European market integration and price convergence: A panel quantile regression analysis of NordLink

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European market integration and price convergence: A panel quantile regression analysis of NordLink

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Abstract

The European Union aims to strengthen electricity market integration as part of its transition to a low-carbon energy system, with substantial investments in cross-border transmission infrastructure. This paper presents the first empirical analysis of a new interconnector, NordLink, on price convergence between southern Norway (NO2) and Germany. Using a novel panel quantile regression model, we estimate the impact of NordLink on the full distribution of hourly electricity prices in both markets. We find that the cable raised average prices in NO2 and lowered them in Germany, but with substantial heterogeneity across the price quantiles. In NO2, lower-quantile prices fell while upper-quantile prices rose. In Germany, the largest reductions occurred in the upper price quantiles. Regarding volatility, NordLink increased price fluctuations in NO2 and reduced them in Germany. We also find that the interconnector has altered the relationship between electricity prices and key fundamentals. Notably, electricity prices in NO2 have become substantially more exposed to gas prices post-NordLink, while Germany has become less exposed. Our findings highlight that market integration influences not only average prices, but also the dynamics and structure of electricity

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prices, with important implications for policymakers and market participants navigating the future of cross-border transmission in Europe.

Keywords: Electricity prices, econometric analysis, interconnector, price volatility, renewables

JEL classification: C31, C33, Q21, Q41

1 Introduction

The European Union (EU) aims to reach a share of 45% of renewables in the energy consumption by 2030.[1] To accommodate the high share of intermittent solar and wind energy, the EU also has ambitious plans to increase the amount of cross-border transmission capacity within the internal market.[2] The European electricity market is already highly integrated through market coupling, which is a mechanism used to harmonize different electricity exchange systems and align electricity prices across regions.[3] By ensuring that electricity flows follow price signals, market coupling promotes the efficient use of grid capacity and production resources. However, market coupling also leads to price convergence, which usually strengthens with an expansion of cross-border transmission capacity. As market integration leads to price contagion from the high-price area to the low-price area, expanding cross-border transmission capacity can be a politically contentious issue. Therefore, it is vital to explore the price effects of current interconnectors to inform the policy debate on the future of the European electricity grid and to allow market participants to better adjust to changes in interconnection capacities.

[1]https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en

[2]Specifically, the EU Action Plan for Grids suggests a doubling in the current cross-country grid capacity by 2030: https://ec.europa.eu/commission/presscorner/api/files/attachment/876888/Factsheet_EU%20Action%20Plan%20for%20Grids.pdf

[3]For an overview of the integration of European electricity markets and the theoretical literature on market integration, see e.g. Batalla, Paniagua, and Trujillo-Baute (2019) and Creti, Fumagalli, and Fumagalli (2010). For more details on the Single Day-ahead Coupling (SDAC), see https://www.entsoe.eu/network_codes/cacm/implementation/sdac/.

To address this issue, we provide an empirical study of NordLink, a subsea cable that for the first time directly connected southern Norway (NO2) to the German electricity market. NordLink began operation on December 9, 2020, and has a transmission capacity of 1400 MW. Although previous research has investigated market integration in different countries (e.g., Valeri, 2009, de Menezes and Houllier, 2015, Figueiredo, Silva, and Cerqueira, 2016, Keppler, Phan, and Pen, 2016, Sapio, 2019), NordLink is particularly interesting as it connected Norway, a market with historically low and stable electricity prices due to flexible hydropower, with Germany, a market characterized by a high share of intermittent renewables and volatile prices. Such interconnectors are especially valuable in the energy transition, as they allow Europe to store excess renewable power generation from one region in the reservoirs of another (e.g., Green and Vasilakos, 2012, Mauritzen, 2013).

To estimate the impact of NordLink on hourly electricity prices in Norway and Germany, we use a novel method for panel quantile regression with fixed effects developed by Machado and Santos Silva (2019). This method allows us to analyze the entire distribution of electricity prices while controlling for individual hourly effects. Although electricity prices are observed on an hourly level, much of the literature has aggregated the data to a daily resolution and applied time series methods to examine the effect of market integration (e.g., Mauritzen, 2013, de Menezes and Houllier, 2016, Do, Nepal, and Jamasb, 2020). However, given that bids in electricity markets are submitted simultaneously for all 24 hours of the following day, it has been argued that hourly electricity prices should not be treated as 24 independent time series, but instead as 24 unique hours observed over time (Huisman, Huurman, and Mahieu, 2007, Peña, 2012, Keppler, Phan, and Pen, 2016, Tselika, 2022). Furthermore, many studies rely on mean regression analysis (e.g., Annan-Phan and Roques, 2018, Batalla, Paniagua, and Trujillo-Baute, 2019, Gugler and Haxhimusa, 2019), which captures only average effects and does not account for the high variability and fat tails of electricity price distributions. By combining quantile regression with panel fixed effects, we aim to overcome these limitations and better capture the full range of price dynamics from market integration.

The opening of NordLink coincided with the onset of the European energy crisis, which began in 2021 when Russia started restricting gas supplies to the continent. This led to a surge in electricity prices in Europe, even in countries with a low share of fossil fuels in their energy mix, such as Norway. In Norway, many stakeholders attributed the soaring electricity prices observed in NO2 to increased exports to Germany after the launch of NordLink, which has led to a growing opposition to cross-country interconnectors.[4] Our identification strategy is to use our quantile regression model to compare the distribution of day-ahead prices in NO2 and Germany before and after NordLink became operational while controlling for fundamental drivers of short-term electricity prices, and in particular to the drivers of the energy crisis.

Beyond its direct effect on prices, NordLink could also have affected price formation indirectly by changing the relationship between day-ahead prices and their fundamental drivers such as gas and renewable energy. There is a large literature that has explored the downward pressure of renewable generation on electricity prices, the so-called merit-order effect (e.g., Cludius et al., 2014, Ketterer, 2014, Paraschiv, Erni, and Pietsch, 2014, Maciejowska, 2020, Tselika, 2022). Further research has also shown that market integration can alter the impact of renewable sources on electricity prices (e.g., Keppler, Phan, and Pen, 2016, Sapio, 2019, Mauritzen and Sucarrat, 2022). Therefore, we also explore whether price formation in NO2 and Germany has changed since NordLink became operational. Similarly to Keppler, Phan, and Pen (2016), we use a standard panel regression model, in which we allow NordLink to modulate the relationship between the day-ahead price and its explanatory variables.

This paper contributes to the literature that uses historical market data and empirical modeling to estimate the impact of market integration on electricity prices (e.g., de Menezes and Houllier, 2015, Gianfreda, Parisio, and Pelagatti, 2016, Figueiredo, Silva, and Cerqueira, 2015, Keppler, Phan, and Pen, 2016, Sapio, 2019). Although prior studies have used quan-

[4]For example, several political parties in Norway have proposed to cut the interconnectors to Denmark when they come up for renewal in 2026: https://www.ft.com/content/f0b621a1-54f2-49fc-acc1-a660e9131740.

tile regression to assess the effects of fundamental factors such as demand, wind, and solar generation on electricity prices (e.g., Bunn et al., 2016, Hagfors et al., 2016, Do, Lyócsa, and Molnár, 2019, Maciejowska, 2020), few have explored its role in market integration. Moreover, despite the availability of high-frequency electricity price data, most quantile regression studies aggregate prices to daily observations, overlooking intraday variability and critical cross-sectional dynamics among hours.

Only a few studies have investigated market integration in electricity markets using quantile regression or panel data frameworks. Sapio (2019) used a quantile regression analysis to study the effect of a new interconnector in Italy using daily time series of prices, finding that the new interconnection led to greater market integration and lower price volatility. Keppler, Phan, and Pen (2016), on the other hand, used panel data regression to estimate the effect of market integration on the hourly spread between German and French electricity prices. They concluded that increased market integration through market coupling reduced the price difference between Germany and France caused by fluctuations in renewable energy production. Our analysis extends these approaches by combining hourly day-ahead prices with quantile regression to examine the impact of market integration on the full distribution of electricity prices.

Finally, in addition to our methodological contribution, our analysis provides important insights for the policy debate on the future of cross-border interconnectors in Europe. Although market integration generally leads to price contagion from high- to low-price areas, interconnectors can provide mutual benefits to both regions. For example, interconnectors can facilitate a more efficient use of generation resources in low-price areas by enabling the transfer of power to higher-price regions, which not only enhances system flexibility and reliability, but also provides increased revenue opportunities for generators in low-price areas. Furthermore, due to the frequent occurrence of zero and even negative prices in Germany caused by high wind and solar production, there are many hours throughout the year in which NordLink could actually reduce the electricity price for consumers in NO2. Given the growing importance of expanding cross-border transmission capacities to accommodate increasing shares of renewables, it is vital to understand how "green" interconnectors such as NordLink impact not only average prices but also the entire price distribution in interconnected regions.

The remainder of the paper is structured as follows. Section 2 describes the data, the construction of the variables, and shows some descriptive statistics for NO2 and Germany. Section 3 explains the method used for the empirical analysis, while Section 4 presents the results. In Section 5, we compare our results with the previous literature and discuss the magnitude of the estimates and their relevance to policy. Section 6 summarizes our main results and provides some concluding remarks.

2 Data

Data on hourly day-ahead electricity prices (EUR/MWh) in NO2 and Germany have been collected from the ENTSO-E Transparency Platform.[5] Our sample starts at the first trading hour on October 1, 2018, and ends at the last trading hour on September 30, 2021. We limit our sample to these three years due to the splitting of the German-Austrian bidding zone in September 2018 and the opening of the new transmission cable, NorthSeaLink, from NO2 to the UK in October 2021. This ensures that the only major market change in both zones during our sample was the opening of NordLink. In total, we have 26,304 hourly price observations for each zone, which means that we have 1,096 observations for each hour.

