, indicating that the influence of certificate prices is highest for prices close to the expected value. Further, the elasticities are quite similar throughout the entire trading day. Considering the low coefficient magnitudes and their low significances overall, we conclude that the electricity certificate price is not an important driver behind the Nord Pool spot prices.

6.8 Summary of Results

Here we briefly summarize the findings for each fundamental variable and its impact on the spot price formation in both EPEX and Nord Pool. A full comparison and conclusion follows in the next chapter.

6.8.1 EPEX

The price sensitivities to lag 1 and lag 7 are quite similar in magnitude in EPEX, but with different impacts throughout the trading day. Lag 1 is most important during night, while lag 7 is primarily influential in the remainder of the day. The impact of volatility differs for upper and lower quantiles; it has a price-increasing effect in quantiles 75% and 95%, mainly during day. During night, the influence is price-reducing in the lower tail. Forecasted demand is significant in all quantiles throughout the entire trading day. The elasticities are positive and decreasing with higher quantiles, and are highest during off-peak periods. PPA elasticities are, as expected, negative in all quantiles. The elasticities increase towards zero with higher quantiles, and the influence is at its highest in the lower tail. Wind production forecasts are negative and significant in all trading periods and quantiles, and are most influential during night in the lower tail. Photovoltaic production forecasts also have negative elasticities, and the impact peaks around noon. However, the coefficient magnitudes are much smaller relative to wind. Coal price elasticities vary non-linearly across the price distribution; the influence is at its highest in the upper quantiles during night, and during day it is a more important determinant behind the lower prices. CO_2 has quite similar quantile curves to coal, but the magnitudes are much lower. The impact of gas price is at its highest during night in the lower price tail, and also has high elasticities for the upper tail in peak-periods. Oil is quite similar to gas, as both are peak load fuels, but it has notably higher coefficient magnitudes overall.

6.8.2 Nord Pool

The influence of the first price lag is positive and highest during night, with elasticities decreasing with higher quantiles. The lag 7 magnitudes peak during late morning and early evening, and are notably lower than those of the first lag. The price volatility increases upper tail prices and decreases the lower tail prices, with no influence on the expected spot price. Demand is only a price-driver in the highest quantile, particularly during morning and early evening, where it has a quite strong positive effect. Supply is also most influential in the highest quantile, with a price-reducing impact. The wind power production elasticities are quite low in magnitude and negative for all quantiles, thus wind is not an important price determinant. Hydro reservoir levels are found to be most influential in the tails of the price distribution, and have a price-dampening impact in the upper tail during night. Somewhat surprisingly, the effect on the lowest quantile is price-increasing, as it is for supply. The influence of coal price is limited, but it is most influential in the highest quantiles during night, with an unexpected negative price impact in the 5% quantile. Gas price has, as expected from the low market share, elasticities of approximately zero throughout the entire trading day and price distribution in Nord Pool. Oil has slightly higher significances and larger coefficients for the tail quantiles than gas, but is overall not an important price driver. The analysis of the sensitivity to the CO_2 price confirms that this variable is closely related to coal, with quite similar quantile curves and lower magnitudes. Electricity certificates are found to be primarily relevant for prices close to the expected level, but have a negligible price impact.

Chapter 7

Conclusion and Recommendations for Further Work

7.1 Conclusion

In this thesis we model the spot price distribution in EPEX and Nord Pool using quantile regression. We analyze and compare how different fundamental variables non-linearly influence the different price quantiles throughout the trading day in each market. This is motivated by the upcoming market integration due to the NordLink cable, which will connect Norway and Germany in 2020. When assessing the price formation dynamics in EPEX and Nord Pool, it is obvious that there are many similarities and differences. The impact from each variable varies throughout the trading day and across the price distribution. Clearly, electricity markets are complex as the relations between fundamental variables and day-ahead prices are highly non-linear across several dimensions.

Autoregressive effects are the most important price drivers in Nord Pool; the first lagged price is the most influential variable and is thus the best price predictor. The seventh lag has notably lower coefficients, but is also a highly influential variable in Nord Pool. The first lag is most influential in off-peak periods and lower tail, while the seventh lag is most relevant in trading periods with higher demand. In EPEX, lagged prices are less important relative to other variables, but the impact of the first lag slightly exceeds that of the seventh lag. The intraday price dynamics are similar to Nord Pool: the first lag is most influential during off-peak, while the seventh lag is more relevant when demand is higher. The volatility of the prices explains the differences in relevance of autoregressive effects. Nord Pool day-ahead prices are much more stable, and it is reasonable that lagged prices are better price determinants. The price impact of the volatility variable is very similar in both markets: it is highly significant in both tails and tends to make prices deviate further from the expected value.

