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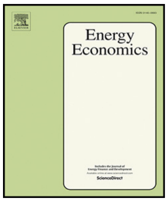

# Quantifying the short-term asymmetric effects of renewable energy on the electricity merit-order curve

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## ABSTRACT

Amidst the growing significance of renewable energy, this paper examines the asymmetric effects of renewable energy on electricity prices and transmission flows in the Nordics using hourly electricity data. Employing a novel panel asymmetric fixed-effects method, we quantify the non-linear impact of renewable generation technologies on the electricity supply curve. Contrary to previous research, our analysis challenges the assumption of wind having symmetric effects in electricity markets. Specifically, we suggest that an increase in renewable energy cannot lead to price reductions of the same magnitude as the price increases caused by a decrease in wind. In addition, we investigate interconnections between regions and explore asymmetries in transmission flows due to wind generation. Our findings reveal the presence of asymmetric effects in the Nordic electricity market, highlighting their significance in achieving a secure electricity system. These results offer valuable insights for governments, policymakers, and market participants for optimizing the electricity generation mix, prioritizing flexible systems, and making informed investment decisions.

## 1. Introduction

Electricity markets have undergone major changes in recent years. The European Union (EU) has decided to phase out coal and nuclear plants in order to make EU the first net-zero continent by 2050 (EC, 2020). Thus, to cover electricity demand, governments have shifted their focus towards renewable energy. Renewable energy sources provide a way of producing electricity with almost zero operating carbon footprint. Hence, renewable energy is playing a crucial role in mitigating climate change worldwide, albeit with costs which are not easily assessed. Electricity market participants and regulators need to consider an important characteristic of renewable energy that can complicate even further the functioning of electricity markets, its intermittent nature. This means that electricity through wind or solar can be produced only when the wind is blowing, and the sun is shining. Thus, uncertainty in electricity production, combined with the uneven distribution of access to economically viable options for scaled storage, further complicate the equilibrium of supply and demand.

The energy sector in the EU has faced many challenges in the last few months. High gas prices, as well as the shortfall of gas deliveries in many EU countries, have forced the EU into an unprecedented energy crisis. Gas prices dragged wholesale electricity prices with them reaching a 30% increase compared to previous years (Eurostat, 2023). Governments had to take action to reduce the financial burden of households and businesses but also secure electricity supply. The global energy crisis causes essential and potentially long-term changes that could accelerate transition towards cleaner and more reliable energy systems (IEA, 2022).

In addition to the challenging circumstances in energy markets, the cost of solar PV and wind is increasing following the global inflation (IEA, 2021). However, despite these obstacles, investments in renewable energy should continue to rise in the upcoming years in order for the EU to achieve its ambitious sustainability goals. On the other hand, market participants are seeking opportunities to increase their profits and grow in the market. Consequently, the role of renewable sources in energy markets is expected to be of higher importance in the future requiring further research in the field.

In this article, we attempt to challenge the hidden assumption of symmetry in electricity markets. Previous research has demonstrated that renewable energy sources, due to their nearly zero marginal costs, are given priority dispatch over other electricity generation

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technologies. As a result, they cause a rightward shift in the supply curve, leading to a decline in wholesale electricity prices. This phenomenon, known as the merit-order effect, in combination with the unique characteristics of electricity markets, creates a complex environment for market participants (Sensfuß et al., 2008; Cludius et al., 2014; Csereklyei et al., 2019) which we aim to explore. Hence, our approach embraces the merit-order effect and extends it by quantifying the non-linear impacts of renewable energy on electricity prices and transmission flows. To achieve this, we employ an asymmetric panel regression using the available hourly observations from the Nordic electricity market. Our primary objective is to explore not only the response of electricity prices to increases in renewable energy, but also their reaction to decreases in renewable energy within electricity markets.

Renewable energy, inherently connected to variable weather conditions, emerges as an intermittent source, and this intermittency can be transmitted to electricity prices in the form of asymmetries (Mulder and Scholtens, 2013; Staffell and Pfenninger, 2018). The elasticity of demand and supply plays an important role in shaping these asymmetries. When weather conditions are favorable, the electricity supply from renewable sources increases, potentially leading to more elastic electricity prices. Consumers, faced with lower prices, may respond by shifting their electricity usage or increasing consumption to benefit from the renewable energy abundance. On the contrary, during periods of decreased renewable energy generation, electricity prices may rise, prompting a more elastic demand as consumers react to higher prices by reducing or shifting their consumption patterns. Therefore, we expect electricity prices to respond asymmetrically to renewable energy sources.

Building on this, Erdogdu (2016) explores the occurrence of supply and demand shocks in electricity markets such as outages and transmission constraints, and the challenges in compensating for these in the short-term. The occurrence of extreme prices, characterized by sudden positive or negative jumps in prices, indicates an asymmetric response of electricity prices to both supply and demand shocks. In this paper, our focus is on investigating the supply shocks resulting from the variable nature of renewable energy. Plenty of research has focused on the extreme negative electricity prices (Hellström et al., 2012; Fanone et al., 2013; De Vos, 2015; Bajwa and Cavicchi, 2017; Seel et al., 2021) and extreme positive prices (Clements et al., 2015; Gayretli et al., 2019; Lu and Suthaharan, 2023) in power markets due to renewable generation. Hence, exploring the asymmetric effects in the electricity markets could provide a more holistic view of renewable sources in the energy sector.

Turning to the cross-border impacts of renewable energy, Figueiredo et al. (2016) detail how the impacts of renewable energy sources can influence neighboring markets, potentially introducing asymmetries in cross-border effects. Different market structures, transmission capacities, and policy frameworks contribute to varied asymmetric responses in electricity prices related to wind power generation. This multifaceted interaction underscores the complexity of the electricity market, where the effects of renewable energy extend beyond national borders, influencing pricing dynamics in interconnected markets.

Transmission of electricity between areas plays a crucial role in developing a reliable power system for society. Transmission flows are the main tool for integrating markets across different countries, supporting the sharing of infrastructure that can increase flexibility in the markets (Yang, 2022). Electricity transmission also enhances competition and profit opportunities for market participants, offering access to other markets with different production characteristics. Therefore, we believe it is important to also explore asymmetries in transmission flows, in this article specifically between Denmark and Sweden.

Until now, electricity prices and renewable energy models have assumed that an increase in renewable energy would have a proportionate decrease in electricity prices as a decrease of renewables would increase prices. Evaluating not only how electricity prices react to an increase in renewable energy production, but also to a reduction of renewables in the market, could provide important insights to participants. Market participants such as producers, storage facilities etc. could discover new profit opportunities, for instance storage facilities could charge the batteries when prices are low and discharge when prices are high. Additionally, regulators could target the market with more efficient policies that consider the sensitivity of prices in increases and reductions of renewables. Accordingly, these opportunities and governmental efforts could enhance the future sustainability of the electricity sector in the EU.

This article contributes to the literature of renewable energy and electricity prices in various aspects. First, it formally investigates the asymmetric impact of renewable energy on electricity prices. We empirically quantify the non-linear effect of renewable generation technologies on the supply curve in the electricity market. This concept, although analyzed theoretically in the literature, has not been numerically investigated in previous research. Secondly, our research explores the relationships between the different regions by investigating the role of asymmetries in the transmission flows due to renewable energy. This aspect is crucial because as Bjørndal et al. (2018) highlight the Nordic market can fail to provide location price signals, resulting in excess transmission flows due to wind power. This could lead to grid congestion, and eventually, jeopardize the stability of the power system. Additionally, we investigate if the non-linear effects of renewable energy on prices are amplified in the case of congestion between the investigated areas.

One of the novel aspects of our research is the effective utilization of hourly power market data by employing a panel framework rather than relying on a traditional time series-based methodology. Specifically, previous research has argued that electricity prices should be treated in a panel framework rather than a time-series setting, using the 24 h of the day as the individual variable in the panel (for more information see Tselika (2022)). The reason is that day-ahead electricity prices are set simultaneously for the following 24 h of the following day (Karakatsani and Bunn, 2008), and the information when setting the prices is common for all the hours (Keppler et al., 2016). Huisman et al. (2007) showed that hourly day-ahead electricity prices display hourly specific mean-reversion and that there is an observable block-structured cross-sectional correlation pattern among the different hours. Thus, we are interested in using a panel methodology, exploiting the high-resolution hourly data and control for time-invariant characteristics among the hours of the day. In this way, we can control for a wide range of market characteristics and isolate the actual non-linear effects (negative and positive shocks) of renewable energy generation on electricity prices.

To the best of our knowledge, this is the first analysis that quantifies the electricity price and transmission asymmetries due to renewable energy using a panel setting in the EU. A paper by Nibedita and Irfan (2022), which is closely linked to our analysis, has examined the asymmetric impact of renewable sources on electricity prices using a NARDL time-series approach, thus ignoring the time-invariant component and the connection with other regions, focusing only on the Indian wholesale market. Our research focuses on Denmark given that it has high wind penetration in its electricity market, it does not have flexible systems, but it is connected to flexible Sweden and Norway. Furthermore, the eastern Danish region (DK2) can be considered as an energy hub since it is squeezed between the Western Danish region and Sweden, making it an interesting case to investigate.

## 2. The merit-order model and asymmetries in electricity markets

In the economic theory of competitive markets, prices are set by the law of supply and demand. Electricity markets follow, as with other commodities, this economic principle to formulate their market prices, but it is identified by unique features which are reflected in its market design. First, electricity demand is inelastic in the short-term (Filippini, 2011; Blázquez et al., 2013; Lim et al., 2014), showing that consumers cannot substitute electricity with another commodity — electricity is needed regardless of the price. Second, the electricity supply or merit-order curve is convex, discontinuous and increases steeply for high demand (Kyritsis et al., 2017).

The electricity supply curve arises from the upward categorization of electricity generation technologies depending on their short-run marginal costs. Production plants with low marginal costs such as nuclear plants are placed in the left part of the supply curve while high marginal cost plants such as gas plants are placed in the right side of the curve. Since the liberalization of electricity markets, marginal pricing has determined the wholesale markets, including the day-ahead market, and consists of a natural way that prices arise in the market. Therefore, electricity prices are generally set by the marginal cost of the most expensive plant that is needed to cover demand and the emerging price is uniform for all the producers and consumers.[1] Marginal pricing has been recently criticized when electricity prices sharply increased due to gas prices but modifying the pricing mechanisms can be burdensome. Regulators have proposed a reform in the electricity market, suggesting to maintain the existing structure in short-term markets. Consequently, gaining a deeper understanding of electricity markets, including nuances such as asymmetries, becomes crucial in reaching the European decarbonization targets.