Figure 1 shows the time series for the hourly day-ahead price in NO2 and Germany during our sample. As seen in the figure, Germany has regularly experienced hours with zero and negative prices both before and after NordLink opened on December 9, 2020. Table 1 presents descriptive statistics for the day-ahead price in NO2 and Germany. On average, the price has been both higher and more volatile in Germany than in NO2. The table shows that the average day-ahead price was nearly 10 EUR/MWh lower in NO2 than in Germany

[5] Data is available at https://transparency.entsoe.eu/.

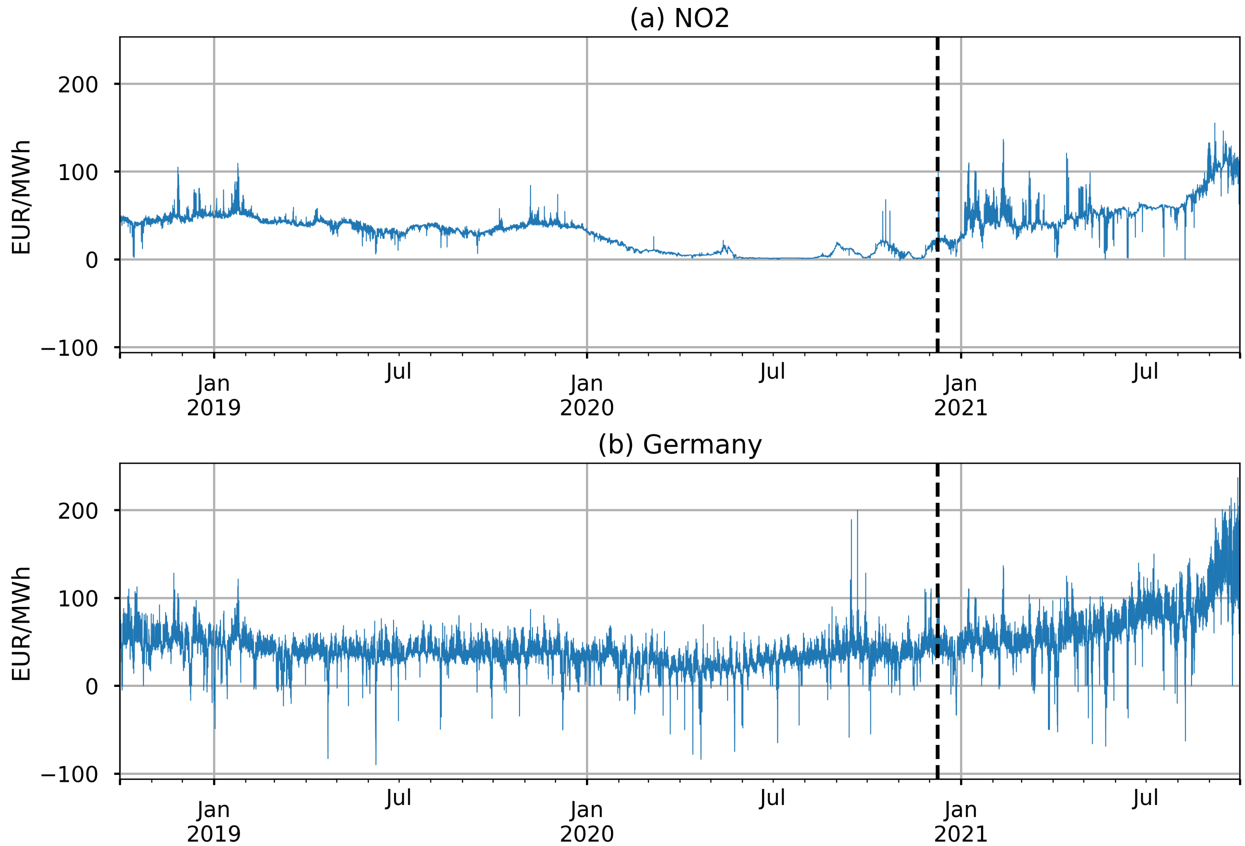

Figure 1: Hourly day-ahead electricity price in (a) NO2 and (b) Germany. Dashed black line indicates the opening of NordLink on December 9, 2020.

before the cable. After NordLink became operational, the day-ahead price rose sharply and almost doubled in both markets, in part driven by the onset of the European energy crisis, a dry year for hydropower and reduced production from nuclear power in Central Europe. As a result, a direct comparison of pre- and post-NordLink prices is not possible without accounting for broader market dynamics, which we address in our regression analysis.

A key finding from the statistics in Table 1 is the change in kurtosis. During the full sample, the kurtosis for both Germany and NO2 exceeded 3, indicating that the price distributions are leptokurtic, which means that they exhibit thick tails with extreme prices. However, before NordLink, NO2 had a kurtosis of 2.01, below the value of 3, indicating a

Table 1: Descriptive statistics for the day-ahead electricity price (EUR/MWh) in NO2 and Germany. NordLink opened on December 9, 2020.

	Mean	Min	Max	St. dev.	Skewness	Kurtosis
Panel A: Before NordLink (n = 19,200)						
NO2	27.0	-1.73	109.5	18.0	-0.0049	2.01
Germany	36.0	-90.0	200.0	18.0	-0.49	7.91
Panel B: After NordLink (n = 7,104)						
NO2	54.8	0.040	155.4	24.1	0.86	3.84
Germany	67.0	-69.0	237.0	34.5	0.65	5.08
Panel C: Full sample (n = 26,304)						
NO2	34.5	-1.73	155.4	23.4	0.74	4.32
Germany	44.4	-90.0	237.0	27.3	1.16	7.95

price distribution with thinner tails and fewer extreme observations. In contrast, Germany had a kurtosis of 7.91, reflecting high volatility in prices with frequent extreme values. After the opening of NordLink, the kurtosis in NO2 increased above 3, while in Germany it dropped to 5.08. This suggests that price volatility in Germany may have been partially transmitted to NO2, leading to more stable prices in Germany, but to increased fluctuations and more extreme price observations in NO2.

To isolate the effect of NordLink on day-ahead prices in both markets, we estimate a model of price formation in which we control for the main determinants of short-term electricity prices. We have collected data on the hourly day-ahead total load forecast (GWh) and day-ahead generation forecast for wind and solar (GWh) from the ENTSO-E transparency platform.[6] The graphical representation of load, wind, and solar displays the standard cyclical

[6]Note that our data for Germany has 840 hours with missing observations for the hourly day-ahead total load forecast. For these hours, we replace the missing values with the actual hourly load. As the day-ahead generation forecast for wind and solar have only a few hours with missing observations, we do not replace these with actual generation.

patterns caused by both intraday and seasonal variability (see Figures A1 and A2 in the appendix). For example, load and wind generation tend to be higher in winter and lower in summer, while solar power is primarily produced during the summer months. However, NO2 did not have solar power generation during our sample period, and although there is a slight increase in NO2 wind generation during the sample period, Germany has substantially higher wind generation than NO2.

In addition, we have collected data on the aggregated filling rate of water reservoirs (%) in NO2 from the Norwegian Water Resources and Energy Directorate (NVE).[7] The data also include the median level for the filling rate, which has been calculated for each week of the year based on the filling rate observed the past 20 years. As the aggregated filling rate is publicly available only at the weekly level, we have linearly interpolated it to the daily level. Finally, we have collected data on the daily gas price (EUR/MWh) and the EU carbon permits (EUA) price (EUR/tCO2) from Bloomberg.[8] Since the market for these commodities is closed on weekends, we replace the missing values with the last observed price to represent the latest information available to market participants. Table A1 in the appendix shows the results of diagnostic tests for our final data.[9]

Figure 2 illustrates the daily gas and EUA price and the daily aggregated filling rate of NO2 water reservoirs during our sample period. As seen in the figure, gas and EUA prices began rising in early 2021, shortly after NordLink became operational. In fact, due to the onset of the European energy crisis, the average prices for gas and EUA nearly doubled

[7]Data is available at `https://www.nve.no/energi/analyser-og-statistikk/magasinstatistikk/`.

[8]The gas price is the physical forward prices for natural gas delivered to Germany. The tickers for gas and EUA prices are "EGTHDAHD BCFV Index" and "DBRST3PA Index", respectively. Bloomberg data require a paid subscription.

[9]In particular, we tested for cross-sectional dependence in our panel data using the Pesaran (2015) CD statistic and examined the stationarity of the series with the Breitung and Das (2005) second-generation panel unit root test. According to Table A1, all series are stationary at the 1% or 10% level, with the exception of gas and EUA prices. This is as expected, as the series for gas and EUA prices have the same value for all hours within a day. However, hourly resolution is necessary to capture short-term market dynamics and apply the MMQR method with hourly fixed effects. Furthermore, quantile regression has been shown to remain asymptotically valid under certain forms of non-stationarity (Portnoy, 1991).

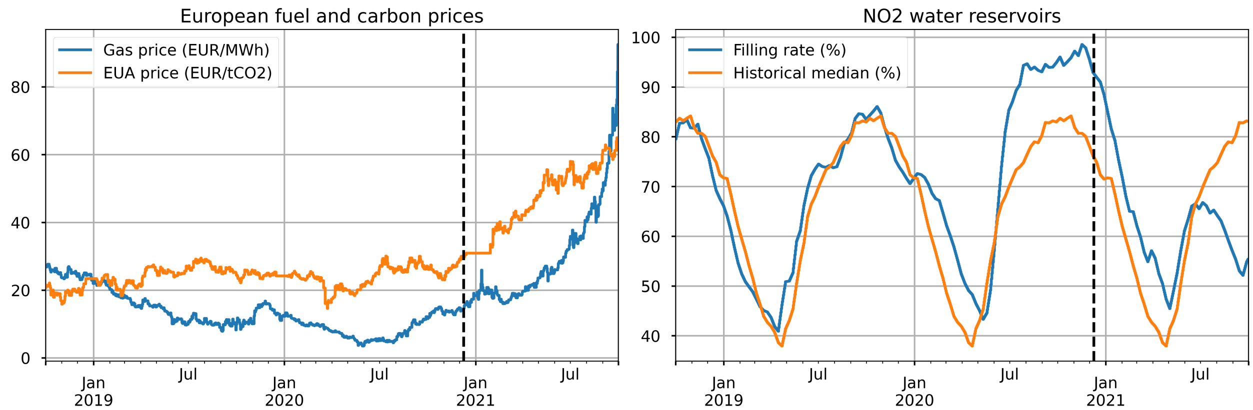

Figure 2: Time series of daily gas and EUA prices in Europe, and the daily interpolated aggregated filling rate of water reservoirs in NO2. Note that the median filling rate is based on the observed filling rate for the past 20 years. Dashed black line indicates the opening of NordLink on December 9, 2020

during our sample period (see Table A2 in the appendix). In NO2, part of the energy crisis was also driven by low reservoir levels. Figure 2 also presents the interpolated median filling rate of NO2 water reservoirs. Before NordLink opened, reservoir levels were unseasonably high but later dropped well below the median, partly due to an extremely wet fall in 2020 followed by a dry summer.

