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The effect of the 2022 energy crisis on electricity markets ashore the North Sea

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ABSTRACT

The European internal energy market has undergone institutional redesign during the last 30 years. It has the objective to deliver secure, affordable and increasingly decarbonized energy supply. Europe experienced its first inherent energy crisis after the global oil price crisis half a decade ago. With skyrocketing energy prices during 2022, electricity generation in Europe was under extreme stress. In this paper we analyse flows and prices of electricity in six distinctive (with respect to generation portfolios) European countries from 2018 to 2022 and investigate if market signals (prices) contributed to security of supply. For a long time, sceptics have argued that liberalized markets would not be able to provide security of supply, and this has not been challenged by real world events thus far. Our empirical results suggest that electricity did indeed move along cross-border transmission lines as the theory suggests, and that cross-border transmission lines were utilized as during normal periods. This is relevant for the current debate on restructuring energy market design and protecting consumers from volatile prices.

1. Introduction

The European Commission reported already in 1985 on an "internal energy market" and spelled out its ambitions in its 1992 Action Programme. The first real overall integrated package for an EU policy resulted in what has become known as the third energy package from 2007 (De Jong, 2008). The package covered the three dimensions of supply security, environment and the market and aimed to boost energy security and competitiveness in the EU. The creation of a truly internal market would also serve to the needs of Member states when it came to security of supply and created some momentum of solidarity in the event of an energy crisis and the effective diversification of energy sources and transport routes. The EU in its Third Energy Package also delivered a vision on energy market design and other issues related to cross-border markets and their integration. It set out rules for more effective cross-border trade and the enhancement of market transparency. As a result, in case of a shortage in the system, price signals would (given the technical feasibility) direct power flows to where it achieves its highest value.

During the years to come security of energy supply was – with the exception of natural gas deliveries from Russia via Ukraine – a theoretical concept, in particular for the internal electricity market. The level of market integration, transparency and competition increased substantially and the political debate lately centered around the design of market rules which would result in a sustainable energy mix in the Union. The Fourth Energy Package implements the Energy Union and, among others, introduced new electricity market rules for renewable energies and for attracting investment. The Fifth Energy Package aims to align EU's energy targets with its climate ambitions for 2030 and 2050. In this context and following the European energy crisis, a reform of the electricity market design was announced and aims to enhance the competitiveness of Europe's net-zero industry.

The debate preceding the third package focused on the transition from previously monopolistic to competitive market structures, and the potential risks this posed to the security of supply. The question arose: could energy systems, underpinned by regulation, ensure the efficient and reliable provision of energy? Joskow (2005) distinguishes between *short-run system operating reliability* and *long-run resource adequacy*. Whereas the latter is threatened by the lack of (investments in) infrastructure/capacity, operating reliability may be at risk by supply disruption. Such disruptions can be caused by physical constraints or non-price rationing. From a policy makers' perspective the prevailing price level is a potential source of concern since consumers in the

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short-run have a very low elasticity of demand. In most European countries, regulation has protected consumers from volatile prices until today. The Agency for the Cooperation of Energy Regulators (ACER) concludes that "the internal energy market is delivering on its objective of delivering secure, affordable, and increasingly decarbonized energy supply" (ACER, 2022).

The regulated electricity and gas markets to date have delivered sufficient signals for investments in the liberalized markets. With the advent of decarbonization in the long run to meet net-zero emission climate change targets comes the requirement of substantial renewable power generation and carbon pricing. It brings back the concern of market sceptics arguing that markets are not able to provide security of supply. During 2022, Europe experienced its first energy (price) crisis since opening up for competition.

This paper looks at electricity market prices in Northern Europe and investigates if markets have delivered and what the role of infrastructure was. In particular, we focus on five electricity market areas physically connected (see Fig. 1.1) around the North Sea. The reason for looking at this region is twofold. First, the reference area Norway (NO2) is an area with a fairly large exchange capacity internationally.[2]

The international aspect is interesting in this context as we want to investigate whether the cross-border electricity exchange between nations was affected by skyrocketing prices in 2022 and not least from the threats of shortage of fuel supply during 2022. Second, it allows us to investigate the difference in efficiency between the market coupling mechanism of electricity and capacity auctioning. The transmission cables between Norway and Germany, Denmark and The Netherlands are all part of the single day-ahead coupling (SDAC) scheme, while the transmission cable between the UK and Norway uses capacity auctioning to allocate capacity. The Norwegian price area NO2 is not only connected to the UK, the Netherlands, Germany and Denmark via transmission cables, but also produces all electricity from renewable sources. Hence, any shocks to coal, natural gas markets or nuclear electricity production outside Norway do not immediately affect Norwegian electricity prices. Hydropower and reservoir levels are the main determinants of electricity prices in NO2 (and Norway). In addition, the electricity market in Norway is highly liquid and trading at NordPool is deep. In the past we have observed substantially lower prices in the Nordics than in Continental Europe. With a physical connection of markets and consequently arising arbitraging opportunities, prices at trading places started to interact too. This paper analyzes the flows of electricity between countries and investigates if and how price shocks propagated between the countries.