Renewable energy enters electricity markets as an almost zero marginal cost technology, thus, it is placed at the bottom of the merit-order curve. Therefore, renewables replace high marginal cost technologies resulting in a shift of the supply curve (S) to the right (S1) (see Fig. 1). This shift results in a lower price equilibrium (P1) and is called the merit-order effect. This indicates that renewable energy generates a reshaped marginal cost structure in electricity markets (Ziel et al., 2015). The merit-order effect has been investigated and eventually validated by previous literature including Sensfuß et al. (2008), Tveten et al. (2013), Cludius et al. (2014), and Antweiler and Muesgens (2021). Nevertheless, renewable energy is characterized by its intermittent nature, which leads to renewables entering the market in highly volatile volumes. For instance, when the wind is blowing, electricity demand can be met by wind power. However, on days when wind resources are scarce, other energy sources become the primary providers of electricity. Consequently, when renewable generation is insufficient in electricity markets, the demand is covered by more expensive technologies, causing a shift in the supply curve (S) to the left (S2) and resulting in higher market prices (P2). Therefore, it is crucial to further investigate the implications of both an increase and a decrease in renewable energy within electricity markets. In this paper, we aim to provide a comprehensive understanding of the overall impact of renewable energy in electricity markets, enabling informed decision-making and policy formulation.

The impact of renewable energy on electricity prices is influenced by different factors in the market. Key elements include how much electricity people need (demand), how much renewable energy is produced, and the shape of the supply curve (how much electricity suppliers are willing to produce at different prices) (Keles et al., 2013). The supply curve is affected by the types of power plants used, how efficient they are, and the costs of fuel and CO2 emissions. If renewable energy replaces expensive or inefficient power sources, it can lead to a bigger reduction in prices. Gelabert et al. (2011) have found that the effect on prices also depends on the type of energy source being replaced by renewable energy. Additionally, as shown in Fig. 1, the impact of increasing renewable energy may not be the same as decreasing it — it can be disproportionate or asymmetric in electricity markets.

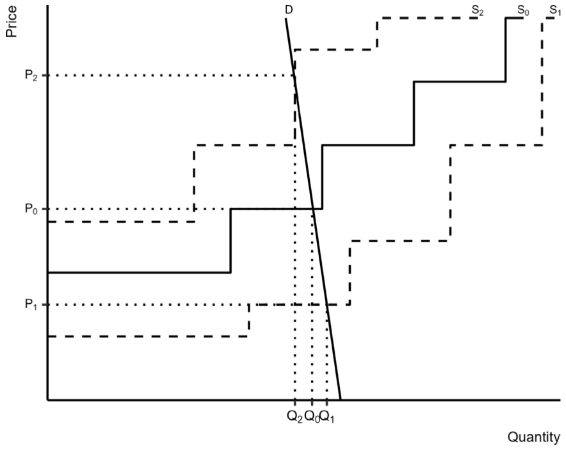

**Fig. 1.** The merit-order effect.

In Denmark's electricity market operation, ensuring a secure electricity supply involves employing diverse strategies. The intermittent nature of renewable energy sources entails rapid responses from other power sources to maintain system balance. Market operations play a pivotal role in the balancing of the market. The day-ahead markets serve to balance supply and demand for the following day. However, in instances of imbalances caused by unexpected outages or wind variability, intraday markets step in to ensure market equilibrium (Danish Energy Agency, 2016). Producers can submit bids an hour before electricity delivery, offering a more dynamic adjustment mechanism. Further there are the real-time balancing markets, operating closest to the actual delivery time. Beyond the market structure, Denmark implements an approach to provide security of supply in its electricity system. This includes using flexible thermal plants, utilizing interconnection capabilities with flexible systems such as Norway's hydropower resources, employing sector coupling strategies, and promoting demand-side flexibility (Danish Energy Agency, 2021). These multifarious approaches collectively reinforce the resilience and security of Denmark's electricity network.

The asymmetric effect of renewable energy on electricity prices stems from the dynamics of electricity markets. In recent years, there has been more research that focus on the non-linearities in the price distribution through various approaches. Maciejowska (2020) used a quantile regression to estimate the impact of solar and wind on electricity prices in Germany. They found that renewable energy has a diverse effect on the price distribution, concluding that policies should take into consideration the complementarity between energy sources. On the other hand, Sirin and Yilmaz (2020) explored the Turkish wholesale electricity market, confirming the merit-order effect in the entire price distribution and its impact on the policy mechanisms in the market. In a recent study by Apergis et al. (2020), copulas were employed to examine the tail dependence of electricity prices in Australia. The study revealed variations in tail dependence across three distinct periods: before, during, and after the implementation of the carbon tax. The key feature of our paper, that diversifies it from previous research, is that, firstly, we differentiate between positive and negative shocks of renewable energy instead of exploring only positive shocks, and secondly, we focus on the non-linearities induced in the supply curve through renewable technologies, rather than breaking down the price distribution.

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[1] Market participants have the opportunity to bid at, above, or below the marginal prices. For instance, if there is supply scarcity producers may bid above marginal prices and if there is overcapacity prices can be set by the marginal cost mechanism.

**Table 1**
Descriptive statistics.

| | Eastern Denmark<br>DK1 | Western Denmark<br>DK2 | Southern Sweden<br>SE4 |
|---|---|---|---|
| Mean price (€/MWh) | 34.821 | 36.847 | 36.963 |
| Mean wind (GWh) | 1.269 | 0.339 | 0.443 |
| Load (GWh) | 2.26 | 1.502 | 2.772 |
| Std. Dev. Price | 14.107 | 15.101 | 13.614 |
| Std. Dev. Wind | 0.93 | 0.275 | 0.338 |

## 3. Data and descriptive statistics

The data employed in this research span from January 1, 2016 until December 31, 2019 providing a dataset of 35 064 observations. We obtained the data for the two Danish areas, the Eastern (DK1) and Western Denmark (DK2) as well as the Southern Swedish area (SE4) from Nordpool AS. We chose this specific timespan to mitigate the influence of extreme events in electricity markets, such as the COVID-19 pandemic, which could significantly impact the investigated asymmetries. We use hourly day-ahead prices ($P_{it}$), forecasted wind generation ($W_{it}$) and forecasted load ($L_{it}$). Given the low share of solar generation, approximately 3%, during the investigated period in Denmark, our primary focus is on wind power, which represents a main source of electricity generation. We present the descriptive statistics of the underlying variables in Table 1. The results indicate that the average price is approximately at the same level in all the regions. The highest average price is found at Western Denmark (DK2) and Southern Sweden (SE4). We believe that this is due to the lack of flexible systems in DK2 and SE4 which can offer significant storage opportunities. On the other hand, DK1 has direct interconnections with the Southeastern Swedish (SE3) region and the Southern Norwegian (NO2) region which also offer storage opportunities, given NO2's high hydropower production capabilities. In addition, the standard deviation shows that the prices in both Danish areas are more volatile than the Swedish prices, with DK2 exhibiting the highest value.

When it comes to wind, DK1 has the highest wind production compared to both the DK2 and SE4 areas. The descriptive statistics project the intricate market characteristics in the Nordic region. Denmark has high wind penetration in the electricity market while Sweden and Norway can offer storage opportunities when there are available interconnections. Furthermore, the Nordic electricity sector can be considered as a well-integrated system with great decarbonizing opportunities. Thus, it is valuable to investigate the asymmetric effects of renewable energy on electricity prices.

Fig. 2 illustrates the relationship between wind power fluctuations (increases and decreases) in the DK2, SE4, and DK1 regions and electricity prices in the DK2 region over the investigated period. Initially, we are calculating the difference between consecutive time steps in wind generation. If the wind change is positive, we categorize it as a wind increase, and if it is negative, we classify it as a wind decrease. We plot the two cases separately as a time series of hourly data to examine the raw price response and the possibility of an asymmetric nature of this response. The analysis reveals a volatile relationship between wind power and electricity prices in the DK2 area. It is evident that increases in wind power do not exhibit a proportionate relationship with electricity prices compared to wind decreases. Therefore, it seems that the relationship between wind power and electricity prices in the DK2 area is asymmetric. However, due to the extensive volume of observations at an hourly resolution, it is challenging to determine whether this effect is stronger for wind increases or decreases. Nonetheless, in the following sections, we will use the high-resolution hourly data to explore the overall impact of wind increases and decreases on electricity prices in both Denmark and Sweden.

Fig. 3 shows the rate of change[2] (in % - panel A) as well as the hourly series (panel B) of the price and wind in DK2 for the 24 h of a day — the 3rd of March 2019. The first thing we notice is that there is high variability during the day in both prices and wind. Thus, it could be valuable to use the hourly data to extract information about nonlinearities in the merit-order curve. As we can see in Fig. 3, there is a decrease in wind between 10.00 and 18.00 and the rate of change ranges approximately between 1%–27%. We also notice that during these hours prices rise with a rate of change (increase) fluctuating from 1% to 5%. Later in the evening, wind production rises sharply as we can see in panel B, and the rate of change reaches more than 50%. During these periods, it becomes evident that a reduction in electricity prices may be attributed to increased wind production and reduced demand. Focusing specifically on the impact of wind on prices, previous studies (Jónsson et al., 2010; Kyritsis et al., 2017) have established that increased wind power, particularly during evening hours, leads to a decrease in electricity prices. Fig. 3 suggests that there may be asymmetric effects of wind on electricity prices, particularly at the hourly resolution, given the substantial variations in wind patterns throughout the day. In Appendix C, Figs. C.1 and C.2, we have aggregated the data and computed the rate of change for the entire investigated period. The observed high variability in the rate of change can support our hypothesis of asymmetric effects of wind in the Danish electricity market. Furthermore, we have calculated the wind penetration which is defined as the amount of demand that is covered by wind ($\frac{W_{it}^{DK2}}{L_{it}^{DK2}}$). We have also computed and visualized the rate of change of wind penetration for the same day (03/01/2019). The corresponding plot can be found in Appendix C, Fig. C.3. We can see that this figure that considers demands exhibits a similar pattern to Fig. 3. Therefore, it can strengthen our research question that wind generation can impact electricity prices asymmetrically.