3 Methodology

3.1 Quantile regression

Quantile regression was introduced by Koenker and Bassett (1978) to explore how explanatory variables influence specific quantiles of a dependent variable, particularly when the statistical distribution of the dependent variable contains outliers. We employ the Method of Moments Quantile Regression (MMQR) developed by Machado and Santos Silva (2019), which uses a location-scale model to estimate the conditional quantiles while controlling for individual fixed effects. Panel regression combines time-series and cross-sectional dimensions of data by observing the same entities over time. In our analysis, the hours of the day represent cross-sectional units, whereas the observations for a single hour serve as time series.

Huisman, Huurman, and Mahieu (2007) were the first to highlight that aggregating hourly electricity market data could overlook important cross-sectional hourly effects in electricity markets caused by significant variation in, for example, electricity demand at different times of the day. In addition, using hourly observations can provide a more detailed understanding of the variability and microstructure of electricity markets (Peña, 2012). Recent research has demonstrated the importance of hourly dynamics in forecasting electricity prices (Karakatsani and Bunn, 2008, Andersson and Lillestøl, 2010), analyzing merit-order effects (Tselika, 2022), and assessing market coupling and cross-border impacts of renewable energy (Keppler, Phan, and Pen, 2016, Pham, 2019). The MMQR approach, which integrates panel data and quantile regression, enables us to examine the impact of NordLink on the entire distribution of electricity prices in NO2 and Germany. In this way, we can account for intraday variability across different hours, providing a comprehensive understanding of how NordLink influences electricity market dynamics.

To explore the impact of NordLink, we use the MMQR to estimate a model of price formation in which we compare prices before and after NordLink opened. Specifically, we estimate the following model separately for NO2 and Germany:

$$
\begin{aligned}
Q_p(\tau) = (\alpha_i + \delta_i q(\tau)) + \beta^C C_t + \beta^L L_{it} + \beta^W W_{it} + \beta^S S_{it} + \beta^R R_t + \beta^G GAS_{t-1} + \beta^E EUA_{t-1} \\
+ D_{it}\varphi + x'_{it}\gamma q(\tau) \quad (1)
\end{aligned}
$$

where Q_p is the τ-th quantile $\in (0,1)$ of the day-ahead electricity price in bidding zone z (zonal subscripts omitted), hour i, day t. The scalar coefficient $(\alpha_i + \delta_i q(\tau))$ is the τ-th quantile fixed effect for hour i, while the error term $x'_{it}\gamma q(\tau)$ captures the τ-th quantile effect of the explanatory variables on the variance of the day-ahead price. Our main variable of interest is C_t, which is a dummy for when the cable opened on December 9, 2020. The variable is equal to 0 for all days before the cable opened and to 1 afterward.

To isolate the impact of NordLink on prices, the model controls for the main determinants of short-term electricity price dynamics. L_{it} is the hourly day-ahead total load forecast, W_{it} is the hourly day-ahead wind generation forecast, and S_{it} is hourly day-ahead solar generation forecast. As NO2 did not have any solar generation during our sample, S_{it} is only included in the model for Germany. R_t controls for the daily aggregated filling rate of water reservoirs, which is included only in the NO2 model as Germany does not have hydropower production. To capture the fact that the effect on prices is likely to depend on whether the aggregated filling rate of reservoirs is above or below its median level, R_t is a dummy for when the filling rate is below its median. The variable is equal to 0 if the daily filling rate is above its median level, and 1 otherwise.

For both zones, we control for the effect of European fuel and carbon prices. GAS_{t-1} is the lagged daily gas price and EUA_{t-1} is the lagged daily price of EU carbon permits. Finally, D_{it} is a vector of control variables, which includes weekend and month dummies to control for seasonality, as well as the one-day lag of the day-ahead price to control for short-term price dynamics.[10] We estimate the model in Eq. (1) from the 10th to the 90th price quantile in increments of 10% for both NO2 and Germany. In all estimations, standard errors are clustered on the hourly level.[11]

In addition to the quantile effects, the MMQR also estimates the location and scale effects of all explanatory variables. The location effect is equal to the average effect from the simple linear regression model, whereas the scale effect measures how the price distribution narrows or widens around its average. Other studies have measured price volatility using the interquantile range (e.g., Maciejowska (2020)) or visually inspecting whether the effects are increasing or decreasing across quantiles (e.g., Sapio (2019)). The MMQR, on the other hand,

[10] Nickell (1981) shows that dynamic models with fixed effects are biased by $1/T$. However, given the length of our time series ($> 1,000$), we expect the bias due to the dynamic formulation to be small.

[11] Note that we have also estimated our baseline model in Eq. (1) with bootstrapped clustered standard errors, which produced almost identical confidence intervals compared to clustered standard errors. Results are available upon request.

use an auxiliary regression to estimate the effect of the explanatory variables on the variance of the dependent variable. A positive scale effect of an explanatory variable indicates an increase in the spread of the dependent variable, whereas a negative scale estimate suggests a decrease (Machado and Santos Silva, 2019). Hence, the MMQR allows us to directly estimate both the average effect of the explanatory variables across the price quantiles and the effect of the explanatory variables on the dispersion of the price distribution.

3.2 Linear regression

We extend our baseline analysis of electricity prices by exploring whether NordLink and market coupling have affected the relationship between the day-ahead price and its explanatory variables. For example, previous research suggests that market integration can affect the merit-order effect of renewables (e.g., Keppler, Phan, and Pen, 2016, Sapio, 2019). To investigate this, we expand our baseline model in Eq. (1) by introducing interaction terms between the cable dummy and the explanatory variables. However, since our focus is on the interaction effects of NordLink, as opposed to the quantile effects, we adapt our baseline model and use a linear panel regression with hourly fixed effects.[12]

This approach allows us to estimate the effect of the interaction terms on the average day-ahead price, providing complementary insights into how market integration influences the impact of key electricity market fundamentals, such as wind generation and fuel prices, on day-ahead prices. Specifically, we estimate the following model separately for NO2 and Germany:

$$\begin{aligned} P_{it} = \big(\beta^C + \beta^L L_{it} + \beta^W W_{it} + \beta^S S_{it} + \beta^R R_t + \beta^G GAS_{t-1} + \beta^E EUA_{t-1} + \theta P_{it-1}\big) \times C_t \\ + \alpha_i + \omega_w + \rho_m + \epsilon_{it} \end{aligned} \quad (2)$$

[12]Additionally, the underlying location-scale model in the MMQR framework makes it computationally challenging to incorporate interaction terms as these terms would influence not only the conditional mean of the day-ahead price but also its variance, causing convergence issues.

where P_{it} is the day-ahead electricity price in bidding zone z (zonal subscripts omitted), hour i, day t, and P_{it-1} is the one-day lag of the day-ahead price. The model includes the same explanatory variables as in Eq. (1), only that they are now interacted with the cable dummy, C_t. As previously, we control for intraday and seasonal variation in day-ahead prices. The term α_i is the fixed effect for the hour, while ω_w and ρ_m are weekend and month fixed effects, respectively.

4 Empirical results

As explained in the previous section, we use quantile regression to estimate the effect of NordLink on the distribution of day-ahead prices in NO2 and Germany, and a linear regression model to explore the interaction effects between NordLink and price fundamentals. In this section, we first present the results from the quantile regression analysis, both the quantile effects and the location and scale effects, and then we present the results from the linear regression model with interaction terms.

4.1 Quantile regression results

4.1.1 Quantile effects of NordLink

Figure 3 illustrates the quantile estimates of the cable dummy from our baseline model in Eq. (1). In the median quantile, we find a small (< 1 EUR/MWh) but positive effect in NO2 and a larger but negative effect in Germany. In other words, the median day-ahead price increased in NO2, while it decreased in Germany after the opening of NordLink. However, as shown in the figure, there is substantial variation between the price quantiles. In NO2, we find a negative effect on prices in the low-price quantiles after the opening of NordLink. For example, we find a decrease of almost -4 EUR/MWh in the 10th price quantile. This decrease is likely due to cheap imports of wind and solar power from Germany in low-demand

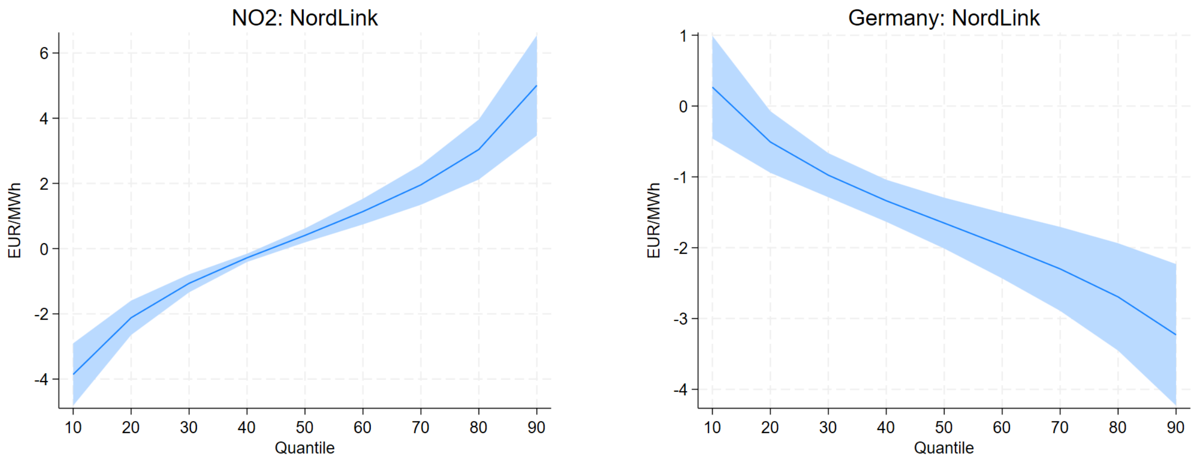

Figure 3: Quantile effects of the cable dummy from the baseline model in Eq. (1) for NO2 and Germany. Solid line shows the change in the price (in EUR/MWh) for each quantile, and shaded area is the 95% confidence interval.

hours, allowing NO2 to reduce hydro generation and store water for later use. In contrast, we find an increase of approximately +5 EUR/MWh in the 90th price quantile in NO2, which could be due to increased exposure to German prices in high-demand periods in which gas power plants often set the marginal price.