Demand has a particularly large impact in EPEX, as the elasticities are high for all quantiles.

Supply in EPEX - expressed through voluntarily reported power plant availability - has a price lowering influence for the entire price distribution. Both the demand and supply parameters in EPEX tend to have lower absolute elasticities with increasing quantiles, implying that the highest prices are driven by other factors. The dynamics are completely opposite in Nord Pool; both demand and supply are only influential in the highest quantile, implying that prices in the normal range are barely influenced by these variables. Note that demand and supply are based on realized production and consumption data, which, although it is remarkably similar to the available forecasts, may slightly alter the results. The differences in impact from changes in demand and supply are related to the energy sources used; the flexibility provided by hydro in Nord Pool smoothly balances load fluctuations. The results support this, as hydro reservoir levels were found to be primarily influential in the tails of the prices.

The lower and upper tails in EPEX have quite different dynamics; some variables are relevant in only one tail, while others influence both tails. In addition to demand and supply strongly impacting the lower tail, wind power production has a notably strong influence - particularly during night when negative prices are known to occur. The fossil fuel prices are important in both tails, but with very different impacts. Coal is most important during day for lower quantiles, while it is most relevant for upper quantiles during night. Gas and oil are similar to each other; the quantile plots have positive peaks during night and early evening, and a slight negative dip in the middle of the day. These dips are unexpected, but are plausibly explained by low cost photovoltaic power substituting the fossil fuels, resulting in lower prices. Both gas and oil are used to cover peak load, hence the positive impact on prices in the highest quantiles in peak demand periods is according to expectations. The irrelevance of both oil and gas in Nord Pool is as anticipated, as the share of fossil fuels is quite low. Coal has a small significant impact, and exhibits similar dynamics as in EPEX during night; the elasticities are positive and increasing with higher quantiles. This is likely due to coal covering the base load and becoming the price setter for the highest prices in off-peak periods. As CO_2 quantile curves closely follow those of coal, the impact is quite similar in both EPEX and Nord Pool. In addition to emphasizing the price impact of coal, an increase in cost of CO_2 also encourages shifting to fuel sources emitting less carbon.

Overall, the analysis of the impact of fundamental variables confirms that the price formation dynamics differ greatly in these two markets. Nord Pool spot prices are primarily driven by autoregressive effects, while other variables, such as demand, are influential only in some quantiles. It appears that much of the potential price impact from fundamental variables is balanced by the large hydro reservoirs. EPEX has a higher number of relevant price drivers compared to Nord Pool. This is likely explained by the structure of the German power market, which consists of large scale thermal power in combination with unpredictable renewable energy sources, resulting in a much less flexible system. Consequently, changes in the balance between production and consumption, or fuel prices, have stronger impacts on the electricity price formation.

A thorough understanding of dynamics in these two markets is important for market participants. Producers benefit from the insights given by this analysis, as it supports investment planning in these markets, and assists in developing hedging strategies. Further, it is valuable for TSOs, as it improves future grid operation and development, as well as investors considering entering or expanding their presence in these markets. Connecting two markets is most beneficial if there are differences in prices and price dynamics, which is clearly the case for Nord Pool and EPEX, as shown in our analysis. Market participants in both EPEX and Nord Pool will mutually benefit and increase trading profits. Further, intermittency issues in Germany are offset and security of supply is enhanced.

7.2 Recommendations for Further Work

There are several extensions that can be considered following this master's thesis. A possibility is conducting scenario analyses to consider how changes in fundamental variables impact the price distribution throughout the trading day. Future research might also attempt to analyze the price impact of the cable in both markets, and assess how changes to the market structure or energy mix may impact the price formation and trading. For instance, one could assess how a large increase in wind in Germany or the Nordics would change price dynamics. Another extension would be to investigate how higher transfer capacity between the two markets would impact the price dynamics.

To expand on the topic of comparing electricity markets we suggest conducting a similar analysis comparing the fundamental drivers in Nord Pool and the UK power markets, motivated by the NSN cable to be completed in 2021. Further, an analysis comparing fundamental price drivers in all three markets would be of interest, in order to assess which interconnection is likely to be most beneficial for market participants. Different econometric models may be used to assess the market dynamics, to confirm that our results are correct. An example would be using copula-based non-linear quantile regression, or a logistical regression.

Appendix A

Additional Tables and Figures

Table A.1: Descriptive statistics of fundamental variables in EPEX.