Finally, we test the cross-sectional dependence of our panel with the Pesaran (2015) CD statistic (Table A.1 in Appendix A) and check the stationarity of the series with the Breitung and Das (2005) panel unit root. Table A.1 in Appendix A shows that all the series are stationary at 1% level, except load in the DK2 and SE4 region, which are stationary at 10%.

## 4. Asymmetric panel regression

Previous research in the energy sector has focused on how an increase in renewable energy will decrease electricity prices, the well-known phenomenon called merit-order effect. This part of the literature has assumed that electricity prices respond symmetrically to renewable energy shocks. This symmetric relationship implies that electricity prices respond in different directions to changes in renewable production, but the magnitude of the effect is identical. However, we have argued in the previous section that electricity prices can respond asymmetrically to renewable energy sources, thus, a symmetric regression model could produce low accuracy results that misrepresent the complicated relationships in electricity markets. Therefore, we chose

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[2] The rate of change is calculated as follows: rate of change = $(\frac{P_{i,t}-P_{i,t-1}}{P_{i,t-1}})\times 100$.

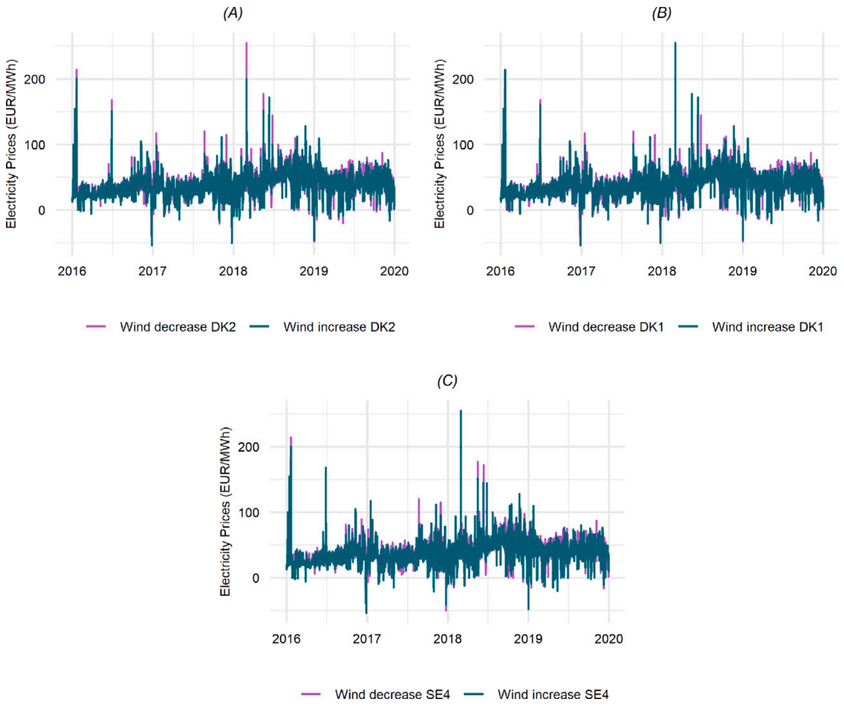

**Fig. 2.** Relationship between wind power fluctuations (increase-decrease) in three Nordic regions and electricity prices in Western Denmark (DK2) over the investigated period.

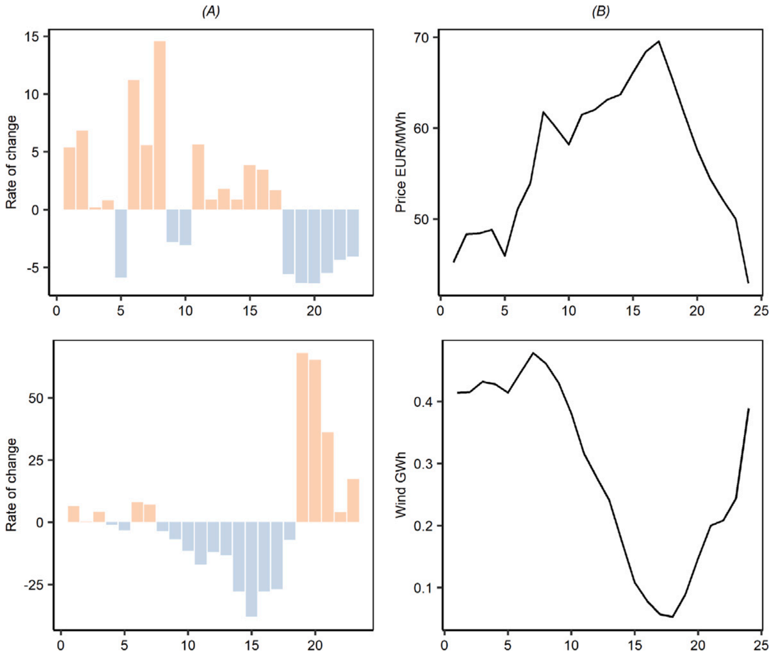

**Fig. 3.** The rate of change and the time series of electricity prices and wind production in DK2 for the 24 h of a day (03/01/2019).

to adopt a methodological approach that can estimate not only the merit-order effect but also the reverse effect.

First, we focus on the reasons for choosing a panel approach in our research and then we detail the methodological framework used to quantify asymmetries in the market. By using the hourly data, we construct a panel that consists of 24 individuals (the cross-section) and 1461 days (the time-series). Huisman et al. (2007) argued that electricity prices should be treated as a panel rather than time series and showed in their research that there is cross-sectional dependence among the hours of the day that should not be overlooked. Subsequently, there have been a considerable number of papers that used the electricity data in a panel framework (Karakatsani and Bunn, 2008; Keppler et al., 2016; Tselika, 2022) but not while investigating the asymmetries in the market. The panel approach allows us to control for time-invariant or individual specific characteristics between the hours of the day. In this way, we can extract the actual asymmetric impact of renewable energy on the merit-order curve, eliminating any extraneous noise. To the best of our knowledge, this is the first research that explores the asymmetries in the electricity sector in a panel framework.

Subsequently, we use an asymmetric fixed-effects model for panel data proposed by Allison (2019) to investigate the non-linear effect of renewable energy on electricity prices. Allison (2019) recommends the decomposition of the independent variables into two dynamic variables such as:

$$\begin{aligned} X_{it}^{+} &= X_{it} - X_{it-1} \text{ if } (X_{it} - X_{it-1}) > 0, \text{ otherwise } 0, \\ X_{it}^{-} &= -(X_{it} - X_{it-1}) \text{ if } (X_{it} - X_{it-1}) < 0, \text{ otherwise } 0. \end{aligned} \tag{1}$$

The variable $X_{it}^{+}$ represents an increase in the independent variable while $X_{it}^{-}$ represents a decrease in the independent variable. We denote $i$ the individual and $t$ the time, with $i = 1 \ldots N$ and $t = 1 \ldots T$. Then, we calculate the individual accumulations of the positive and negative changes in X such as:

$$\begin{aligned} Z_{it}^{+} &= \sum_{s=1}^{t} X_{is}^{+} \\ Z_{it}^{-} &= \sum_{s=1}^{t} X_{is}^{-} \end{aligned} \tag{2}$$

Then the model simply becomes:

$$Y_{it} = \mu_t + \beta^{+} Z_{it}^{+} + \beta^{-} Z_{it}^{-} + \alpha_i + \varepsilon_{it} \tag{3}$$

where $\mu_t$ is the intercept, $\alpha_i$ is the hourly fixed-effect and $\varepsilon_{it}$ is the idiosyncratic error term. We conduct a series of chi square tests to assess the significance of the asymmetric effects. Additionally, the method assumes that there is first order autocorrelation in the model, but we also use a robust method to calculate the standard errors. Specifically, we use the cluster robust standard errors by Bell and McCaffrey (2002), which deal with datasets with few clusters and run parallel with heteroscedasticity and serial correlation-consistent variance estimators.

### 4.1. Wind power and prices in DK2 and SE4

In the first model, we investigate the effect of wind on electricity prices in DK2 and SE4. Following Mauritzen et al. (2022) that showed wind in Nordic adjacent areas affects each other's prices and should be included in electricity prices models, the specification of our models become as follows:

$$\begin{aligned} P_{it}^{DK2} &= \mu_t + \beta_1^{+} W_{it,DK2}^{+} + \beta_1^{-} W_{it,DK2}^{-} + \beta_2^{+} W_{it,DK1}^{+} \\ &\quad + \beta_2^{-} W_{it,DK1}^{-} + \beta_3^{+} W_{it,SE4}^{+} + \beta_3^{-} W_{it,SE4}^{-} + \beta_4^{+} L_{it,DK2}^{+} \\ &\quad + \beta_4^{-} L_{it,DK2}^{-} + \alpha_i^{DK2} + \varepsilon_{it}^{DK2} \end{aligned} \tag{4}$$

$$\begin{aligned} P_{it}^{SE4} &= \mu_t + \beta_1^{+} W_{it,DK2}^{+} + \beta_1^{-} W_{it,DK2}^{-} + \beta_2^{+} W_{it,DK1}^{+} \\ &\quad + \beta_2^{-} W_{it,DK1}^{-} + \beta_3^{+} W_{it,SE4}^{+} + \beta_3^{-} W_{it,SE4}^{-} + \beta_4^{+} L_{it,SE4}^{+} \\ &\quad + \beta_4^{-} L_{it,SE4}^{-} + \alpha_i^{SE4} + \varepsilon_{it}^{SE4} \end{aligned} \tag{5}$$

where $P_{it}$ represents electricity prices in DK2 or SE4 area and $W_{it}$ is the forecasted wind in the three Nordic areas. $W_{it,DK2}^{+}$ denotes an increase of wind in the DK2 region while $W_{it,DK2}^{-}$ represents a decrease in wind in DK2. The wind variables for the other regions have the exact same explanation. In this way, we can discover the asymmetric effect of wind generation on electricity prices. We use load $L_{it}$ from the investigated area as a control variable for seasonal effects in an aggregate level while $\alpha_i$ controls the hourly fixed effects. Finally, $\varepsilon_{it}$ is the error term of the models. To ensure the robustness of our findings, we perform an alternative specification analysis, which yields consistent results. For details on the robustness outcomes, please refer to Appendix B.