Zachmann (2008) shows the lack of market integration before implementation of the third legislative package. For the same time period and also using daily data, Bunn and Zachmann (2010) identify inefficiencies in European electricity markets. Uribe et al. (2020) provides recent evidence of integration in electricity markets in the Nordpool area. Similarly, Ciferri et al. (2022) find evidence of integration between Italy, France, the Netherlands, Poland, and the integrated market of Germany and Austria. This paper uses hourly flow and price data to test the existence of a single European electricity market. By means of bilateral flow and multivariate cointegration analysis we show that the Nordic market was able to deliver security of supply during crisis. Norway, delivering purely from renewable electricity sources and physically connected to four central European neighbours, served as "swing" supplier for systems under stress.

The price area NO2 is the largest (out of five) price area in Norway with respect to production capacity. In 2022, total production in the price area was 42 TWh of electricity, while Norway in total produced 142 TWh of electricity. Located in the Southern part of the country, NO2 is interconnected with the price areas NO5 (Bergen) and NO1 (Oslo) domestically. In 1977, the first Skagerrak-transmission cable to Denmark became operational and the transmission capacity has increased incrementally to 1700 MW today. In 2007, the transmission cable NordNed from NO2 to the Netherlands (700 MW) became operational. In December 2020, the transmission cable Nordlink (1400 MW) from NO2 to Germany started commercial operation and in October 2021 the transmission cable Northsealink (NSL) (1400 MW) from NO2 to the United Kingdom became operational.

The transmission cables between NO2 and the Netherlands, Germany and Denmark are handled with the pan-European single day ahead coupling (SDAC) mechanism. This system allocates cross-border transmission capacity efficiently across all member states by coupling wholesale electricity markets from different regions through a common algorithm, ensuring optimal flow of electricity. The hourly spot prices in the market coupled areas are calculated jointly (day ahead) with the transmission capacities (and the resulting import/export of electricity) as an integrated part of the hourly spot price estimations.

The NSL cable connecting NO2 with the UK does not participate in any of the market solutions in the internal European energy market due to Brexit. The flow between Norway and the UK on this cable is handled with explicit daily auctions for transmission capacity on NSL. The two transmission system operators Statnett and National Grid introduced a separate day-ahead auction between NO2 and UK, serving as implicit market coupling, where participants deliver bids and offers for every hour on the Norwegian and British side of the connection, respectively. The auction is executed daily (day ahead) and closes at 10:50. Participants then have until 12:00 to update and submit bids to the SDAC-auction, taking the results from the NSL-auction into account. The flow of NSL will follow the price difference between NO2 and UK as submitted to the NSL-auction. The flow may therefore, in some cases, deviate from the logical flow that the price difference between UK and the real spot price of NO2 dictates, as the spot price for NO2 is not yet known at the time of the auction. Thus, we expect less compliance of flows with the price signal for the NSL than the other cables investigated in this paper.[3]

To add a broader perspective to our analysis we also look at the flows between the price areas DK1 in Denmark and Germany, as well as price area SE4 in Sweden and Denmark (DK2). The time period for this analysis is restricted to 01 January 2021 until 31 December 2022 due to data availability. This will provide insights as to if there are any differences in cooperation between full members of the EU in contrast to the cooperation between Norway and full members of the EU. Finally, We also consider the flow within Norway, by considering the neighbouring price areas NO1 and NO2. This allows insights if Norway acts differently internally, compared to the country's behaviour when interacting with other countries with regards to the flow of electricity.

We are also interested in the utilization of the transmission cables. Assuming that reduced capacities and outages of the transmission

[2] As an EEA member Norway has adopted and implemented EU regulation. It is only recent (and with increasing domestic electricity prices) that this has come under scrutiny. The status of the internal market was measured and monitored in four Annual Benchmarking reports (2001–2005) by the Commission. In its last version the UK and Norway were identified as class best with respect to having implemented competition. However, the report also notes that "Whether the improvements [...] are adequate to achieve the objectives of the internal market remains to be seen, especially if Member States take a minimalist approach to the transposition of the current legislation" (EC, 2005).

[3] Physical factors bring additional complexity: The maximum ramping volume for Nordlink is 600 MW/h. For NSL the ramping volume is capped at 475 MW/h. We expect that the longer time period needed to change the direction of the flow on NSL will increase the amount of hours the flow goes against the price signal over NSL compared with Nordlink. Grid loss is also different for the transmission cables in this analysis. On Nordlink grid loss is estimated to 3.1%, NorNed 3.2% and for NSL the grid loss is 3.4%. The SDAC algorithm does take grid loss and ramping restrictions into consideration when calculating optimal flows of electricity.