	Demand	PPA	Wind	PV	Coal	Gas	Oil	CO_2	Vol
Mean	54850	55146	5297	2514	71.23	23.21	74.17	9.35	8.63
Median	54852	55535	3894	93	70.69	24.00	75.73	7.76	7.33
Maximum	79884	64169	26256	24525	99.02	39.50	83.78	16.84	134.53
Minimum	29201	40016	229	0	51.49	11.15	61.03	2.48	1.78
Standard Dev.	10082	4894	4432	4280	11.6	4.1	4.8	4.3	5.8
Skew	-0.05	-0.27	1.52	2.04	0.24	-0.63	-0.72	0.28	6.23
Excess Kurtosis	-1.04	-0.77	2.30	3.75	-1.08	0.88	-0.35	-1.48	82.04
Jarque-Bera	1776	1426	23299	49469	2220	3804	3537	4008	11031893

Table A.2: Descriptive statistics of fundamental variables in Nord Pool.

	Demand	Supply	Wind	Reservoir	Coal	Gas	Oil	CO_2	El.cert	Vol
Mean	45468	45264	1171	69.97	71.23	23.21	74.17	9.35	23.40	3.76
Median	44282	44191	915	73.84	70.69	24.00	75.73	7.76	23.37	2.56
Maximum	71773	74093	4494	109.61	99.02	39.50	83.78	16.84	42.85	79.48
Minimum	22245	23011	1	19.94	51.49	11.15	61.03	2.48	1.19	0.28
Standard Dev.	9400	9636	951	25.10	11.59	4.13	4.78	4.33	4.06	4.32
Skew	0.34	0.30	0.89	-0.26	0.24	-0.63	-0.72	0.28	0.25	5.80
Excess Kurtosis	-0.63	-0.51	-0.02	-1.10	0.88	-0.35	-1.08	-1.48	1.24	57.30
Jarque-Bera	1371	990	5045	2364	2220	3804	3537	4008	2854	5473298

Table A.3: Overview of the variables chosen for modeling the EPEX spot price.

Variable, units	Description	Data source	Resolution
Lagged spot price, €/MWh	Market clearing price for the same hour of the last relevant delivery day – lag 1 and lag 7 have been used	European Power Exchange (EEX)	Hourly
Expected demand, MWh	Demand forecast for the relevant hour on the delivery day as modelled in Paraschiv et al. (2014)	Own data, German Weather Service	Hourly
Expected wind power infeed, MWh	Expected infeed published by German transmission system operators following the electricity price auction	Transmission system operators http://www.50hertz.com/de/, http://amprion.de/ https://www.transnetbw.com/en, http://www.tennet.eu/nl/home.html	Hourly
Expected photovoltaic infeed, MWh	Expected infeed published by German transmission system operators following the electricity price auction	Transmission system operators http://www.50hertz.com/de/, http://amprion.de/ https://www.transnetbw.com/en, http://www.tennet.eu/nl/home.html	Hourly
Expected power plant availability, MWh	Ex ante expected power plant availability for electricity production (voluntary publication) on the delivery day, published daily at 10:00 am	European Power Exchange and transmission system operators: ftp://infoproducts.eex.com	Daily
Coal price, €/12,000 t	Latest available price (daily auctioned) of the front-month Amsterdam-Rotterdam-Antwerp (ARA) futures contract before the electricity auction takes place	European Power Exchange	Daily
Gas price, €/MWh	Last price of the NCG day-ahead natural gas spot price on the day before the electricity price auction takes place	Bloomberg, Ticker: GTHDAHD Index	Daily
Oil price, €/bbl	Last price of the active ICE BrentCrude futures contracton the day before the electricity price auction takes place	Bloomberg, Ticker: COA Comdty	Daily
Price for EUA, € 0.01/EUA 1000 t CO_2	Latest available price of the EEX Carbon Index (Carbix), daily auctioned at 10:30 am	European Power Exchange (EEX)	Daily
Spot price volatility	Volatility at each data point based on an EWMA model	European Power Exchange(EEX)	Hourly

Table A.4: Overview of the variables chosen for modeling the Nord Pool spot price.