We extend our research on electricity prices by incorporating congestion in the models. It has been shown that congestion can play a crucial role in determining the relationship between renewable energy and electricity prices. For instance, Mauritzen (2013) has unveiled that when there is congestion and excess supply in the Nordic market, wind generation in the DK2 region has a stronger impact on its own prices since there is no opportunity to transfer electricity to flexible neighboring countries. This makes us wonder what the role of congestion in the asymmetric effects of renewable generation on electricity prices is, if there is any.

To formally investigate the role of congestion, we use a specification where the dynamic wind variables interact with an indicator variable for congestion. Congestion is present in electricity markets when prices between the regions diverge. Reversely, when prices are equal between two bidding areas, the markets are integrated and electricity flows with no constraints (except the physical constraints that define the maximum transfer through a cable). The model including congestion is as follows:

$$\begin{aligned} P_{it}^{DK2,CONG} &= \mu_t + \beta_1^{+} W_{it,DK2}^{+} + \beta_1^{-} W_{it,DK2}^{-} + \beta_2^{+} W_{it,DK1}^{+} + \beta_2^{-} W_{it,DK1}^{-} \\ &\quad + \beta_3^{+} W_{it,SE4}^{+} + \beta_3^{-} W_{it,SE4}^{-} + \beta_4^{+} W_{it,DK2}^{+} I_{it,DK1} \\ &\quad + \beta_4^{-} W_{it,DK2}^{-} I_{it,DK1} \\ &\quad + \beta_5^{+} W_{it,DK1}^{+} I_{it,DK1} + \beta_5^{-} W_{it,DK1}^{-} I_{it,DK1} + \beta_6^{+} W_{it,SE4}^{+} I_{it,DK1} \\ &\quad + \beta_6^{-} W_{it,SE4}^{-} I_{it,DK1} + \beta_7^{+} W_{it,DK2}^{+} I_{it,SE4} + \beta_7^{-} W_{it,DK2}^{-} I_{it,SE4} \\ &\quad + \beta_8^{+} W_{it,DK1}^{+} I_{it,SE4} + \beta_8^{-} W_{it,DK1}^{-} I_{it,SE4} + \beta_9^{+} W_{it,SE4}^{+} I_{it,SE4} \\ &\quad + \beta_9^{-} W_{it,SE4}^{-} I_{it,SE4} + \beta_{10}^{+} L_{it,DK2}^{+} + \beta_{10}^{-} L_{it,DK2}^{-} + \alpha_i^{DK2} + \varepsilon_{it}^{DK2} \end{aligned} \tag{6}$$

where $W_{it}$ represents forecasted wind, and the subscript shows to which region it refers to. The plus and minus signs illustrate the asymmetric effects as explained in the previous specifications. Thus, a plus sign illustrates an increase while a minus sign shows a decrease in a variable. $I_{it}$ is the congestion indicator which is set equal to 1 ($I_{it} = 1$) when the prices between the investigated areas are different or 0 ($I_{it} = 0$) otherwise. As mentioned earlier, we include congestion indicators for the DK1-DK2 and DK2-SE4 regions. Thus, $I_{it,DK1}$ represents the congestion in the transmission between DK1 and DK2, while $I_{it,SE4}$ refers to congestion in the transmission between DK2 and SE4. With this specification, we can investigate the impact of wind under both congested and uncongested conditions among the regions. Overall, the combination of asymmetries and congestion provide valuable information about how congestion affects the asymmetric impacts of wind in the Nordic region.

### 4.2. Wind power and transmission

Transmission of electricity between areas plays a key role in integrating electricity systems, balancing supply, and eventually developing a reliable energy system. The existing literature has validated a strong relationship between renewable energy, electricity transmission, and electricity prices. Research by Green and Vasilakos (2012) and Mauritzen (2013) has established that an increase in wind power generation in Denmark leads to a rise in net exports to neighboring countries, such as Norway and Sweden. Furthermore, Mauritzen et al.

(2022) has demonstrated that the impact of wind power on transmission in Denmark varies across different deciles of wind power, with a predominant one-sided transmission towards hydropower regions. To gain a more comprehensive understanding of these relationships and to aid governments in strategically allocating electricity transmissions, ensuring the smooth flow of electricity in the system and enhancing grid reliability, it is important to investigate the asymmetric effects of wind power on net transmission flows. This approach allows us to investigate not only the effects of an increase in wind power on net transmissions but also to analyze how a decrease in wind within the electricity system would influence transmission dynamics. Therefore, we develop a model for the transmission between the DK2-SE4 and DK1-DK2 regions. We use the net exchange (in MWh) – the sum of imports (−) and exports (+) over any given hour – between these regions as well as the load from Denmark to control for seasonal effects. We specify two models to explore the interconnections of the entire system:

$$\begin{aligned} NT_{it}^{DK2-SE4} &= \delta_t + \beta_1^{+} W_{it,DK2}^{+} + \beta_1^{-} W_{it,DK2}^{-} + \beta_2^{+} W_{it,DK1}^{+} \\ &\quad + \beta_2^{-} W_{it,DK1}^{-} + \beta_3^{+} W_{it,SE4}^{+} + \beta_3^{-} W_{it,SE4}^{-} + \beta_4^{+} L_{it,DK2}^{+} \\ &\quad + \beta_4^{-} L_{it,DK2}^{-} + \alpha_i^{DK2-SE4} + \varepsilon_{it}^{DK2-SE4} \end{aligned} \tag{7}$$

$$\begin{aligned} NT_{it}^{DK2-DK1} &= \delta_t + \beta_1^{+} W_{it,DK2}^{+} + \beta_1^{-} W_{it,DK2}^{-} + \beta_2^{+} W_{it,DK1}^{+} \\ &\quad + \beta_2^{-} W_{it,DK1}^{-} + \beta_3^{+} W_{it,SE4}^{+} + \beta_3^{-} W_{it,SE4}^{-} + \beta_4^{+} L_{it,DK1}^{+} \\ &\quad + \beta_4^{-} L_{it,DK1}^{-} + \alpha_i^{DK1-DK2} + \varepsilon_{it}^{DK1-DK2} \end{aligned} \tag{8}$$

where $NT_{it}^{DK2-SE4}$ and $NT_{it}^{DK2-DK1}$ represent the net exchange between DK2-SE4 and DK1-DK2 respectively. The wind variables have the same explanation as in the previous section. $\alpha_i$ depicts the hourly fixed effect while $\varepsilon_{it}$ is the idiosyncratic error term. The regions in the models are shown by the superscripts.

Our choice of employing an asymmetric panel regression method offers a comparative advantage over alternative methodological approaches in the context of investigating the impact of wind fluctuations on electricity prices. Firstly, in contrast to traditional regression models that assume symmetrical relationships, our asymmetric approach allows for a nuanced examination of the effects of both increases and decreases in wind power on electricity markets. Consequently, the panel asymmetric model provides a more accurate representation of the complex relationships within electricity markets, providing valuable insights for optimal generation mixes, targeted policy recommendations, and facilitating more effective decision-making among market participants. Secondly, traditional approaches often face challenges in capturing non-linearities in the relationship between wind power and electricity prices. In contrast, our chosen methodology addresses this limitation by effectively identifying and quantifying non-linear responses, facilitating a more realistic exploration of the dynamics in electricity markets. Lastly, the use of the data in a panel framework provide several advantages. Panel data, by significantly increasing the number of data points, enhances the efficiency of econometric estimates. Moreover, the panel framework facilitates the control for unobserved heterogeneity across different hours of the day. These methodological benefits make panels superior to traditional time-series methods, offering greater predictive power and deeper insights.

## 5. Empirical results

### *5.1. Wind power and electricity prices*

Table 2 presents the asymmetric effects of wind from the DK2, DK1 and SE4 regions on electricity prices in eastern Denmark (DK2) and southern Sweden (SE4), while Table 3 tests the presence of significant asymmetries in the markets.

All the results are statistically significant and follow an expected pattern regarding the direction of the estimates. The findings indicate that an increase in wind power – across all the regions – leads to a decrease in electricity prices in both the DK2 and SE4 regions. This phenomenon, commonly referred to as the merit-order effect, illustrates that the inclusion of renewable energy in electricity markets results in lower electricity prices. Similarly, as expected, an increase in electricity demand corresponds to an increase in electricity prices, while a decrease in demand has the opposite effect.

**Table 2**
The asymmetric effects of wind power on the DK2 and SE4 electricity prices.

| Variables | (4) $P_{it}^{DK2}$ | (5) $P_{it}^{SE4}$ | (6) $P_{it}^{DK2,CONG}$ |
|---|---|---|---|
| $W_{it,DK2}^{+}$ | −9.242 *** | −4.142*** | −5.308*** |
| $W_{it,DK2}^{-}$ | 10.136*** | 4.171*** | 5.851*** |
| $W_{it,DK1}^{+}$ | −2.006*** | −1.217*** | −2.563*** |
| $W_{it,DK1}^{-}$ | 2.071*** | 1.089*** | 2.829*** |
| $W_{it,SE4}^{+}$ | −3.012*** | −3.965*** | −1.77*** |
| $W_{it,SE4}^{-}$ | 1.63*** | 3.037*** | 0.604** |
| $L_{it,DK2}^{+}$ | 37.663*** | | 35.475*** |
| $L_{it,DK2}^{-}$ | −36.07*** | | −33.881*** |
| $L_{it,SE4}^{+}$ | | 14.265*** | |
| $L_{it,SE4}^{-}$ | | −13.947*** | |
| $W_{it,DK2}^{+} \times I_{it,DK1}$ | | | −1.205* |
| $W_{it,DK2}^{-} \times I_{it,DK1}$ | | | 2.774*** |
| $W_{it,DK1}^{+} \times I_{it,DK1}$ | | | 0.584** |
| $W_{it,DK1}^{-} \times I_{it,DK1}$ | | | −1.505*** |
| $W_{it,SE4}^{+} \times I_{it,DK1}$ | | | 0.268 |
| $W_{it,SE4}^{-} \times I_{it,DK1}$ | | | 0.316 |
| $W_{it,DK2}^{+} \times I_{it,SE4}$ | | | −14.894*** |
| $W_{it,DK2}^{-} \times I_{it,SE4}$ | | | 16.101*** |
| $W_{it,DK1}^{+} \times I_{it,SE4}$ | | | 0.075 |
| $W_{it,DK1}^{-} \times I_{it,SE4}$ | | | −0.564 |
| $W_{it,SE4}^{+} \times I_{it,SE4}$ | | | −1.433* |
| $W_{it,SE4}^{-} \times I_{it,SE4}$ | | | 1.427** |
| Intercept | 0.10 | 0.156*** | −0.045* |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels, (iii) The last column shows the effect of wind power on the electricity prices in the DK2 area conditional on congestion.