In Germany, on the other hand, we find no effect of the cable dummy on prices in the lowest price quantiles, but a decrease of approximately −3 EUR/MWh in the highest price quantiles. This suggests that NordLink has little impact on prices in Germany when the price is already low, likely due to the high amount of renewable generation. However, when renewable generation is low and the price is set by costlier generation technologies, NordLink can help reduce extreme price spikes by providing access to cheaper Norwegian hydropower. Table A3 in the appendix shows the estimated coefficients and standard errors in all quantiles.

4.1.2 Quantile effects of other explanatory variables

Figure 4 shows the quantile estimates for load and renewable generation technologies. An increase in the load (i.e., demand) generally leads to higher day-ahead prices across all price quantiles in both markets, except in the lowest price quantiles in NO2. The impact of load on day-ahead prices is strongest in high-price quantiles in NO2 and in low-price quantiles in Germany. As expected, we observe a downward pressure of renewables on day-ahead prices. In Germany, both wind and solar generation lead to price reductions in all quantiles, although the effect diminishes at higher price levels. This is likely due to the high capacity of renewables in Germany, which can lead to oversupply and price drops when demand is low. However, when the price is already high, demand is likely near its peak, in which case the price is largely determined by expensive dispatchable generation.

In NO2, an additional unit (GWh) of wind generation results in a significantly larger price decrease compared to Germany, which is expected given the relatively low wind capacity of NO2. This effect is strongest in high-price quantiles, indicating that wind generation displaces higher-cost marginal generation, leading to a larger price decrease. Finally, the level of the water reservoirs also influences the day-ahead price in NO2. When the aggregated filling rate falls below its median level, the day-ahead price generally increases, with the strongest effect in low-price quantiles.

Figure 5 illustrates the quantile estimates of gas and EUA prices. Higher gas and EUA prices are associated with an increase in the day-ahead price in Germany, with the effect becoming more pronounced in higher price quantiles. This is not surprising, as the marginal price in Germany is usually set by conventional power plants when demand is high (or renewable generation is low). When gas or EUA prices increase, the cost of production also increases, leading to higher day-ahead prices. Although fossil fuels are not part of the electricity mix in Norway, NO2 remains exposed to fuel and carbon prices due to its interconnection with the European electricity market. As a result, we also find a positive effect of gas and EUA prices on the day-ahead price in NO2. However, the magnitude of this effect is substantially smaller than in Germany.

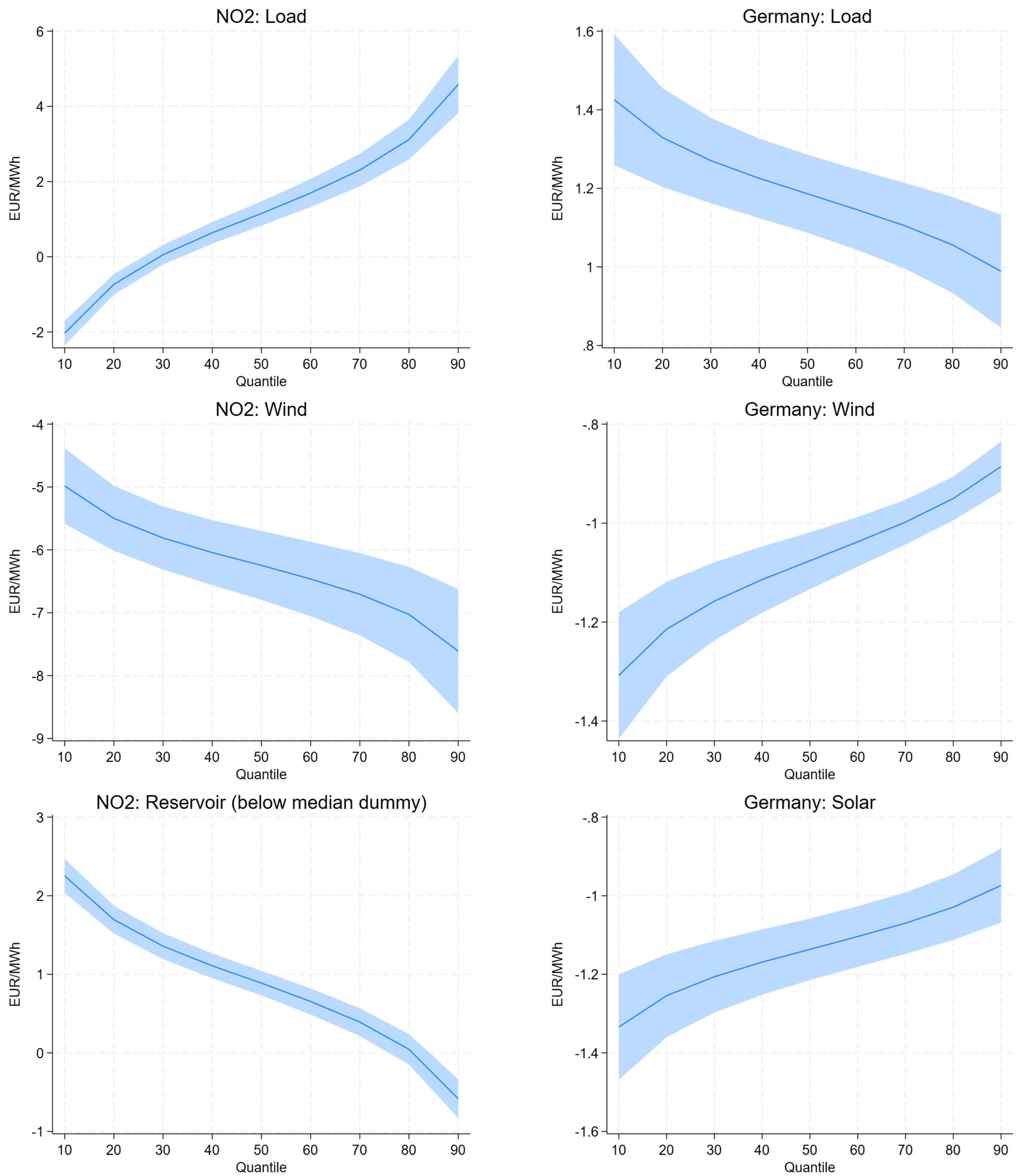

Figure 4: Quantile effects of load, wind, solar and below-median reservoir level from the baseline model in Eq. (1) for NO2 and Germany. Solid line shows the change in the price (in EUR/MWh) for each quantile, and shaded area is the 95% confidence interval.