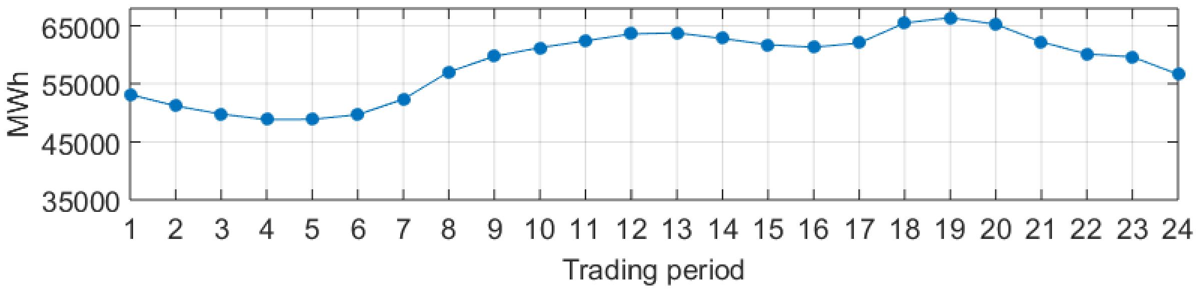
Variable, units	Description	Data source	Resolution
Lagged spot price	Market clearing price for the same hour of the previous delivery day - lag 1 and lag 7 have been used	Montel/Nord Pool	Hourly
Consumption, MWh	Realized consumption for the relevant hour on the relevant day	Montel/Nord Pool	Hourly
Water reservoir level, TWh	Weekly reservoir levels in Nord Pool in TWh, includes Norway, Sweden and Finland. Daily data obtained by linearly interpolating between weekly data points	Nord Pool	Weekly
Wind power production, MWh	Realized wind power production for the relevant hour on the relevant day	Energinet.dk	Hourly
Supply, MWh	Realized production for the relevant hour on the relevant day	Montel/Nord Pool	Hourly
Coal price, €/12,000 t	Latest available price (daily auctioned) of the front-month Amsterdam-Rotterdam-Antwerp (ARA) futures contracts before the electricity auction takes place	European Power Exchange (EEX)	Daily
Gas price, €/MWh	Last price of the NCG day-ahead natural gas spot price on the day before the electricity price auction takes place	European Power Exchange (EEX)	Daily
Oil price, €/bbl	Last price of the active ICE BrentCrude futures contract on the day before the electricity price auction takes place	Bloomberg, Ticker: COA Comdty	Daily
Price for EUA, € 0.01/EUA 1000 t CO_2	Latest available price of the EEX Carbon Index (Carbix), daily auctioned at 10:30 am	European Power Exchange (EEX)	Daily
El-certificate price, €/ certificate	Swedish electricity certificate average price (volume-weighed), converted from SEK/certificate to €/certificate	Macrobond	Daily
Spot price volatility	Volatility at each data point based on an EWMA model	European Power Exchange (EEX)	Hourly

Table A.5: Correlations between variables in EPEX.

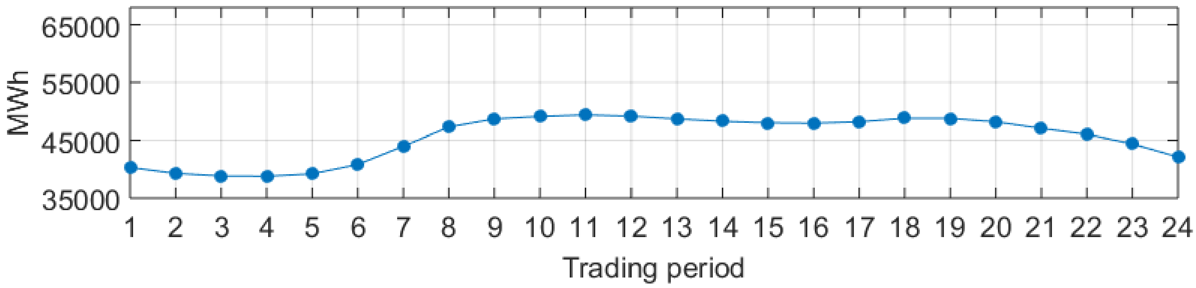
	EPEX Spot	Demand	PPA	Wind	PV	Coal	Gas	Oil	CO_2	Vol
EPEX Spot	1									
Demand	0.66	1								
PPA	0.03	0.34	1							
Wind	-0.33	0.06	0.20	1						
PV	0.01	0.29	-0.25	-0.09	1					
Coal	0.34	0.01	-0.22	-0.04	-0.11	1				
Gas	-0.01	-0.04	0.06	0.08	0.15	0.02	1			
Oil	-0.13	-0.09	-0.04	0.08	0.22	-0.12	0.71	1		
CO_2	0.29	0.06	-0.11	-0.15	-0.20	0.56	-0.64	-0.67	1	
Vol	-0.19	-0.02	0.16	0.29	-0.02	-0.06	0.23	0.15	-0.19	1

Table A.6: Correlations between variables in Nord Pool.