When exploring the DK2 region, the analysis reveals that an increase in DK2 wind power corresponds to a significant decrease of 9.242 €/MWh in electricity prices. Conversely, a decline in wind power in DK2 leads to a substantial increase of 10.136 €/MWh in prices. This indicates that a decline in DK2 wind has a greater impact on price increases compared to the effect of wind increase on price reduction. Thus, the results confirm our hypothesis that asymmetric effects of renewable energy may exist in the Nordic market. The significance of the observed asymmetries has been tested and confirmed in Table 3, which demonstrates statistical significance at the 1% level. In terms of the SE4 region's influence on DK2 prices, the impact of wind is relatively weaker but still exhibits asymmetrical behavior. Specifically, an increase in SE4 wind power results in a reduction of 3.012 €/MWh in prices, while a decrease in wind leads to a 1.63 €/MWh increase in DK2 prices. It is important to highlight that SE4 wind has a more pronounced effect in reducing prices compared to increasing prices, whereas DK2 wind has a greater impact on price increases than on decreases. Additionally, SE4 wind shows the strongest asymmetric impact in the market. Finally, although the asymmetries are not statistically significant, DK1 wind power significantly affects prices in the DK2 region. Therefore, both positive and negative changes in wind power proportionally influence prices in DK2.

The merit-order effect has been extensively explored in the literature. Jónsson et al. (2010) utilized daily day-ahead electricity data,

**Table 3**
Test of asymmetric significant results for the DK2 and SE4 price models.

| Variables | $P_{it}^{DK2}$ $(chi^2)$ | $P_{it}^{SE4}$ $(chi^2)$ | $P_{it}^{DK2,CONG}$ $(chi^2)$ |
|---|---|---|---|
| $W_{it,DK2}$ | 13.95 *** | 0.03 | 6.2*** |
| $W_{it,DK1}$ | 0.65 | 2.4 | 12.40*** |
| $W_{it,SE4}$ | 30.16*** | 44.49*** | 19.67*** |
| $L_{it,DK2}$ | 23.95*** | | 16.44*** |
| $L_{it,SE4}$ | | 2.97* | |
| $W_{it,DK2} \times I_{it,DK1}$ | | | 14.27*** |
| $W_{it,DK1} \times I_{it,DK1}$ | | | 45.50*** |
| $W_{it,SE4} \times I_{it,DK1}$ | | | 2.07 |
| $W_{it,DK2} \times I_{it,SE4}$ | | | 4.38** |
| $W_{it,DK1} \times I_{it,SE4}$ | | | 8.47*** |
| $W_{it,SE4} \times I_{it,SE4}$ | | | 0.0001 |

*Note*: $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

**Table 4**
The asymmetric effects of wind power on the net transmission between DK1-DK2 and DK2-SE4.

| Variables | (7) $NT_{it}^{DK2-SE4}$ | (8) $NT_{it}^{DK2-DK1}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | 1332.39 *** | 81.216*** |
| $W_{it,DK2}^{-}$ | −1224.03*** | −101.813*** |
| $W_{it,DK1}^{+}$ | 94.547*** | −127.506*** |
| $W_{it,DK1}^{-}$ | −108.323*** | 134.803*** |
| $W_{it,SE4}^{+}$ | −495.551*** | 168.888*** |
| $W_{it,SE4}^{-}$ | 412.704*** | −143.176*** |
| $L_{it,DK2}^{+}$ | −1208.46*** | −54.001*** |
| $L_{it,DK2}^{-}$ | 1107.88*** | 55.549*** |
| Intercept | 8.15*** | −3.873*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

employing a non-parametric regression model, and observed a substantial reduction in electricity prices due to wind generation in Denmark. Mauritzen (2013) also delved into the impact of wind power on Danish electricity prices, using daily data and a time-series methodology, revealing a price dampening effect of 0.031 €/MWh. On the other hand, Tselika (2022) employed hourly day-ahead prices and wind forecasts, uncovering a more pronounced impact on electricity prices, ranging from −6.159 €/MWhh to −4.848 €/MWh, depending on the part of the price distribution. The literature consistently indicates a negative influence of wind increases on prices in Denmark, albeit with varying magnitudes. Our results align with the literature, yet our estimates differ in magnitude since we utilize a different methodological approach. Tselika (2022) has also showed that using daily electricity data can lead to underestimated estimates concerning the impact of renewable energy on electricity prices. While our findings are consistent with existing literature, we contribute to the gap by exploring the asymmetric effects of renewable energy sources, a dimension not investigated in prior research.

Focusing on the SE4 region, the results suggest that significant asymmetries exist only in the case of SE4 wind. While both positive and negative changes in DK2 and DK1 wind significantly affect SE4 electricity prices, tests for asymmetries (see Table 3) indicate that these impacts are not statistically significant. As a result, it appears that the SE4 electricity market is less affected by asymmetries that may arise from neighboring markets. This could be attributed to its direct connection with the Swedish region (SE3), which has high storage capacity due to its hydropower reservoirs. Consequently, these flexible systems enable the market to efficiently manage the variable nature of wind power and its impact on prices. An interesting finding is that DK1 wind power does not exhibit significant asymmetrical impacts on both DK2 and SE4 prices. This could also be attributed to its connection with high storage capacity regions, such as the Norwegian and Swedish hydropower reservoirs.

### 5.2. *Asymmetries and congestion*

After confirming the asymmetric impacts of wind in both the DK2 and SE4 regions, we are now interested in exploring the asymmetrical effects that occur during periods of congestion between the Nordic regions. Given that we mainly observed asymmetries from neighboring countries in the DK2 region, our congestion analysis will predominantly concentrate on examining the prices within this particular region. The results including congestion are presented in Table 2 while the significance of asymmetric effects can be found in Table 3.

The findings suggest that congestion has a significant impact on the DK2 region's electricity prices, leading to amplified asymmetric effects and altering the dynamics within the market. Focusing on the congestion between DK2-SE4, we found that an increase in DK2 wind will decrease prices by −5.308 €/MWh without congestion and −20.202 €/MWh with congestion. With no possibility to transfer electricity to the neighboring area, an increase in DK2 wind will suppress electricity prices in its own area. On the other hand a decrease in DK2 wind will increase DK2 prices by 5.851 €/MWh while when there is congestion the effect will increase to 21.952 €/MWh. Therefore, when the DK2-SE4 line is congested the asymmetric effect of DK2 wind on prices increases by 1.207 €/MWh. Additionally, our findings indicate that DK1 wind also has an asymmetric effect on DK2 prices in the presence of congestion. However, it is important to note that the estimates of DK1 wind's impact on DK2 prices are not statistically significant when the DK2-SE4 line is congested.

Focusing on the asymmetric results observed during congestion between the Danish areas, the findings reveal that only DK2 and DK1 wind exhibit asymmetric impacts on prices in the DK2 region. While both increases and decreases in SE4 wind have significant effects on DK2 prices, the asymmetrical tests indicate that these effects are proportional. When the DK2-DK1 line is congested, the asymmetry between increases and decreases of DK2 wind on prices increase by 2.112 €/MWh. Notably, this disparity is predominantly positive, indicating that congestion amplifies the positive impact on DK2 electricity prices when DK2 wind decreases. Furthermore, in the case of DK1 wind, we notice that when there is congestion in the market the negative impact of DK1 wind decrease from −2.563 €/MWh to −1.979 €/MWh. This is because, when the line is congested, wind from the DK1 region cannot be efficiently transferred to the neighboring DK2 area to alleviate prices. Lastly, the analysis reveals that wind originating from the SE4 region does not significantly contribute to the asymmetric price dynamics in DK2 when there is congestion in both transmission lines. Overall, our results make it evident that congestion amplifies the asymmetric effects of wind in the Nordics on DK2 electricity prices.

### 5.3. *Net transmission and asymmetric effects of wind*

Table 4 showcases the influence of both increasing and decreasing DK1, DK2, and SE4 wind power on net transmission between the DK2-DK1 and DK2-SE4 areas, revealing asymmetrical effects. In Table 5, we test for the significance of these asymmetries and conclude that all the impacts of wind are significantly asymmetric at 1% level.

We observe that an increase in DK2 wind results in a stronger boost in electricity transmission to SE4 compared to the reduction in exports

**Table 5**
Test of asymmetric significant results for the transmission models.

| Variables | $NT_{it}^{DK2-SE4}$ ($chi^2$) | $NT_{it}^{DK2-DK1}$ ($chi^2$) |
|---|---|---|
| $W_{it,DK2}$ | 32.68 *** | 14.89*** |
| $W_{it,DK1}$ | 18.35*** | 21.51*** |
| $W_{it,SE4}$ | 76.71*** | 31.47*** |
| $L_{it,DK2}$ | 38.61*** | 0.52 |

*Note*: ***,**,* respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

caused by a decrease in wind. Excess wind in DK2, characterized by a surplus of wind-generated electricity, leads to the transportation of electricity to neighboring areas for storage purposes. Mauritzen (2013) also demonstrated that the rise in Danish wind power results to an increase in net transmission to neighboring countries. However, our estimates diverge in magnitude due to our consideration of intraday variability in the data, setting our findings apart. Moreover, our study unveils an asymmetric influence of wind on net transmission between regions, a dimension not previously explored in this context.

In terms of SE4 wind, an increase in wind significantly increases exports to DK2 compared to the impact of a decrease in wind on imports to SE4. This discovery underscores the pivotal role of the DK2 electricity system as a robust energy hub capable of facilitating electricity transfers between well-connected hydro regions. Conversely, the behavior of DK1 wind exhibits a varied pattern, whereby a decrease in wind influences stronger imports than a wind increase influences exports.