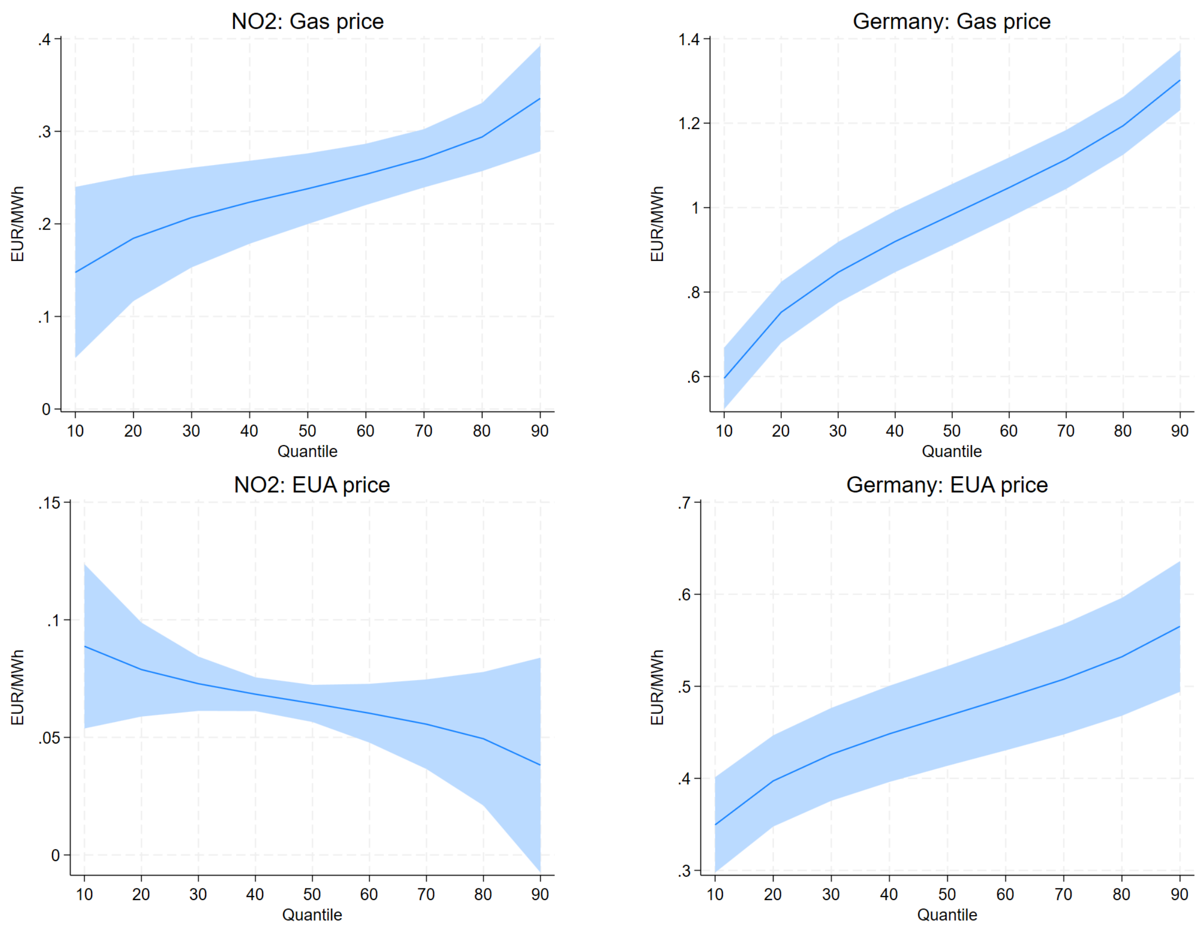

Figure 5: Quantile effects of gas and EUA prices from the baseline model in Eq. (1) for NO2 and Germany. Solid line shows the change in the price (in EUR/MWh) for each quantile, and shaded area is the 95% confidence interval.

4.1.3 Location and scale effects

In addition to the quantile effects, the MMQR estimates the effect of the explanatory variables on the location and scale parameters of the day-ahead price. As noted in Section 3.1, the location effect captures the average effect on day-ahead prices, whereas the scale effect captures the effect on the variance of the day-ahead price. Table 2 shows the estimated location and scale effects for the explanatory variables in Eq. (1). The table shows that the average day-ahead price increased by $+0.516$ EUR/MWh in NO2 and decreased by -1.634 EUR/MWh in Germany after NordLink opened. We also find a statistically significant effect of the cable dummy on the variability of the day-ahead price in both markets. Specifically, we find that the day-ahead price has become less volatile in Germany but more volatile in NO2 after the cable was opened. This suggests that the access to flexible hydropower in NO2 granted by NordLink has improved the stability of the German electricity market. In NO2, on the other hand, market integration has increased price volatility by exposing NO2 to fluctuations in German fuel prices and intermittent energy production.

For the other explanatory variables, both their location and scale effects are statistically significant, except for the scale effect of the EUA price in NO2. An increase in the load is associated with a similar increase in the day-ahead price in both markets. However, a higher load is associated with more volatile prices in NO2 but less volatility in Germany. This suggests that the NO2 market is more exposed to sudden demand changes, particularly given its homogeneous generation mix. Germany, on the other hand, has a more diversified market that may grant greater flexibility to absorb demand shocks through imports and dispatchable generation.

Regarding renewable generation, an additional unit of wind or solar generation reduces the day-ahead price by approximately 1 EUR/MWh in Germany. In NO2, the downward pressure of wind generation is about six times stronger. However, greater wind and solar generation is associated with higher price volatility in Germany, while in NO2, increased wind generation leads to reduced volatility. In other words, the intermittent nature of wind and solar leads to

Table 2: Estimates of location and scale effects from the quantile regression model in Eq. (1) for NO2 and Germany.

	NO2		Germany	
	Location	Scale	Location	Scale
NordLink	0.516***	2.683***	-1.634***	-1.068***
	(0.135)	(0.384)	(0.186)	(0.248)
Load	1.232***	2.002***	1.188***	-0.133***
	(0.183)	(0.138)	(0.051)	(0.037)
Wind	-6.279***	-0.795***	-1.078***	0.129***
	(0.289)	(0.175)	(0.031)	(0.022)
Solar	-	-	-1.138***	0.110***
			(0.041)	(0.025)
Reservoirs	0.853***	-0.858***	-	-
	(0.075)	(0.056)		
Gas	0.240***	0.057***	0.980***	0.216***
	(0.019)	(0.020)	(0.036)	(0.006)
EUA	0.064***	-0.015	0.467***	0.066***
	(0.004)	(0.012)	(0.028)	(0.009)
Observations	26,277	26,277	26,279	26,279

Note: Standard errors (in parenthesis) are clustered on the hourly level. ***, ** and * denote statistical significance on the 1%, 5% and 10% level, respectively.

rapid price fluctuations in Germany when the generation changes unexpectedly. In contrast, wind generation in NO2 appears to stabilize prices by potentially offsetting demand peaks or allowing electricity to be stored in reservoirs for later use. Lastly, gas prices exhibit a positive relationship with the average day-ahead price in both markets, although in Germany a 1 EUR increase in the gas price is almost fully passed on to the day-ahead price.

4.1.4 Robustness

In this section, we perform several robustness checks of our baseline model in Eq. (1). Specifically, we assess the robustness of our main findings on the effect of NordLink on prices by considering alternative controls for fuel prices, reservoir levels, and short-term price dynamics. First, we replace the gas price in the model with the coal price. Although gas is the dominant fossil fuel in Germany's energy mix, coal also contributes a significant share of electricity production. Therefore, we incorporate the one-day lag of the coal price in the model for both NO2 and Germany.[13] Second, we extend our baseline model for both markets by including a seven-day lag of the day-ahead price to further account for short-term price dynamics. Finally, in the NO2 model, we replace the dummy variable indicating whether the aggregated reservoir level is below its median with the actual daily filling rate of the reservoirs.

Figures A3 and A4 in the appendix show the quantile plots for the cable dummy in all robustness checks for NO2 and Germany, respectively. For comparison, the figures also include the quantile plot for the cable dummy from the baseline model. As shown, our main findings remain robust in all alternative model specifications. Although there is some variation in the quantile estimates, we consistently observe a positive effect on median prices in NO2 and a negative effect on median prices in Germany following the opening of NordLink. Moreover, the results exhibit similar patterns across quantiles in all robustness checks. In NO2, we find a negative effect on prices in low-price quantiles and a positive effect on prices in high-price quantiles. In Germany, there is little to no effect on prices in low-price quantiles, while the negative effect on prices becomes more pronounced in higher quantiles.

[13] As with gas and EUA prices, the coal price is measured daily and sourced from Bloomberg (ticker: "API21MON OECM Index").

4.2 Interaction effects of NordLink

In this section, we explore the mechanisms through which NordLink affected the day-ahead price in NO2 and Germany by estimating the linear regression model in Eq. (2) that contains interaction terms between the cable dummy and the other explanatory variables. In particular, we want to explore whether the relationship between the day-ahead price and its fundamentals has changed since NordLink opened. Columns (2) and (4) in Table 3 report the results of the linear regression model for NO2 and Germany, respectively. For comparison, columns (1) and (3) show the results of estimating the model without interaction terms between the cable dummy and the explanatory variables.[14] By comparing the estimates from the model with and without interaction terms, we observe that the relationship between the day-ahead price and most of its underlying fundamentals has changed in both markets following the opening of NordLink. Except for the dummy variable that indicates below-median reservoir levels in NO2, all other interaction terms with the cable dummy are statistically significant.

Interestingly, we find that the downward pressure of intermittent renewables has intensified in both NO2 and Germany after the opening of NordLink. This can be attributed to improved renewable utilization as surplus wind and solar generation in Germany can now be exported to NO2, potentially minimizing curtailment and amplifying the downward pressure on prices. Furthermore, with increased cross-border transmission capacity, conventional power plants face greater competition. This moves them further down the merit order curve, causing them to be dispatched less frequently, which may increase the downward pressure of renewables.

We also find that the influence of fuel and carbon prices on the day-ahead price has changed after NordLink, but in opposite directions in the two markets. In NO2, gas and EUA prices have a stronger impact on the day-ahead price post-NordLink, while in Germany,

[14] Note that these estimates correspond to the location effects from the quantile regression model in Table 2

Table 3: Estimates for explanatory variables in the linear regression model in Eq. (2) for NO2 and Germany, with and without interaction terms with the cable dummy.

	NO2		Germany	
	(1)	(2)	(3)	(4)
Load	1.232***	0.251**	1.188***	1.112***
	(0.191)	(0.105)	(0.053)	(0.042)
Wind	-6.279***	-3.660***	-1.078***	-0.995***
	(0.300)	(0.190)	(0.032)	(0.020)
Solar	-	-	-1.138***	-1.012***
			(0.042)	(0.022)
Reservoir	0.853***	0.804***	-	-
	(0.076)	(0.085)		
Gas	0.240***	0.183***	0.980***	1.184***
	(0.020)	(0.016)	(0.037)	(0.032)
EUA	0.064***	0.154***	0.467***	0.672***
	(0.004)	(0.012)	(0.029)	(0.029)
PriceLag1	0.820***	0.908***	0.154***	0.053***
	(0.013)	(0.007)	(0.012)	(0.007)
Load x NordLink		2.871***		0.566***
		(0.400)		(0.041)
Wind x NordLink		-5.767***		-0.402***
		(0.403)		(0.046)
Solar x NordLink		-		-0.539***
				(0.050)
Reservoir x NordLink		-0.042		
		(0.158)		
Gas x NordLink		0.319***		-0.280***
		(0.031)		(0.027)
EUA x NordLink		0.080***		-0.163***
		(0.014)		(0.048)
PriceLag1 x NordLink		-0.307***		0.140***
		(0.016)		(0.017)
Observations	26,277	26,277	26,279	26,279

Note: Standard errors (in parenthesis) are clustered on the hourly level. ***, ** and * denote statistical significance on the 1%, 5% and 10% level, respectively.

their influence has weakened. This indicates that NO2 has become more exposed to fuel and carbon prices as a result of its interconnection with Germany. Germany, on the other hand, appears to have gained greater price stability from access to Norwegian hydropower.