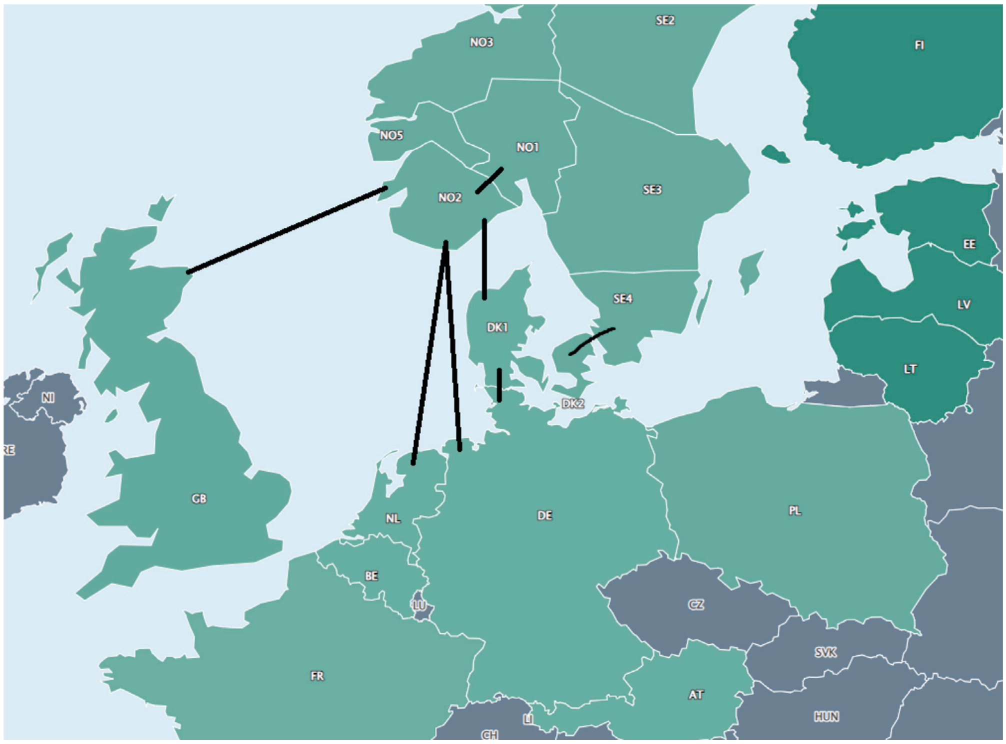

Fig. 1.1. Schematic overview of the price areas. Note: Transmission cables are displayed as black lines.
Source: Map based on Nordpool (https://www.nordpoolgroup.com).

cables are to some extent legitimate due to technical errors and maintenance, we will calculate how much of the available capacity is actually used for transmission of electricity between countries in line with the price signal. ACER (2023a) provides a detailed analysis for the availability of electricity transmission cables throughout 2022.[4]

2. Methodology

For our evaluation of the functioning of the internal market in the Nordic region we will follow a three step procedure. First, we will analyse actual hourly flows via transmission cables to see if electricity flows as theory suggests (from low-priced to high-priced areas). Second, we calculate the utilization of the transmission cables before we empirically test the hypothesis of market integration using multivariate cointegration analysis.

2.1. Comparison of the electricity flows between price areas

When comparing electricity flows between countries we compare the proportion of hours the flows of electricity between the price areas move in the expected direction with respect to the price signal. We adjust for availability of transmission cables by removing the hours where there are known unavailabilities of transmission cables from our calculations. To test whether or not the price signal determines the flow we count the hours when the price is higher in one area compared to NO2 and the electricity flow goes from NO2 to the area with the higher price. Similarly, we count the hours when the price is higher in NO2 than the neighbouring price area and the electricity flows into NO2.

Thus, our estimator for testing the price signal can be expressed mathematically as the proportion of hours the electricity flows in the direction the price signal indicates divided by the total number of hours.

$$PS_t = \frac{\text{Number of hours in compliance with price signal}}{\text{Total number of hours}} \tag{2.1}$$

PS_t denotes the proportion of the hours in time period t which are in line with the price signal mechanism for electricity transmission.

To test whether the proportion of hours in compliance with the price signal changes from year to year we use the test statistic

$$Z = \frac{PS_2 - PS_1}{\sqrt{PS_{1,2} \times (1 - PS_{1,2})(\frac{1}{n} + \frac{1}{m})}}. \tag{2.2}$$

Z's distribution is standard normal ($N(0,1)$). We use this statistic to test the different time periods, divided into yearly time periods with 8760 h (8784 in 2020) each.

2.2. Utilization of electricity transmission cables

We are interested in the utilization of the transmission cables. For this, we calculate the annual flows of electricity as a proportion of the yearly average availability of the electricity transmission cable, where we separate the flows going in and out of NO2 in two different ways.[5] First, we calculate the average flows of electricity annually:

$$\overline{F_{C,d}} = \frac{\sum_{h=1}^{H} Flow_{C,d,h}}{H} \tag{2.3}$$

$\overline{F_C}$ denotes average flow on transmission cable C, d is the direction of the flow with NO2 as reference, h is the hourly index over the year and H denotes the total number of hours in the year. Similarly

[4] For a more thorough introduction to how the EU measures market integration and evaluates it current status we refer to ACER (2023b).

[5] We assume that outages on the transmission cables are only due to maintenance or technical errors and not due to TSOs manipulating electricity flows to help alleviate internal grid congestions.

we calculate the average availability of transmission over transmission cable C throughout the year:

$$\overline{A_{C,d}} = \frac{\sum_{h=1}^{H} A_{C,d,h}}{H}, \tag{2.4}$$

where $\overline{A_C}$ denotes average available flow on transmission cable C. Finally, our proxy for the proportion of the cable made available to cross-border flow is calculated by

$$P_{C,d} = \frac{\overline{F_{C,d}}}{\overline{A_{C,d}}}. \tag{2.5}$$

The average utilization proportion, P_C, of the cable C is then a measure for how much of available capacity is utilized with flows of electricity between countries connected to cable C.