We observe quite different outcomes in the case of DK2-DK1 net transmissions. A decrease in DK2 wind amplifies imports by DK1 to a greater extent than an increase in wind enhances exports to DK1. This discovery highlights the increased demand for electricity during reduced DK2 wind conditions, surpassing the need to export electricity when wind power is on the rise. On the contrary, while an increase in DK1 wind will enhance imports to the DK2 region, it will not match the magnitude of the increase in exports from DK2 to DK1 caused by a decrease in DK1 wind. Overall, the wind power generated in all three regions exhibits asymmetric effects on the net transmission of the DK2 area to its neighboring countries. These findings emphasize the importance of considering the influence of wind power when studying the electricity system and striving towards the goal of a fully-integrated system.

### *5.4. Robustness analysis*

In order to validate the results of our research, we have conducted different robustness analysis. We aggregate the data to daily by averaging the 24 h of the day and investigate how our findings would be altered if we would time-series models.

Firstly, we use a non-linear autoregressive distributed lag (NARDL) model[3] to directly explore the short-term effect of wind increases and decreases on electricity prices and transmission. The NARDL model have been used in previous research by Nibedita and Irfan (2022) analyzing a similar research question. The NARDL results can be found in Appendix F, Table F.1.[4] The NARDL results exhibit the same patterns as our main asymmetric regression model, but as expected the magnitudes differ. The utilization of the asymmetric panel regression allows us to account for the intraday variability of wind power and electricity prices. Consequently, we anticipate differences in the estimates compared to traditional time series models.

Secondly, we utilize a fundamental time-series model to further investigate the robustness of our findings.[5] We use the constructed daily data to implement an Autoregressive Integrated Moving Average (ARIMA) model[6] using the same variables as in the main panel model. ARIMA models have been widely applied in the exploration of electricity prices and market dynamics by various researchers (Mauritzen, 2010; Karabiber and Xydis, 2019; Rintamäki et al., 2017; Lucic and Xydis, 2023, among others). The ARIMA results are detailed in Appendix F, Tables F.2 and F.3, applied to both the price and net transmission models.

The ARIMA outcomes exhibit similar patterns with the NARDL and asymmetric panel regression findings. As previously noted, the estimates' magnitudes differ from our main model, which is expected given the data aggregation and the diverse estimation techniques employed. Despite these differences, the qualitative interpretations of the results remain consistent when applying both NARDL and ARIMA models.

## 6. Conclusion

In recent years, the energy sector has encountered numerous challenges, leading to an energy crisis that has significantly impacted the EU. However, amidst these difficulties, renewable energy has emerged as a pivotal solution, playing a vital role in addressing the crisis within the electricity sector while reducing emissions. While renewable energy integration in the electricity mix holds immense potential, it also presents certain challenges due to its intermittent nature. Therefore, it is crucial to thoroughly examine the implications of renewable energy on electricity markets and all stakeholders involved.

This paper aims to challenge the prevailing assumption of symmetric effects regarding renewable energy's influence on electricity prices and transmission in the Nordics. To achieve this, we employ an asymmetric panel regression by Allison (2019) to investigate the impacts of both increases and decreases in wind power generation within the Nordic electricity system. By adopting an asymmetric panel regression, we can examine the potential non-linear effects of varying wind power generation on electricity prices and transmission between regions. While previous research has assumed that the positive and negative fluctuations of renewable energy are proportionate, we argue that the electricity market structure and dynamics could result in disproportionate effects of renewable energy. Therefore, the asymmetric panel methodology allows us to capture the impacts that arise when wind power experiences both positive and negative fluctuations in the Nordics. Our research focuses on the two Danish (DK1, DK2) bidding zones, and one Swedish (SE4) zone, with main focus on the Western Danish (DK2) region, as they represent areas of significant wind generation with connections to regions with high electricity storage capacity.

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[3] We investigate if the aggregated data are stationary and we find that they are integrated at level 1. Hence, we are using models adjusted to these tests.

[4] Our primary focus is on the main models presented in the paper. Due to resource limitations, particularly the computational capacity of the available hardware, we have prioritized the examination of these models, excluding the analysis of the congestion model to mitigate computational constraints.

[5] We thank an anonymous reviewer for their valuable recommendations and constructive feedback. Their insights have provided avenues for further investigating the robustness of our results.

[6] We use the auto arima function in R that generates the model with the optimal AIC and BIC.

**Table A.1**
Diagnostic tests.

| Variable | $W_{DK1}$ | $W_{DK2}$ | $W_{SE4}$ | $P_{DK2}$ | $P_{SE4}$ | $L_{DK2}$ | $L_{SE4}$ | $NT^{DK2-SE4}$ | $NT^{DK2-DK1}$ |
|---|---|---|---|---|---|---|---|---|---|
| Cross-sectional dependence | | | | | | | | | |
| CD-Pesaran | 501.479 *** | 500.521 *** | 505.909 *** | 460.955*** | 492.606*** | 553.097*** | 607.246*** | 382.582*** | 303.216 *** |
| $p$−value | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| Unit root | | | | | | | | | |
| Breitung and Das with trend | −5.5856 *** | −6.9860 *** | −7.0375*** | −5.6227*** | −4.5612*** | −1.3158* | −1.5549* | −9.8954*** | −12.6661*** |
| $p$−value | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | 0.094 | 0.06 | <0.01 | <0.01 |

*Notes*: (i) $p$−values close to zero at the cross-sectional dependence test indicate data are correlated across panel groups, (ii) the unit root hypothesis is rejected when the $p$−value is lower than the chosen significance level.

We utilized the available hourly electricity data to construct a panel dataset consisting of daily observations for 24 individuals, representing the hours of the day. Previous research has argued that the use of hourly data resolution as the most suitable approach for studying electricity markets (Huisman et al., 2007; Tselika, 2022). This perspective emphasizes that day-ahead prices are determined for the 24 h of the following day and treating them as time-series could potentially lead to misleading results. Consequently, to account for the high variability in the market, we have opted for a panel approach that incorporates the cross-sectional correlation among the different hours of the day. By adopting this methodology, we aim to enhance the accuracy of our estimates and provide more robust insights into the dynamics of electricity markets.

The findings demonstrate that wind power has asymmetric effects on electricity prices in both the investigated price regions. This asymmetry can be more pronounced when it comes to price increases or decreases. For instance, in the Western Danish (DK2) region, a decrease in wind power leads to a greater increase in Danish prices compared to the reduction in electricity prices resulting from an increase in wind power. In the case of the Swedish region, significant asymmetries are observed only in relation to Swedish wind power. The Swedish region benefits from its direct connection to a region with high storage capacity. This connection enables the region to mitigate the effects caused by the high variability of wind power, ultimately contributing to market stabilization. Our results also reveal that the presence of congestion in the Western Danish transmission line, in conjunction with neighboring regions, amplifies the asymmetric effects of wind generation on electricity prices in Denmark. Consequently, when the transmission lines experience congestion and hinder the unrestricted flow of electricity to and from the Western Danish region, it leads to higher discrepancies in the influence of wind power fluctuations.

During our investigation into the asymmetries in net transmission between the Nordic regions, we have observed that these asymmetries are even more pronounced compared to our previous model. Specifically, we have found that an increase in Western Danish (DK2) wind power leads to a stronger export of electricity to Sweden, whereas a reduction in wind power results in a smaller decrease in exports. Conversely, a decrease in Western Danish (DK2) wind power amplifies the imports by Eastern Denmark (DK1) more than an increase in wind power enhances exports to this region. These findings highlight the significance of an efficient transmission system and a higher level of market integration. They demonstrate that fluctuations in wind power, whether increasing or decreasing, can cause disparities in the volumes of electricity imported and exported between different regions. Therefore, it emphasizes the need for a well-functioning transmission infrastructure and a robust level of market integration to effectively manage these variations.

The findings of this research hold considerable significance for governments and participants in the electricity market, as they offer a comprehensive understanding of the dynamics of the electricity market and the influence of wind power fluctuations on electricity prices and transmissions. These insights provide valuable insights for policymakers, allowing them to make informed decisions regarding energy policies and infrastructure development. The insights derived from the asymmetric impacts on prices can be of great value to governments as they seek to optimize the generation mix and enhance the security of the electricity supply. By leveraging this information, policymakers can identify an optimal combination of generation sources that effectively balances supply and demand, thereby ensuring a more secure and stable energy system. Furthermore, recognizing the importance of addressing asymmetries in both electricity prices and net transmission flows, governments can prioritize the development of flexible systems. These systems can effectively mitigate the discrepancies caused by variations in wind power, thereby fostering market stability and integration. This becomes especially crucial in light of recent unprecedented crises experienced in electricity markets, highlighting the need for proactive measures to enhance their resilience. The asymmetric impacts on prices when transmission lines are congested signify the need for improvement in transmission infrastructure, enhancing interconnections between regions, and promoting the efficient allocation of electricity resources.

Moreover, the research outcomes are equally valuable for electricity market participants, such as electricity producers. By comprehending the intricate relationship between wind power variations and electricity prices, market participants can strategize their operations and investment decisions more effectively. Specifically, they can capitalize on the identified asymmetries, where decreases in wind power have a more pronounced impact on increasing prices compared to increases in wind power reducing prices. Exploiting these asymmetries can offer market participants a competitive advantage and, eventually, promote future investments in renewable energy capacity, facilitating the decarbonization of the electricity sector. Overall, the holistic perspective of electricity markets enables market participants to anticipate and adapt to market dynamics, optimizing their strategic positions and maximizing their profitability.

## CRediT authorship contribution statement

**Kyriaki Tselika:** Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. **Maria Tselika:** Formal analysis, Methodology, Software, Validation, Writing – original draft. **Elias Demetriades:** Supervision, Validation, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no conflicts of interest regarding this research.

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## Appendix A

See Table A.1.