	NP Spot	Demand	Supply	Wind	Reservoir	Coal	Gas	Oil	CO_2	El.cert	Vol
NP Spot	1										
Demand	0.45	1									
Supply	0.33	0.97	1								
Wind	-0.14	0.21	0.22	1							
Reservoir	-0.40	-0.22	-0.13	0.01	1						
Coal	0.27	-0.07	-0.07	-0.08	0.13	1					
Gas	-0.22	0.12	0.19	0.14	0.26	0.02	1				
Oil	-0.47	0.00	0.11	0.13	0.12	-0.12	0.71	1			
CO_2	0.54	-0.13	-0.22	-0.18	-0.23	0.56	-0.64	-0.67	1		
El.cert	0.44	0.20	0.07	-0.05	-0.40	-0.22	-0.35	-0.41	0.29	1	
Vol	0.26	0.22	0.20	-0.05	-0.02	0.09	-0.03	-0.12	0.07	0.00	1

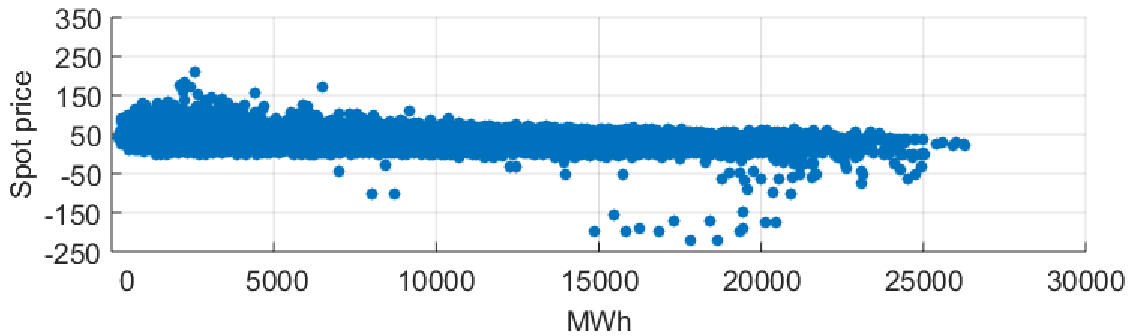


(a) EPEX.

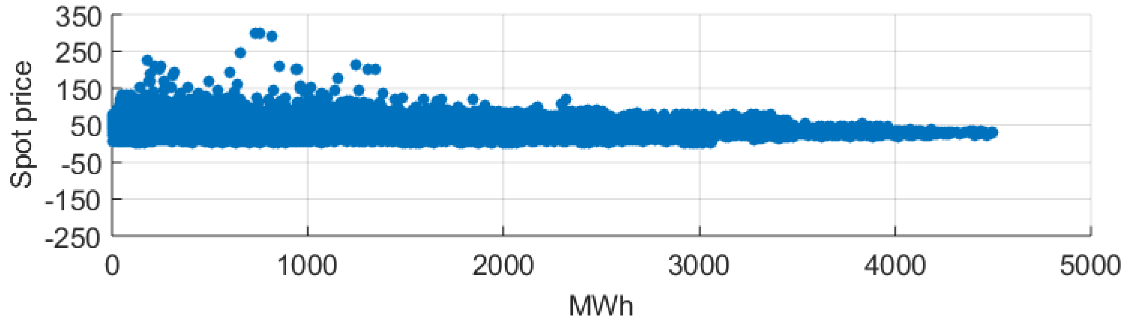


(b) Nord Pool.

Figure A.1: Overview of average hourly demand.



(a) EPEX.



(b) Nord Pool.

Figure A.2: Scatter plots of wind power production versus spot price.

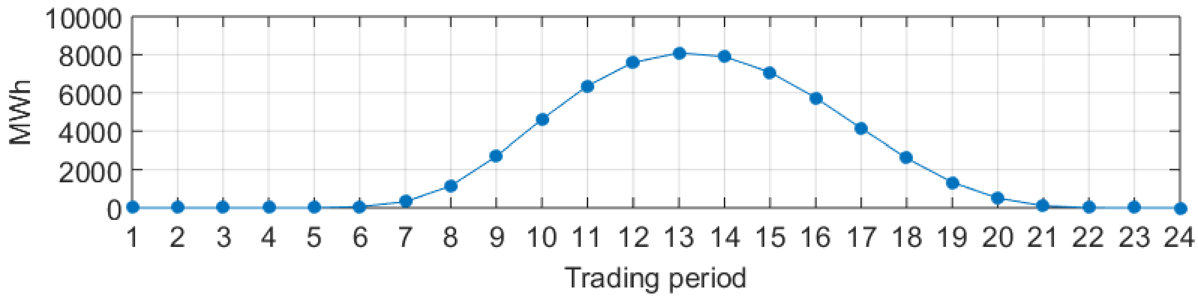


Figure A.3: Average hourly photovoltaic power production in EPEX.

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