2.3. Cointegration analysis

Market integration is a long term goal of the European Union. For the internal energy market this aims to ensure security of supply, affordability, and the integration of renewable energy supply in a cost effective manner. We use the concept of cointegration to test if the electricity markets are cointegrated. More specifically, cointegration analysis allows us to test if the prices in the different markets share a common stochastic trend in the long run. If the hypothesis of price cointegration cannot be rejected, this indicates that the prices in the different price areas share a long term equilibrium and respond to common fundamental factors. This in turn can then be interpreted as market integration. It is worth noting here that electricity generation in NO2 is based close to 100% on renewable energy sources.

This paper employs the Johansen's cointegration test which can detect multiple cointegrating vectors in a multivariate system. We use cointegration analysis to test if the electricity systems in NO2 and NO1, Germany, the Netherlands, Denmark and the United Kingdom are in fact cointegrated and share a common stochastic trend. The test involves estimating the following Vector Error Correction Model (VECM):

$$\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t \tag{2.6}$$

where Y_t is a vector of the variables, Π is the matrix of long-run multipliers, Γ_i is the matrix of short-run multipliers, and ε_t is a vector of error terms.

The null hypothesis of the Johansen's test is that there are at most r cointegrating vectors, where r is less than the number of variables in the system. The trace and maximum eigenvalue statistics are used to determine the number of cointegrating vectors.

If cointegration is confirmed, a Vector Error Correction Model (VECM) is estimated to examine both the short-run and long-run dynamics among the variables. The VECM is given by:

$$\Delta Y_t = \alpha\beta' Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t \tag{2.7}$$

where α is the matrix of adjustment coefficients, β is the matrix of cointegrating vectors, and other symbols are as defined previously.

The adjustment coefficients in α show the short-run speed at which the variables adjust towards the long-run equilibrium after a shock, while the cointegrating vectors in β represent the long-run equilibrium relationships among the variables. For a more thorough description of cointegration using the Johansen procedure we recommend Johansen (1995) or Enders (2015).

Table 3.1
Descriptive statistics.

	Count	Mean	Median	SD	Min	Max	Skewness	Kurtosis
NO2	1828	75.59	43.55	90.98	0.90	660.06	2.70	11.87
DEU	1828	88.89	46.79	100.97	−42.24	699.44	2.41	9.45
NL	1828	94.07	51.07	98.08	−5.45	693.83	2.24	8.52
DK1	1828	82.86	45.50	96.53	−14.37	699.44	2.65	11.10
UK	1828	103.56	63.42	95.28	−11.09	773.30	2.19	8.74
NO1	1828	71.83	43.55	81.55	0.90	655.27	2.65	12.03

Table 3.2
ADF and KPSS test results for log level and first difference of log level.

	Log level		First difference of log level	
	ADF	KPSS	ADF	KPSS
NO2	−2.81*	9.54*	−14.26	0.024
DK1	−2.35*	11.29*	−17.18	0.026
NL	−2.74*	12.11*	−15.58	0.058
DEU	−3.11*	12.33*	−17.255	0.060
UK	−2.78*	11.92*	−15.35	0.015
NO1	−2.54*	5.58*	−13.72	0.031

The asterisk indicates rejection of stationarity at the 5% level.

3. Data

3.1. Description of the dataset

When analysing the flow of electricity between the price areas of Norway area 2 (NO2), Germany (DE), the Netherlands (NL), Denmark area 1 (DK1), the United Kingdom (UK) and Norway area 1 (NO1) we use hourly spot price data. In addition we use the hourly allocated flows of electricity as allocated through the market coupling mechanisms and day ahead auctions (for the NO2-UK transmission) through the spot markets. We choose to use the financially allocated transmission capacities rather than the physical flows since physical flows are adjusted to physical balancing needs in the electricity systems in the respective markets, overruling the price signal. The hourly price data were collected from Nordpool Spot (DK1, NO2, UK, NO1) and the European Power Exchange (DE, NL) for the time period 1/1-2018 to and including 31/12-2022.

For the cointegration analysis we use daily spot price data from the respective countries. Using daily data for analysing cointegration relationships limits the impact from the substantial autocorrelation structures in the hourly data. We transform the data using the log-transformation and add a constant+1 that is equal to the lowest negative price in all the time series to all the observations to enable the log transformation. Fig. 3.1 shows the non-transformed prices whilst descriptive statistics of the time series are provided in Table 3.1.

3.2. Stationary properties of the data

Financial time series are generally not covariance stationary. Thus, we will perform two tests to check for unit roots in the time series and identify the degree of integration of each time series. A time series that is stationary after differencing d times is integrated of order d with the notation *I(d)*. We apply the Augmented Dickie–Fuller test (ADF) and the Kwiatkowski–Phillips–Schmidt–Shin test (KPSS). The ADF test is based on the null hypothesis of non-stationarity introduced in Cheung and Lai (1995), while the KPSS test uses the null hypothesis of stationarity as described in Kwiatkowski et al. (1992).