**Table B.1**
The asymmetric effects of wind power on the DK2 and SE4 electricity prices without wind from the DK1 region.

| Variables | $P_{it}^{DK2}$ | $P_{it}^{SE4}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | −13.554 *** | −6.751*** |
| $W_{it,DK2}^{-}$ | 14.529 *** | 6.501*** |
| $W_{it,SE4}^{+}$ | −4.462 *** | −4.795*** |
| $W_{it,SE4}^{-}$ | 3.228*** | 3.875*** |
| $L_{it,DK2}^{+}$ | 37.583 *** | |
| $L_{it,DK2}^{-}$ | −35.951*** | |
| $L_{it,SE4}^{+}$ | | 14.247*** |
| $L_{it,SE4}^{-}$ | | −13.959*** |
| Intercept | 0.005 | 0.14*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) ***,**,* respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Table B.2**
Test of asymmetric significant results for the DK2 and SE4 price robustness models.

| Variables | $P_{it}^{DK2}$ $(chi^2)$ | $P_{it}^{SE4}$ $(chi^2)$ |
|---|---|---|
| $W_{it,DK2}$ | 13.00 *** | 5.01** |
| $W_{it,SE4}$ | 27.77*** | 32.27*** |
| $L_{it,DK2}$ | 23.34*** | |
| $L_{it,SE4}$ | | 2.52 |

*Note*: ***,**,* respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

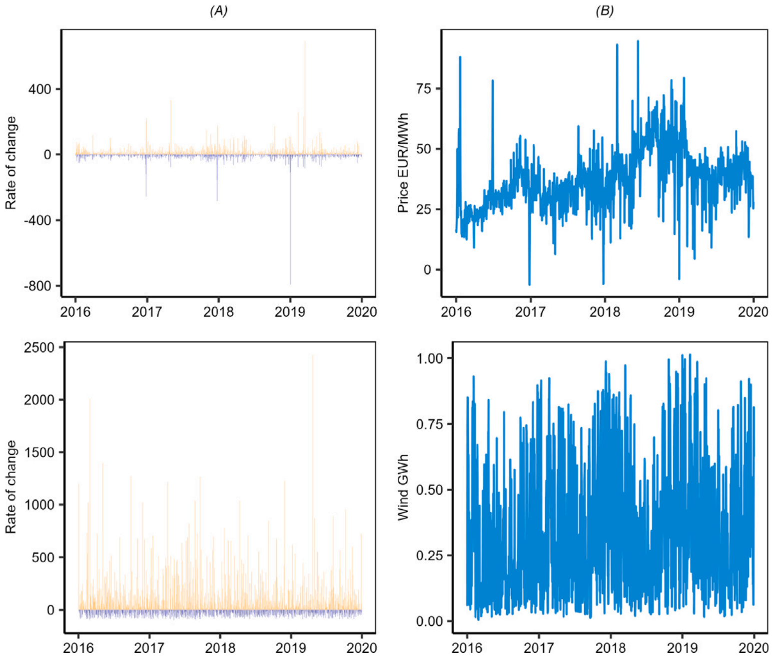

**Fig. C.1.** The averaged daily rate of change and the time series of electricity prices and wind production in DK2 for the entire investigated period.

## Appendix B

See Tables B.1 and B.2.

## Appendix C

See Figs. C.1–C.3.

## Appendix D

See Tables D.1–D.6.

## Appendix E

See Tables E.1 and E.2.

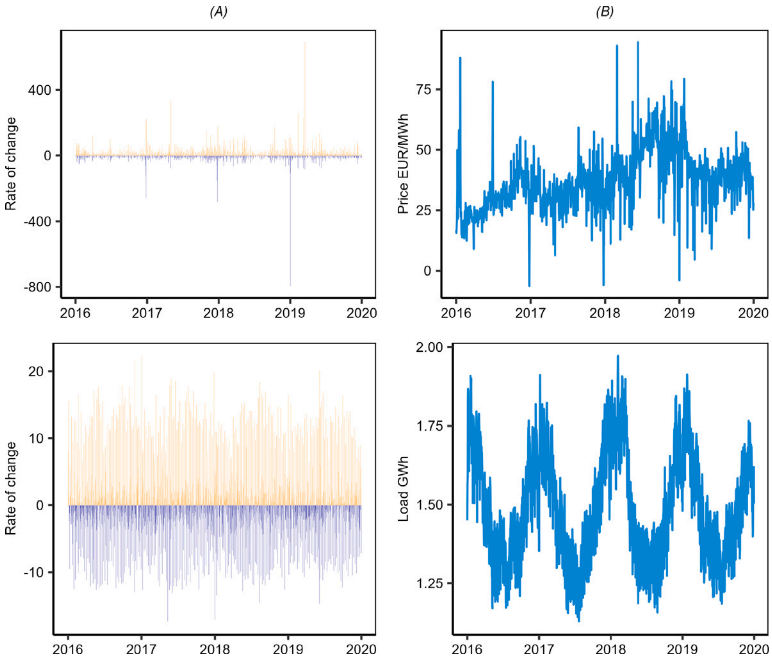

**Fig. C.2.** The averaged daily rate of change and the time series of electricity prices and load in DK2 for the entire investigated period.

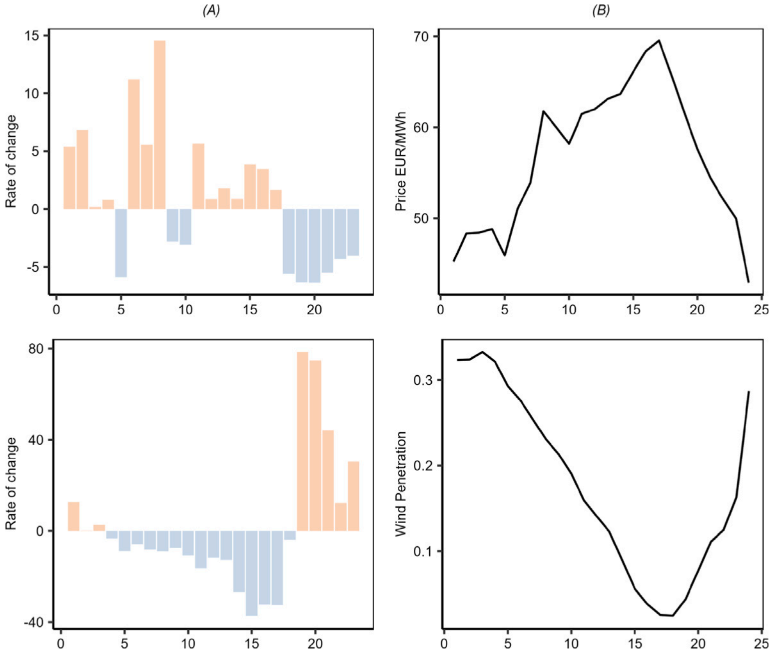

**Fig. C.3.** The rate of change and the time series of electricity prices and wind penetration, defined as the amount of wind that covers demand ($\frac{W_{it}^{DK2}}{L_{it}^{DK2}}$)in DK2 for the 24 h of a day (03/01/2019).

**Table D.1**
The asymmetric effects of wind power on the DK2 and SE4 electricity prices with weekend control variables.

| Variables | (4)<br>$P_{it}^{DK2}$ | (5)<br>$P_{it}^{SE4}$ | (6)<br>$P_{it}^{DK2,CONG}$ |
|---|---|---|---|
| $W_{it,DK2}^{+}$ | −9.37 *** | −4.22 *** | −5.42*** |
| $W_{it,DK2}^{-}$ | 10.33 *** | 4.28 *** | 6.09*** |
| $W_{it,DK1}^{+}$ | −1.98 *** | −1.20 *** | −2.56*** |
| $W_{it,DK1}^{-}$ | 2.05 *** | 1.09 *** | 2.83*** |
| $W_{it,SE4}^{+}$ | −3.11 *** | −4.01*** | −1.81*** |
| $W_{it,SE4}^{-}$ | 1.75 *** | 3.11 *** | 0.69** |
| $L_{it,DK2}^{+}$ | 33.35 *** | | 30.84*** |
| $L_{it,DK2}^{-}$ | −32.90 *** | | −30.64*** |
| $L_{it,SE4}^{+}$ | | 13.06 *** | |
| $L_{it,SE4}^{-}$ | | −13.32 *** | |
| $W_{it,DK2}^{+} \times I_{it,DK1}$ | | | −1.22* |
| $W_{it,DK2}^{-} \times I_{it,DK1}$ | | | 2.68*** |
| $W_{it,DK1}^{+} \times I_{it,DK1}$ | | | 0.63** |
| $W_{it,DK1}^{-} \times I_{it,DK1}$ | | | −1.53*** |
| $W_{it,SE4}^{+} \times I_{it,DK1}$ | | | 0.22 |
| $W_{it,SE4}^{-} \times I_{it,DK1}$ | | | 0.45 |
| $W_{it,DK2}^{+} \times I_{it,SE4}$ | | | −14.72*** |
| $W_{it,DK2}^{-} \times I_{it,SE4}$ | | | 16.08*** |
| $W_{it,DK1}^{+} \times I_{it,SE4}$ | | | 0.09 |
| $W_{it,DK1}^{-} \times I_{it,SE4}$ | | | −0.60 |
| $W_{it,SE4}^{+} \times I_{it,SE4}$ | | | −1.58** |
| $W_{it,SE4}^{-} \times I_{it,SE4}$ | | | 1.52** |
| Intercept | −0.26*** | −0.02 | −0.31*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels, (iii) The last column shows the effect of wind power on the electricity prices in the DK2 area conditional on congestion.