These results highlight the importance of considering not only the impact of market integration on average day-ahead prices but also its influence on price formation. Our quantile regression analysis provides evidence of price convergence between NO2 and Germany following the opening of NordLink, with significant distributional effects in both markets. However, the findings of our linear regression analysis suggest that, beyond the direct price effect of the cable, there is also an indirect effect that stems from changes in the relationship between the day-ahead price and its underlying fundamentals.

5 Discussion

In this section, we first discuss and compare our empirical results with the previous literature, and then we provide a discussion of the magnitude of the effects found in our empirical analysis and the relevance of these effects for day-ahead prices and consumers in both markets.

5.1 Comparison to the literature

In general, our findings align with previous research on market integration while providing new insight into the distributional effects of interconnection. Similarly to, e.g. Figueiredo, Silva, and Cerqueira (2015) and Sapio (2019), we observe price convergence following an increase in transmission capacity. As expected from theory, we find an increase in the average day-ahead price in NO2 and a decrease in Germany. However, our analysis reveals substantial heterogeneity across price quantiles and between the two markets. In Germany, consumers have mainly benefited from a price reduction in the most expensive hours, but with little or no effect on prices in the cheapest hours. For consumers in NO2, NordLink may have increased prices during high-price hours, but it may also have reduced prices during low-price hours. This aligns with Mauritzen (2013), which found that interconnection with Denmark allows Norway to import and store cheap wind power in hydro reservoirs, reducing the price. Thus, our analysis highlights the importance of considering the asymmetric impacts of interconnection, which depend on the underlying market conditions.

In addition, our analysis supports de Menezes and Houllier (2015) and Annan-Phan and Roques (2018), which shows that interconnectors can influence price volatility. For example, Annan-Phan and Roques (2018) found that an increase in transmission capacity between Germany and France can reduce price volatility in both markets. However, we find that NordLink has had an opposite effect on price volatility in the two markets. Due to the stability of Norwegian hydropower, prices have become less volatile in Germany after NordLink opened, while in NO2, prices have become more volatile. In other words, it appears that Germany has not only exported some of its higher average prices to NO2, but also some of its volatility caused by fluctuations in intermittent energy production and fuel prices.

Our results also confirm the merit-order effect of renewables documented in the literature (e.g., Cludius et al., 2014, Paraschiv, Erni, and Pietsch, 2014, Tselika, 2022). We contribute to this literature by showing that both wind and solar generation in Germany reduce prices the most during low-price hours, which contrasts with Maciejowska (2020), who finds that solar energy has a more pronounced impact in higher quantiles. Interestingly, we find the opposite pattern in NO2, where wind generation reduces prices the most in high-price quantiles. In addition, unlike Kyritsis, Andersson, and Serletis (2017) and Maciejowska (2020), we find that both solar and wind power lead to more volatile prices in Germany. Our findings demonstrate that the effect of renewables on the price distribution is also highly market dependent and is shaped by differences in national generation mixes.

Finally, in addition to the direct effect of market integration on price formation, market integration can also have an indirect effect by altering market dynamics (e.g., Gianfreda, Parisio, and Pelagatti, 2016, Keppler, Phan, and Pen, 2016, Sapio, 2019). As in Sapio (2019), we find that interconnection has strengthened the downward pressure of renewables on day-ahead prices in both markets. However, when it comes to the sensitivity of the day-ahead price to fuel and carbon prices, we demonstrate that market integration can have a very different effect depending on the generation mix in the two markets. Despite the dominance of hydro in the NO2 generation mix, we find that the day-ahead price in NO2 has become more sensitive to gas and EUA prices after NordLink opened, while the day-ahead price in Germany has become less sensitive. This suggests that interconnection has also allowed Germany to export some of its exposure to fluctuations in fuel and carbon prices to NO2.

5.2 Magnitude of effects

From our quantile regression analysis in Section 4.1, we found that the day-ahead price in NO2 and Germany has converged following the opening of NordLink. Specifically, in our baseline model, the day-ahead price in NO2 increased by an average of +0.516 EUR/MWh, while it decreased by −1.634 EUR/MWh in Germany. However, compared to the average price levels in the two markets, the magnitude of price convergence appears moderate. As shown in Table 1, the average day-ahead price before NordLink opened was 27 EUR/MWh in NO2 and 36 EUR/MWh in Germany. Thus, the price increase in NO2 corresponds to approximately +2% of its average pre-NordLink price $((0.516/27) \times 100)$, while the price decrease in Germany represents a −4.5% reduction relative to its pre-NordLink average $((-1.634/36) \times 100)$.[15]

In fact, our analysis indicates that other explanatory variables have had a significantly larger impact on day-ahead prices in the two markets during our sample period than NordLink. In particular, the sharp increase in fuel prices played a key role in driving the European energy crisis. During our sample period, the average gas price more than doubled from 13.1 EUR/MWh to 29.5 EUR/MWh after NordLink opened (see Table A2). In our baseline model,

[15]Note that our result for NO2 aligns with reports from Statnett, the transmission system operator in Norway. Using simulation tools, they found a +10% increase in the average day-ahead price in NO2 from the joint effect of the new transmission cables to Germany and the UK: https://www.statnett.no/om-statnett/nyheter-og-pressemeldinger/nyhetsarkiv-2022/nye-kabler-star-for-rundt-10-av-de-hoye-stromprisene/

we found that a 1 EUR increase in the gas price is associated with a 0.24 EUR increase in the average day-ahead price in NO2 (see Table 2). Based on this estimate, the increase in gas prices corresponds to an increase of approximately 3.9 EUR in the NO2 day-ahead price $((29.5-13.1)\times 0.24)$. In other words, the impact of rising gas prices on NO2 day-ahead prices is more than seven times larger than the increase associated with the opening of NordLink.

However, our analysis of the interaction effects of NordLink in Section 4.2 reveals a statistically significant change in the relationship between day-ahead prices and most explanatory variables in both markets after the cable opened. In NO2, the day-ahead price has become considerably more sensitive to changes in gas prices. As shown in Table 3, a 1 EUR increase in the gas price was associated with a 0.183 EUR increase in the NO2 day-ahead price before NordLink, with an additional impact of 0.319 EUR/MWh after NordLink. This implies that before the cable, the observed increase in the average gas price during our sample period would have led to an increase of approximately 3 EUR/MWh $((29.5-13.1)\times 0.183)$ in NO2. However, after NordLink opened, the same increase in gas prices is associated with a significantly larger increase of 8.2 EUR/MWh $((29.5-13.1)\times(0.183+0.319))$. In Germany, we observe the opposite effect, a reduction in the exposure of day-ahead prices to fluctuations in gas prices. According to the estimates in Table 3, the increase in the German day-ahead price associated with the increase in the average gas prices decreased from 19.4 EUR/MWh $((29.5-13.1)\times 1.184)$ before NordLink to 14.8 EUR/MWh $((29.5-13.1)\times(1.184-0.280))$ after the cable opened.

In other words, beyond its direct effect on price convergence between the two markets, interconnection can also influence prices indirectly by changing the relationship between day-ahead prices and their fundamental drivers. Compared to both the average day-ahead price and other key explanatory variables, such as gas prices, the direct effect of NordLink appears moderate, but the indirect effects can still be large. For example, the impact of gas prices on the NO2 day-ahead price more than doubled after NordLink opened, while in Germany the exposure decreased by nearly a quarter. It is important to note that some of these indirect effects of market integration can potentially benefit consumers in both markets, such as the increased downward pressure of wind and solar generation on day-ahead prices.

An important caveat to the back-of-the-envelope calculations presented here is that they are based on the effect on the average day-ahead price, but as shown in the quantile regression analysis, the impact of NordLink varies significantly across the price distribution. In NO2, we found that the day-ahead price decreased during low-price hours but increased substantially during high-price hours after NordLink opened. For consumers, the benefit of lower prices during off-peak periods may not fully offset the burden of higher prices during peak hours. Furthermore, our findings suggest that Germany may have transmitted some of its price volatility to NO2 after the cable opened. Greater price volatility can create challenges for consumers, making it more difficult to anticipate prices and adjust consumption to avoid high-cost periods. Therefore, it is vital that a welfare analysis not only considers the effect of market integration on average prices but instead considers the effect on the full distribution of prices, including its volatility.

6 Conclusion

The European Union plans to further strengthen electricity market integration by expanding the cross-border transmission capacity between countries. By aligning electricity prices across regions, market integration improves grid stability and facilitates the large-scale adoption of intermittent renewable energy. A well-integrated market ensures that electricity flows to where it is most valuable, fostering a more resilient and sustainable energy system. In this paper, we examine the effect of NordLink, a new transmission cable between southern Norway (NO2) and Germany, on prices in both markets. Although interconnectors such as NordLink can help integrate renewables into the European grid, they also contribute to price contagion, transmitting price effects from high-price to low-price markets, which can be a contentious issue. As Germany has a higher average electricity price than NO2, theory predicts that market integration will increase the price in NO2. However, there are two confounding factors. First, the opening of NordLink coincided with the beginning of the European energy crisis. Second, although Germany has a higher price on average, there are many hours in which the price is lower than in NO2 due to Germany's high share of wind and solar power.

To assess the impact of NordLink on prices and detangle its effect from that of the energy crisis, we use a novel estimator for panel quantile regression with fixed effects. Our method allows us to analyze the entire distribution of electricity prices and its volatility while accounting for the heterogeneity between hours caused by variations in supply and demand at different hours of the day. Unlike traditional time-series methods, the panel approach, using hourly electricity prices, can provide more detailed exploration and capture the dynamic characteristics of electricity markets (Huisman, Huurman, and Mahieu, 2007, Peña, 2012). To estimate the effect of NordLink, we use panel quantile regression to estimate a model of price formation separately for NO2 and Germany, in which we compare prices before and after NordLink opened.