Table 3.2 presents the results of the unit root tests for the log-transformed data and the first differences of the log-transformed data. The results from both the ADF-and the KPSS-tests indicate non-stationarity for the log-transformed data. When we apply the first difference on the log-transformed data, then both the ADF-test and the KPSS-test indicate stationarity. Thus, we conclude that the time series are *I(1)* and cointegration analysis is the appropriate tool to investigate the joint properties of these time series.

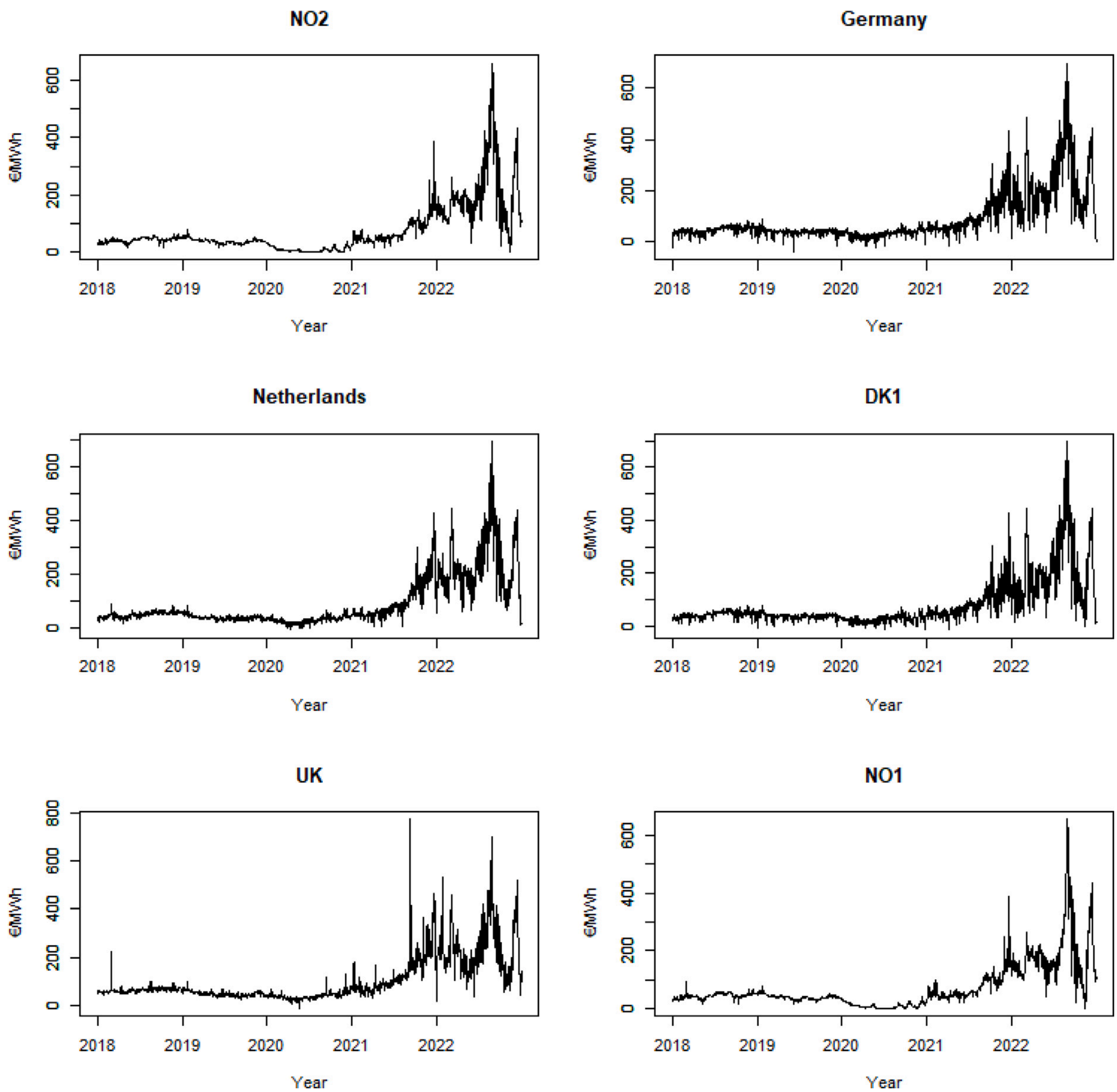

Fig. 3.1. Daily day ahead electricity prices.

4. Results and discussion

We present our estimates of the price signal effect out of and into NO2 in Table 4.1. Since the transmission cable between Norway and Germany became operational in December 2020, we only include the years 2021 and 2022. Similarly, since the cable between Norway and UK became operational in November 2021, we only include year 2022 for this transmission cable.

The first thing to notice is the high level of compliance with the price signal in the operation of the transmission cables when the flow goes out of price area NO2. The cable between NO2 and Germany is almost at 100% compliance level in 2022 (99.71%). It is also worth noting that the NordLink-cable operates with a higher degree of compliance with the price signal in 2022, than in 2021 (99.09%).[6] The Skagerrak-cable between NO2 and DK1 (direction Denmark) operates at a slightly lower level in 2022 compared with earlier years, but the differences are small. The same holds for the NorNed-cable between NO2 and the Netherlands, where compliance with the price signal in 2022 appears to be the same as for previous years.