**Table D.2**
Test of asymmetric significant results for the DK2 and SE4 price models with weekend control variables.

| Variables | $P_{it}^{DK2}$<br>$(chi^2)$ | $P_{it}^{SE4}$<br>$(chi^2)$ | $P_{it}^{DK2,CONG}$<br>$(chi^2)$ |
|---|---|---|---|
| $W_{it,DK2}$ | 16.61 *** | 0.17 | 9.74*** |
| $W_{it,DK1}$ | 0.88 | 1.95 | 12.38*** |
| $W_{it,SE4}$ | 28.72 *** | 36.69 *** | 18.48*** |
| $L_{it,DK2}$ | 3.18 *** | | 0.28 |
| $L_{it,SE4}$ | | 1.75 | |
| $W_{it,DK2} \times I_{it,DK1}$ | | | 12.11*** |
| $W_{it,DK1} \times I_{it,DK1}$ | | | 41.12*** |
| $W_{it,SE4} \times I_{it,DK1}$ | | | 2.54 |
| $W_{it,DK2} \times I_{it,SE4}$ | | | 5.29** |
| $W_{it,DK1} \times I_{it,SE4}$ | | | 9.60*** |
| $W_{it,SE4} \times I_{it,SE4}$ | | | 0.02 |

*Note*: $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

**Table D.3**
The asymmetric effects of wind power on the net transmission between DK1-DK2 and DK2-SE4 with weekend control variables.

| Variables | (7)<br>$NT_{it}^{DK2-SE4}$ | (8)<br>$NT_{it}^{DK2-DK1}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | 1338.86*** | 77.53*** |
| $W_{it,DK2}^{-}$ | −1233.06*** | −97.42*** |
| $W_{it,DK1}^{+}$ | 93.04*** | −126.51*** |
| $W_{it,DK1}^{-}$ | −107.91*** | 133.95*** |
| $W_{it,SE4}^{+}$ | −493.51*** | 167.25*** |
| $W_{it,SE4}^{-}$ | 407.95*** | −141.50*** |
| $L_{it,DK2}^{+}$ | −1009.49*** | −168.21*** |
| $L_{it,DK2}^{-}$ | 997.74*** | 159.24*** |
| Intercept | 43.66*** | −6.01*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Table D.4**
Test of asymmetric significant results for the transmission models with weekend control variables.

| Variables | $NT_{it}^{DK2-SE4}$<br>$(chi^2)$ | $NT_{it}^{DK2-DK1}$<br>$(chi^2)$ |
|---|---|---|
| $W_{it,DK2}$ | 32.88*** | 14.31*** |
| $W_{it,DK1}$ | 20.57*** | 31.78*** |
| $W_{it,SE4}$ | 89.84*** | 22.85*** |
| $L_{it,DK2}$ | 0.50 | 4.75** |

*Note*: $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

**Table D.5**
The asymmetric effects of wind power on the net transmission between DK1-DK2 and DK2-SE4 including load from the SE4 and DK1 region.

| Variables | (7)<br>$NT_{it}^{DK2-SE4}$ | (8)<br>$NT_{it}^{DK2-DK1}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | 1333.33*** | 79.61*** |
| $W_{it,DK2}^{-}$ | −1222.87*** | −99.23*** |
| $W_{it,DK1}^{+}$ | 94.54*** | −127.04*** |
| $W_{it,DK1}^{-}$ | −108.16*** | 134.20*** |
| $W_{it,SE4}^{+}$ | −495.88*** | 168.50*** |
| $W_{it,SE4}^{-}$ | 412.93*** | −142.47*** |
| $L_{it,DK2}^{+}$ | −1126.26*** | −124.25*** |
| $L_{it,DK2}^{-}$ | 1022.12*** | 102.88** |
| $L_{it,SE4}^{+}$ | −41.33 | |
| $L_{it,SE4}^{-}$ | 44.88*** | |
| $L_{it,DK1}^{+}$ | | −1.61 |
| $L_{it,DK1}^{-}$ | | 13.01 |
| Intercept | 7.68*** | −3.97*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Table D.6**
Test of asymmetric significant results for the transmission models including load from the SE4 and DK1 region.

| Variables | $NT_{it}^{DK2-SE4}$<br>$(chi^2)$ | $NT_{it}^{DK2-DK1}$<br>$(chi^2)$ |
|---|---|---|
| $W_{it,DK2}$ | 34.24*** | 12.82*** |
| $W_{it,DK1}$ | 17.08*** | 20.00*** |
| $W_{it,SE4}$ | 78.07*** | 32.70*** |
| $L_{it,DK2}$ | 8.35*** | 2.52 |
| $L_{it,SE4}$ | 0.06 | |
| $L_{it,DK1}$ | | 2.77 |

*Note*: $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

## Appendix F

See Tables F.1–F.3.

## Appendix G. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107471.

**Table E.1**
The asymmetric effects of wind power on the DK2 and SE4 electricity prices with lag 1 and 7 of the prices.

| Variables | (4) $P_{it}^{DK2}$ | (5) $P_{it}^{SE4}$ | (6) $P_{it}^{DK2,CONG}$ |
|---|---|---|---|
| $W_{it,DK2}^{+}$ | −7.98*** | −3.04 *** | −4.33*** |
| $W_{it,DK2}^{-}$ | 8.85*** | 3.33*** | 4.62*** |
| $W_{it,DK1}^{+}$ | −2.33*** | −1.53*** | −2.80*** |
| $W_{it,DK1}^{-}$ | 2.37*** | 1.40*** | 3.04*** |
| $W_{it,SE4}^{+}$ | −2.16*** | −3.40*** | −1.19*** |
| $W_{it,SE4}^{-}$ | 1.22*** | 2.70*** | 0.28** |
| $L_{it,DK2}^{+}$ | 32.26*** | | 31.62*** |
| $L_{it,DK2}^{-}$ | −30.08*** | | −27.97*** |
| $L_{it,SE4}^{+}$ | | 12.38*** | |
| $L_{it,SE4}^{-}$ | | −10.60*** | |
| $W_{it,DK2}^{+} \times I_{it,DK1}$ | | | −1.29** |
| $W_{it,DK2}^{-} \times I_{it,DK1}$ | | | 2.42*** |
| $W_{it,DK1}^{+} \times I_{it,DK1}$ | | | 0.73*** |
| $W_{it,DK1}^{-} \times I_{it,DK1}$ | | | −1.30*** |
| $W_{it,SE4}^{+} \times I_{it,DK1}$ | | | −0.04 |
| $W_{it,SE4}^{-} \times I_{it,DK1}$ | | | −0.03 |
| $W_{it,DK2}^{+} \times I_{it,SE4}$ | | | −13.97*** |
| $W_{it,DK2}^{-} \times I_{it,SE4}$ | | | 16.05*** |
| $W_{it,DK1}^{+} \times I_{it,SE4}$ | | | −0.01 |
| $W_{it,DK1}^{-} \times I_{it,SE4}$ | | | −0.07 |
| $W_{it,SE4}^{+} \times I_{it,SE4}$ | | | −0.93 |
| $W_{it,SE4}^{-} \times I_{it,SE4}$ | | | 1.03 |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels, (iii) The last column shows the effect of wind power on the electricity prices in the DK2 area conditional on congestion.

**Table E.2**
Test of asymmetric significant results for the DK2 and SE4 price models with lag 1 and 7 of the prices.

| Variables | $P_{it}^{DK2}$ $(chi^2)$ | $P_{it}^{SE4}$ $(chi^2)$ | $P_{it}^{DK2,CONG}$ $(chi^2)$ |
|---|---|---|---|
| $W_{it,DK2}$ | 10.39*** | 2.58 | 2.89* |
| $W_{it,DK1}$ | 0.37 | 3.57* | 13.69*** |
| $W_{it,SE4}$ | 33.59*** | 29.54*** | 23.57*** |
| $L_{it,DK2}$ | 15.08*** | | 51.90*** |
| $L_{it,SE4}$ | | 19.10*** | |
| $W_{it,DK2} \times I_{it,DK1}$ | | | 18.63*** |
| $W_{it,DK1} \times I_{it,DK1}$ | | | 36.65*** |
| $W_{it,SE4} \times I_{it,DK1}$ | | | 0.05 |
| $W_{it,DK2} \times I_{it,SE4}$ | | | 20.41*** |
| $W_{it,DK1} \times I_{it,SE4}$ | | | 0.44 |
| $W_{it,SE4} \times I_{it,SE4}$ | | | 0.09 |

*Note*: $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis that a coefficient is symmetric at 1%, 5% and 10% significance levels.

**Table F.1**
The non-parametric distributed lag (NARDL) asymmetric effects of wind power on the DK2 and SE4 electricity prices.

| Variables | (4) $P_{it}^{DK2}$ | (5) $P_{it}^{SE4}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | −16.867*** | −12.082*** |
| $W_{it,DK2}^{-}$ | 18.674*** | 11.023*** |
| $W_{it,DK1}^{+}$ | −4.709*** | −3.535*** |
| $W_{it,DK1}^{-}$ | 5.721*** | 3.451*** |
| $W_{it,SE4}^{+}$ | −13.182*** | −9.118*** |
| $W_{it,SE4}^{-}$ | 12.073*** | 8.986*** |
| $L_{it,DK2}^{+}$ | 36.625*** | |
| $L_{it,DK2}^{-}$ | −36.459*** | |
| $L_{it,SE4}^{+}$ | | 13.06*** |
| $L_{it,SE4}^{-}$ | | −13.55*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Table F.2**
The ARIMA asymmetric effects of wind power on the DK2 and SE4 electricity prices.

| Variables | (4) $P_{it}^{DK2}$ | (5) $P_{it}^{SE4}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | −10.28*** | −4.861*** |
| $W_{it,DK2}^{-}$ | 10.961*** | 5.225*** |
| $W_{it,DK1}^{+}$ | −2.002*** | −1.537*** |
| $W_{it,DK1}^{-}$ | 1.507*** | 1.521*** |
| $W_{it,SE4}^{+}$ | −2.663*** | −3.095*** |
| $W_{it,SE4}^{-}$ | 4.044*** | 3.482*** |
| $L_{it,DK2}^{+}$ | 33.269*** | |
| $L_{it,DK2}^{-}$ | −33.396*** | |
| $L_{it,SE4}^{+}$ | | 11.657*** |
| $L_{it,SE4}^{-}$ | | −11.591*** |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

**Table F.3**
The ARIMA asymmetric effects of wind power on net transmission.

| Variables | (4) $NT_{it}^{DK2-SE4}$ | (5) $NT_{it}^{DK2-DK1}$ |
|---|---|---|
| $W_{it,DK2}^{+}$ | 1357.026*** | 82.644** |
| $W_{it,DK2}^{-}$ | −1401.384*** | −62.791 |
| $W_{it,DK1}^{+}$ | 68.115*** | −120.086*** |
| $W_{it,DK1}^{-}$ | −36.63 | 112.622*** |
| $W_{it,SE4}^{+}$ | −421.639*** | 129.495*** |
| $W_{it,SE4}^{-}$ | 393.644*** | −142.316*** |
| $L_{it,DK2}^{+}$ | −1070.928*** | |
| $L_{it,DK2}^{-}$ | 1102.421*** | |
| $L_{it,SE4}^{+}$ | | −68.297* |
| $L_{it,SE4}^{-}$ | | 67.727* |

*Notes*: (i) Standard errors are computed with the clustered robust variance estimator. (ii) $^{***}$,$^{**}$,$^{*}$ respectively denotes rejection of the null hypothesis of insignificant coefficient at 1%, 5% and 10% significance levels.

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