In our baseline model, we find a moderate change in the average day-ahead price in NO2 and Germany after NordLink opened. Specifically, we find an increase in the average day-ahead price of 0.516 EUR/MWh in NO2, and a decrease of 1.634 EUR/MWh in Germany. This corresponds to a change of approximately $+2\%$ and -4.5% relative to the average day-ahead price observed in our sample before NordLink opened in NO2 and Germany, respectively. However, the impact of NordLink on prices varies significantly between different price quantiles. In NO2, prices in the lower quantiles decreased by approximately 4 EUR/MWh after the cable opened, while prices in the higher quantiles increased substantially by around 5 EUR/MWh. In contrast, in Germany, NordLink had no effect on prices in the lowest quantiles, but led to a price reduction of about 3 EUR/MWh in the highest quantile. Furthermore, NordLink affected price volatility in both markets. In NO2, price volatility increased after cable opening, while in Germany it decreased. This suggests that Germany has not only transmitted some of its higher prices to NO2, but also exported part of its price volatility, leading to greater fluctuations in the Norwegian market.

In addition to its direct effect on prices, NordLink can also influence the market by changing the relationship between day-ahead prices and fundamental variables. To examine these effects, we estimate a simple linear regression model of price formation in both markets, incorporating interaction terms between NordLink and the other explanatory variables in the model. This approach allows us to assess whether the impact of key factors such as renewables and fuel prices has changed after NordLink started operating. Our analysis confirms that the relationship between day-ahead prices and key explanatory variables has changed. In particular, the relationship between day-ahead prices and gas prices in NO2 more than doubled after NordLink opened, whereas in Germany, this relationship weakened. In other words, price convergence between the two markets has occurred not only through NordLink's direct impact on prices, but also through its indirect influence on the relationship between day-ahead prices and their underlying determinants.

Our analysis is related to the literature that has used hourly data to explore electricity markets (e.g., Karakatsani and Bunn, 2008, Pham, 2019, Tselika, 2022), and it contributes to the literature by illustrating the importance of accounting for hourly effects in the context of market integration. Existing research has mainly used aggregated daily data (e.g., de Menezes and Houllier, 2015, Sapio, 2019), which overlooks intraday variability. Although previous studies have applied quantile regression to examine the relationship between day-ahead prices and their fundamental drivers (e.g., Bunn et al., 2016, Hagfors et al., 2016, Maciejowska, 2020), we extend this literature by integrating quantile regression with hourly fixed effects to assess the impact of market integration on the full price distribution and its variability. Our results demonstrate that market integration affects different parts of the price distribution in different ways and has significant implications for price volatility. We also show that market integration has not only a direct effect on prices but also an indirect effect on price formation through its interaction with fundamental price drivers. As shown in our analysis, the interaction between interconnection and fundamental price drivers can be significant, further shaping price dynamics beyond direct price effects.

For policymakers, our findings have important implications for evaluating the impact of market integration on consumers, particularly in terms of price dynamics, volatility, and affordability. Understanding how market integration affects different segments of the price distribution can facilitate more informed decisions about regulatory frameworks, tariff structures, and mechanisms to mitigate potential negative effects. For market participants, changes in interconnection capacity can significantly impact their trading strategies, investment decisions, and risk management. By understanding how interconnectors influence price convergence across different price levels and market conditions, participants can better predict price movements, optimize their bidding strategies, and manage exposure to market volatility.

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A Appendix

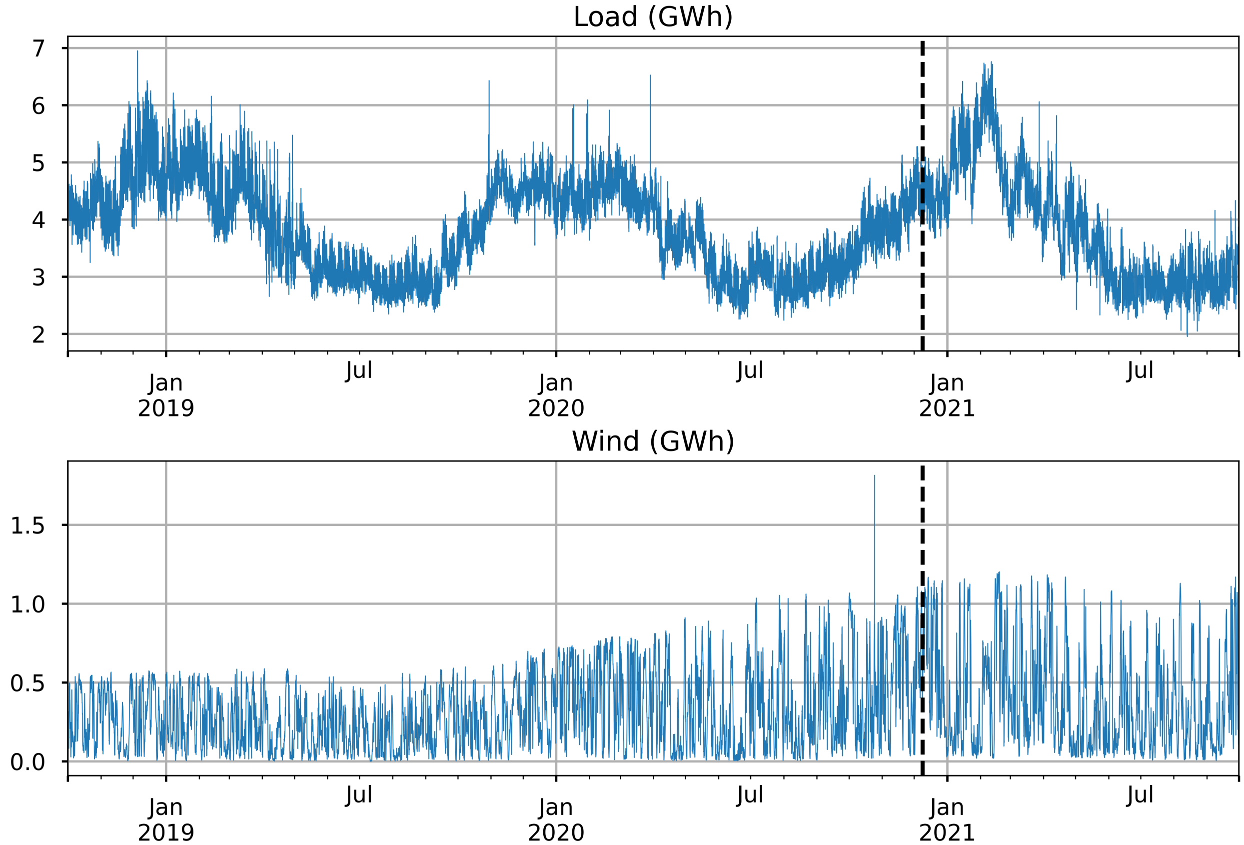


Figure A1: Time series of load and wind generation in NO2. Dashed black line indicates the opening of NordLink on December 9, 2020.

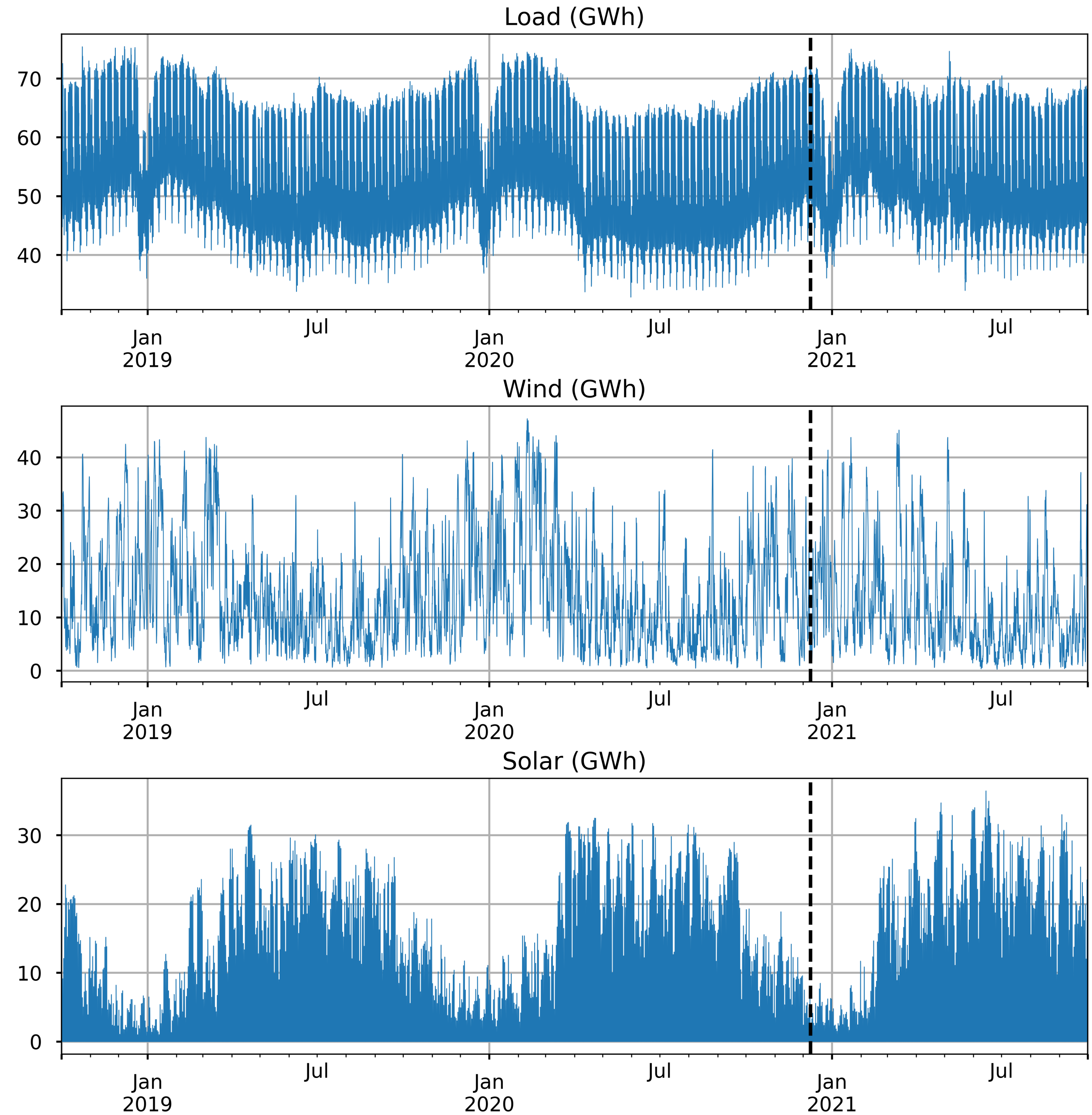


Figure A2: Time series of load, wind and solar generation in Germany. Dashed black line indicates the opening of NordLink on December 9, 2020.