We see similar results when the electricity flows are directed into NO2. The compliance rates are generally higher in 2022 compared with earlier years. Note that electricity flows are slightly less efficient when the direction of the flow is towards NO2, rather than out of NO2. Also note the comparably low numbers for flow between NO2 and UK. This illustrates the increased efficiency due to market coupling rather than separate capacity auctions for transmission lines. For a more formal statistical test of the differences of the directional electricity flows, we refer to Tables A.1 and A.2 in Appendix A.

The results show that the transmission cables between EU-countries are slightly more in line with expectations than those between Norway and EU-countries in 2021 and 2022. The flow of electricity between Southern Sweden (SE4) and Eastern Denmark (DK2) performs at a high level and we see no drop in utilization during the energy crisis of 2022. The flow between NO1 and NO2 delivers at a high level as there are no ramping restrictions on cables internally in Norway. In addition, there is no loss functionality on this transmission cable, so the flow may change direction without delay from one hour to the next without loss. We find similar high utilization for the cable between Denmark and Germany. Due to grid constraints in Northern Germany, Germany has

[6] 2021 was the first full year in operation of the NordLink-cable between NO2 and Germany. The line did not reach normal operations until March 2021, affecting available capacities during the first quarter of 2021.

Table 4.1
Flow and share of hours in the correct direction for NO2 and price areas outside NO2 between 2018 and 2022.

Flow out of NO2					
Flow out of NO2 into:	2022	2021	2020	2019	2018
DEU	0.9971	0.9909	–	–	–
NL	0.9969	0.9984	0.9990	0.9984	0.9994
DK1	0.9870	0.9932	0.9965	0.9922	0.9925
UK	0.9019	–	–	–	–
NO1 to NO2	1	1	1	1	–
Flow into NO2					
Flow into NO2 from:	2022	2021	2020	2019	2018
DEU	0.9940	0.8695	–	–	–
NL	0.9677	0.9519	0.9558	0.9918	0.9659
DK1	0.9591	0.9558	0.9635	0.9728	0.9640
UK	0.8660	–	–	–	–
NO2 to NO1	1	1	1	1	–
Areas outside NO2					
	2022	2021	2020	2019	
SE4 to DK2	0.9986	0.9988	–	–	–
DK2 to SE4	1	0.9990	–	–	–
DK1 to DEU	0.998	1	–	–	–
DEU to DK1	0.999	1	–	–	–

committed to financially compensate Denmark for the loss of electricity flow due to poor grid capacity in Germany. This ensures that the flow of electricity follows the price signal during almost all hours. However, given the constraint on the grid this is a financial flow. Thus, the utilization rate figures are inflated compared to the physical flow of electricity.

The results in Table 4.1 indicate that during 2022 the market mechanism was working as suggested by theory. While there are differences in compliance with the price signal over the years, these are very small. For the interconnectors NO2-NL and NO2-DK1, the compliance with the price signal is slightly smaller in 2022 than in the preceding years. For the interconnector between Germany and NO2, the compliance of transmission with the price signal increased in 2022, compared to 2021.

A more detailed examination of the results from the calculations of utilization rates are shown in Tables 4.2–4.4.[7] These provide a more intricate understanding of adherence to market price signals compared to merely analyzing the direction of electricity flows. On a general level, the utilization rate sheds light on the extent to which available capacity on an electricity interconnector is being used by transmission service operators in response to price signals. We present utilization rates across various levels of price differences between pricing areas. Table 4.2 shows the utilization rates for small price differences, ranging from slightly above 0% up to and including 5%. Given such a narrow price margin, we examine utilization within the context of grid loss across High Voltage Direct Current (HVDC) interconnectors. The results show a significant difference between the land-based Alternating Current (AC) interconnector linking NO1 and NO2 and the international High Voltage Direct Current (HVDC) interconnectors.[8] The range of results is due to the different regulatory characteristics of HVDC cables compared to domestic AC land-based cables. The AC cable between NO1 and NO2 allows for more responsive and adaptable electricity flow in these areas in line with price signals, as it experiences neither grid loss nor ramping restrictions. In contrast, HVDC cables have minimal interconnector utilization when price differentials are low due to grid

[7] The observations for the utilization of transmission cables using the full sample of data can be found in Table A.3 in the Appendix A. Note that these results include data also when the prices in the respective price areas are identical.

[8] The grid loss in HVDC transmission slightly exceeds 3%.

Table 4.2
Utilization of available capacity for transmission cables connected with NO2 when the price difference between the price areas is above 0% and less than or equal to 5%.

Out of NO2	2022	2021	2020	2019	2018
DEU	39.8%	42.8%	–	–	–
NL	31.3%	41%	49.6%	37.4%	48.8%
DK1	57.6%	63.7%	81.6%	71.6%	59.8%
UK	42.8%	–	–	–	–
NO1	100%	99.9%	100%	99.4	67.5%
Into of NO2	2022	2021	2020	2019	2018
DEU	29.5%	24.7%	–	–	–
NL	25.5%	28.3%	34.3%	35.4%	27.5%
DK1	39.8%	44.2%	58.2%	59.8%	53.8%
UK	21.5%	–	–	–	–
NO1	100%	100%	100%	100%	100%

Table 4.3
Utilization of available capacity for transmission cables connected with NO2 when the price difference between the price areas is above 5% and less than or equal to 100%.

Out of NO2	2022	2021	2020	2019	2018
DEU	96.7%	95.7%	–	–	–
NL	97.8%	99.1%	98.4%	97.3%	99.5%
DK1	89%	95.7%	94.7%	95.3%	87%
UK	74.4%	–	–	–	–
NO1	100%	100%	100%	99.5%	67.5%
Into of NO2	2022	2021	2020	2019	2018
DEU	84.3%	69%	–	–	–
NL	83.7%	81.7%	66.9%	95.4%	87.8%
DK1	64.9%	72%	67.2%	89.2%	92.5%
UK	45.3%	–	–	–	–
NO1	98.7%	100%	100%	100%	100%

loss and the maximum ramping volume per hour. These restrictions are imposed by the TSOs to ensure grid stability in the respective countries interconnected by HVDC cables. Due to the several-hour time-lag required to reverse the direction of flow, Transmission System Operators (TSOs) may allow for under-utilization during periods when the price difference is lower than the grid loss.

Next, we analyse the utilization rates for price differences between price areas exceeding 5% and up to and including 100%. The results (Table 4.3) reveal a marked increase in utilization rates for the HVDC interconnectors. Notably, the interconnector between NO2 and the UK exhibits suboptimal performance, particularly when electricity is transmitted from the UK to NO2. The utilization below maximum can be attributed to several factors. Primarily, flow from the UK to NO2 is infrequent because the UK has consistently experienced significantly higher spot prices than NO2 over an extended period. Additionally, the fact that this cable is not integrated into the SDAC system adds complexity and increases the potential for deviations of observed from expected electricity flows. We also note that for this interconnector, the utilization rate escalates substantially with an increasing price differential between the respective price areas.

As a supplement, we include Table 4.4 that specifically addresses instances where price differences between price areas exceed 100%. The findings corroborate the observation that utilization rates for HVDC cables elevate in tandem with increasing price disparities. It is important to note that occurrences where the price difference between NO1 and NO2 surpasses 100% have been rare between 2018 and 2022, with some years recording no such instances.

Turning to the empirical analysis of the degree of market integration we use bivariate and multivariate cointegration analysis. The bivariate test results (Table 4.5) support the assumption that the Northern-European electricity markets are (highly) integrated.

Observing the bivariate cointegration relationships between NO2 and the connected countries, all statistically significant, we also analyse the cointegration relationships of higher order. The results are displayed in Table 4.6.

Table 4.4
Utilization of available capacity for transmission cables connected with NO2 when the price difference between the price areas is above 100%.

Out of NO2	2022	2021	2020	2019	2018
DEU	100%	98.3%	–	–	–
NL	100%	98.7%	99.9%	65.7%	100%
DK1	100%	97.7%	99.7%	95.5%	96.6%
UK	93.2%	–	–	–	–
NO1	*	84.7%	14.6%	*	98.4%
Into of NO2	**2022**	**2021**	**2020**	**2019**	**2018**
DEU	99.2%	92.5%	–	–	–
NL	96.7%	95.5%	90.7%	100%	98.3%
DK1	87.2%	94.2%	76.5%	98.9%	112%
UK	64%	–	–	–	–
NO1	100%	65.1%	82%	*	*

Table 4.5
Results bivariate cointegration test.

		DEU	NL	DK1	UK	NO1
NO2	$H_0 : r = 0$	35.78***	32.60***	35.62***	41.73***	35.26***

Note: Using entire dataset. *** denotes 1% significance level.

Table 4.6
Results multivariate cointegration test.

	H_0	NO2
DEU, NL	r ≤ 1	33.52***
DEU, DK1	r ≤ 1	34.61***
DEU, UK	r ≤ 1	36.84***
NL, DK1	r ≤ 1	33.30***
NL, UK	r ≤ 1	30.27***
DK1, UK	r ≤ 1	37.15***
DEU, NO1	r≤ 1	34.13***
NL, NO1	r ≤ 1	27.69***
DK1, NO1	r ≤ 1	34.29***
UK, NO1	r ≤ 1	34.29***
DEU, NL, DK1	r ≤ 2	33.19***
DEU, NL, UK	r ≤ 2	31.02***
DEU, DK1,UK	r ≤ 2	36.73***
DEU, NL, NO1	r ≤ 2	27.88***
DEU, UK, NO1	r ≤ 2	30.40***
DEU, DK1, NO1	r ≤ 2	33.52***
NL, DK1, NO1	r ≤ 2	27.69***
NL, DK1, UK	r ≤ 2	30.22***
DEU, NL, DK1, UK	r ≤ 3	30.10***
DEU, NL, DK1, NO1	r ≤ 3	27.66***
DEU, NL, UK, NO1	r ≤ 3	27.43***
NL, DK1, UK, NO1	r ≤ 3	27.45***
DEU, NL, DK1, UK, NO1	r ≤ 4	27.36***

Note: Using entire dataset. *** denotes 1% significance level.