Table A1: Diagnostic tests for the day-ahead price and its fundamentals.

	NO2			Germany				European prices	
	Price	Load	Wind	Price	Load	Wind	Solar	Gas	EUA
Panel A: Cross-sectional dependence									
CD-Pesaran (2004)	530.826	522.28	424.14	470.963	474.347	473.996	230.573	549.745	549.745
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Panel B: Unit root									
Breitung and Das (2005)	-1.4395	-2.9174	-6.1358	-3.5966	-3.7053	-7.8562	-3.9285	3.4294	1.8608
p-value	0.075	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.9997	0.9686

Note: Under the null hypothesis of cross-section independence, *p*-values close to zero indicate that data are correlated across panel groups. Under the null hypothesis that panels contain unit roots, *p*-values close to zero indicate that panels are stationary. The unit root test includes five lags.

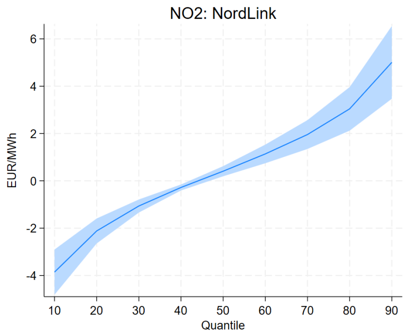
Table A2: Mean values and standard deviations (in parenthesis) of the day-ahead price and price fundamentals. NordLink opened on December 9, 2020.

	Before NordLink (n = 19,200)	After NordLink (n = 7,104)	Full sample (n = 26,304)
Panel A: NO2			
Price (EUR/MWh)	27.0 (18.03)	54.8 (24.15)	34.5 (23.40)
Load (GWh)	3.9 (0.80)	3.9 (1.02)	3.9 (0.87)
Wind (GWh)	0.3 (0.23)	0.4 (0.32)	0.3 (0.26)
Reservoir (%)	72.0 (16.42)	63.7 (11.55)	69.8 (15.70)
Panel B: Germany			
Price (EUR/MWh)	36.0 (17.97)	67.0 (34.52)	44.4 (27.33)
Load (GWh)	55.3 (9.52)	55.4 (8.94)	55.3 (9.36)
Wind (GWh)	14.5 (10.15)	12.3 (9.58)	13.9 (10.05)
Solar (GWh)	4.8 (7.41)	5.9 (8.57)	5.1 (7.76)
Panel C: European prices			
Gas (EUR/MWh)	13.1 (5.91)	29.5 (14.74)	17.5 (11.70)
EUA (EUR/tCO2)	24.0 (3.02)	46.4 (10.08)	30.0 (11.55)

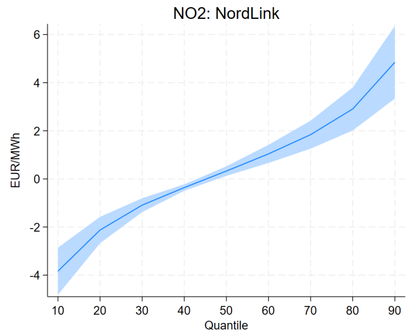
Table A3: Quantile estimates for all explanatory variables from the baseline model.

	Quantiles								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Panel A: NO2									
NordLink	-3.858***	-2.119***	-1.064***	-0.281***	0.407***	1.138***	1.957***	3.042***	5.007***
	(0.487)	(0.269)	(0.140)	(0.064)	(0.109)	(0.201)	(0.311)	(0.470)	(0.785)
Load	-2.031***	-0.734***	0.054	0.638***	1.151***	1.696***	2.307***	3.117***	4.582***
	(0.168)	(0.140)	(0.132)	(0.147)	(0.165)	(0.189)	(0.220)	(0.270)	(0.389)
Wind	-4.983***	-5.498***	-5.811***	-6.043***	-6.247***	-6.463***	-6.706***	-7.028***	-7.610***
	(0.307)	(0.263)	(0.255)	(0.264)	(0.280)	(0.302)	(0.334)	(0.386)	(0.503)
Reservoir	2.252***	1.696***	1.358***	1.108***	0.888***	0.654***	0.392***	0.045	-0.584***
	(0.110)	(0.090)	(0.084)	(0.081)	(0.080)	(0.085)	(0.090)	(0.099)	(0.126)
Gas	0.148***	0.184***	0.207***	0.223***	0.238***	0.254***	0.271***	0.294***	0.336***
	(0.047)	(0.035)	(0.027)	(0.023)	(0.019)	(0.017)	(0.016)	(0.019)	(0.029)
EUA	0.089***	0.079***	0.073***	0.068***	0.064***	0.060***	0.056***	0.049***	0.038
	(0.018)	(0.010)	(0.006)	(0.004)	(0.004)	(0.006)	(0.010)	(0.014)	(0.023)
Panel B: Germany									
NordLink	0.267	-0.508**	-0.976***	-1.337***	-1.653***	-1.969***	-2.299***	-2.695***	-3.230***
	(0.370)	(0.222)	(0.159)	(0.151)	(0.183)	(0.237)	(0.302)	(0.387)	(0.509)
Load	1.426***	1.329***	1.271***	1.225***	1.186***	1.146***	1.105***	1.056***	0.989***
	(0.085)	(0.064)	(0.055)	(0.052)	(0.051)	(0.052)	(0.056)	(0.062)	(0.073)
Wind	-1.308***	-1.214***	-1.158***	-1.114***	-1.076***	-1.038***	-0.998***	-0.950***	-0.886***
	(0.065)	(0.049)	(0.040)	(0.034)	(0.029)	(0.026)	(0.023)	(0.023)	(0.026)
Solar	-1.334***	-1.254***	-1.206***	-1.169***	-1.136***	-1.104***	-1.070***	-1.029***	-0.974***
	(0.068)	(0.054)	(0.047)	(0.042)	(0.040)	(0.039)	(0.040)	(0.043)	(0.048)
Gas	0.596***	0.752***	0.847***	0.920***	0.983***	1.047***	1.114***	1.194***	1.302***
	(0.037)	(0.037)	(0.037)	(0.037)	(0.037)	(0.036)	(0.036)	(0.035)	(0.036)
EUA	0.349***	0.397***	0.426***	0.448***	0.468***	0.487***	0.508***	0.532***	0.565***
	(0.026)	(0.025)	(0.026)	(0.027)	(0.028)	(0.029)	(0.031)	(0.033)	(0.036)

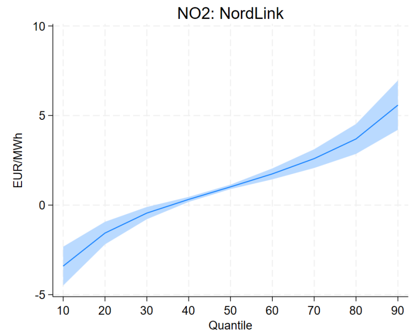
Note: Standard errors (in parenthesis) are clustered on the hourly level. ***, ** and * denote statistical significance on the 1%, 5% and 10% level, respectively.



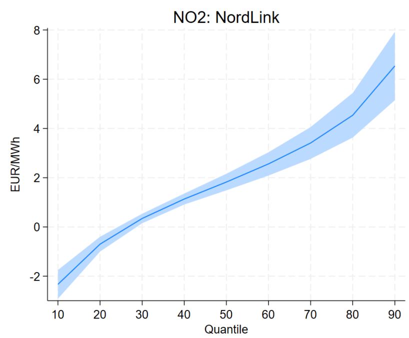
(a) Baseline



(b) Coal price

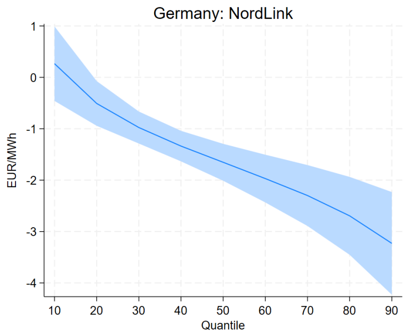


(c) 7-day price lag

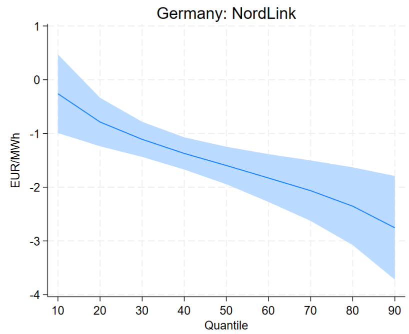


(d) Filling rate

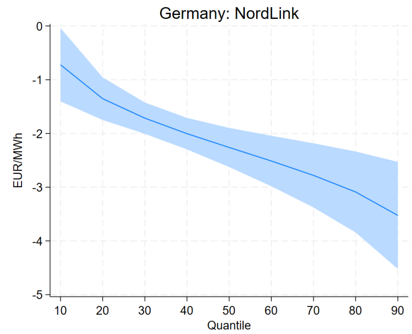
Figure A3: Quantile effects of the cable dummy from robustness analysis for NO2. Solid line shows the change in the price (in EUR/MWh) for each quantile, and shaded area is the 95% confidence interval.



(a) Baseline



(b) Coal price



(c) 7-day price lag

Figure A4: Quantile effects of the cable dummy from robustness analysis for Germany. Solid line shows the change in the price (in EUR/MWh) for each quantile, and shaded area is the 95% confidence interval.

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