All our results from bi- and multivariate analysis confirm cointegration of all price areas. We find strong evidence for shared price dynamics in this region of Europe. This is consistent with the results of Lago et al. (2018) and de Menezes and Houllier (2016) and expected as it is the result of increased physical integration of the markets via new transmission cables of electricity between countries. We also find cointegration between NO2 and the UK although the connecting transmission cable only became operational in late 2021. This indicates that other variables than physical transmission capacity between countries play a part in pricing electricity. For instance, Ferkingstad et al. (2011) and de Menezes et al. (2016) have shown the effect of fuel prices on electricity prices in the UK, Germany and the Netherlands. The results of our cointegration analysis indicate that Norwegian hydro-producers also price the expected electricity production stored in hydro reservoirs using fuel prices. This is a direct result of physical transmission cables to price areas that do price their electricity through the production of electricity with gas fired or coal fired power plants. In periods with high inflow of water into reservoirs, Norwegian hydro producers can price their reservoir production just below the marginal cost of the relevant technology in the production stack in neighbouring price areas and export electricity. During dry months the hydro-producers can do the opposite and price their water above a certain level of marginal cost in the merit order in the neighbouring countries and import electricity instead. Thus, the reservoirs in Norway act as a swing producer in the greater region of Northern Europe. Although this is not possible to infer from this cointegration analysis, we believe that the new transmission cables from Norway to UK and Germany have made the prices in NO2 more similar to the electricity prices in continental Europe and in the UK. Another issue that separates the NO2-UK-interconnector from the others is that while the flow on the transmission lines between NO2 and Germany, Denmark and the Netherlands are market coupled, the flow between NO2 and the UK is determined by use of daily auctions. This in turn increases the risk of inefficient use of the transmission cable, as our analysis indicates (see Table 4.1).

5. Conclusion

European countries have tried to solve the issues of sustainability, security of supply and affordability with market solutions and market integration through incremental reform over the past 30 years. Considering the international nature of these arrangements it is crucial that the agreements are respected when the electricity system is stressed. The year 2022 was a year of great stress in the European energy system due to the war in Ukraine and the subsequent sudden drop in natural gas supplies from Russia. Our analysis shows that market solutions delivered efficient security of supply, in a selected European region, throughout a period of severe and unforeseen circumstances. Electricity flows were directed to areas where demand was greatest, thus increasing the robustness and efficiency of electricity supplies on a European level. Our analysis shows that countries upheld the agreements that were initiated in times of abundant supply in periods with significant stress in the electricity system. This is crucial if Europe intends to increase security of supply using market solutions on a pan-European level.

Revisiting the central inquiry of this paper, the findings from Tables 4.1 to 4.4 offer no evidence of divergent national behaviours during the 2022 energy crisis. Throughout the majority of hours from 2018 to 2022, the direction of electricity flows aligns consistently with the prevailing price signals. Furthermore, the utilization rates of the electricity transmission cables connected to NO2 exhibit notable variations across years. Despite these variations, our analysis reveals no discernible patterns or consistent shifts in behaviour specifically during the year 2022. However, the results from our analysis warrant an in-depth ex-post evaluation of specific elements from the legislative framework such as the 70% rule policy or the effect of implementing SDAC.

CRediT authorship contribution statement

Bjarne Sæther: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Anne Neumann:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Table A.1
Difference in compliance with the price signal for transmission out of NO2.

	2021	2020	2019	2018
NO2-DEU-22	0.0062**	–	–	–
NO2-NL-22	−0.0014**	−0.0021**	−0.0015*	−0.002**
NO2-DK1–22	−0.0062**	−0.010**	0.0052**	0.0055**

Note: Values refer to the difference in compliance with the price signal on the specific transmission cable between 2022 compared to previous years. ** (*) implies statistical significant differences between the years at 1% (5%) confidence level.

Table A.2
Difference in compliance with the price signal for transmission into NO2.

	2021	2020	2019	2018
DEU-NO2–22	0.0396**	–	–	–
NL-NO2–22	0.016**	0.012**	−0.024**	0.0018**
DK1-NO2–22	0.0033**	−0.0044**	−0.014**	0.005**

Note: Values refer to the difference in compliance with the price signal on the specific transmission cable between 2022 compared to previous years. ** (*) implies statistical significant differences between the years at 1% (5%) confidence level.

Table A.3
Utilization of available capacity for transmission cables connected with NO2 for the full sample.

Out of NO2	2022	2021	2020	2019	2018
DEU	75.4%	78.5%	–	–	–
NL	80.1%	88.9%	98.4%	70.5%	85.7%
DK1	78.7%	84.8%	92.6%	82%	81.9%
UK	74.6%	–	–	–	–
NO1	33%	45.2%	39.2%	46.7%	51.9%
Into of NO2	**2022**	**2021**	**2020**	**2019**	**2018**
DEU	76.3%	72.1%	–	–	–
NL	79.4%	77.6%	82.7%	83.3%	72.5%
DK1	74.4%	72.4%	71.5%	81.0%	94.1%
UK	73.8%	–	–	–	–
NO1	68.15%	59.2%	33.2%	39.1%	35.4%

Appendix A. Detailed tables

First we present statistical tests of the differences in directional flows going into and out of NO2 over HVDC-interconnectors.

Table A.3 shows results for the utilization of transmission cables using the full sample. Note that these observations include data where the prices between the price areas are identical.

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