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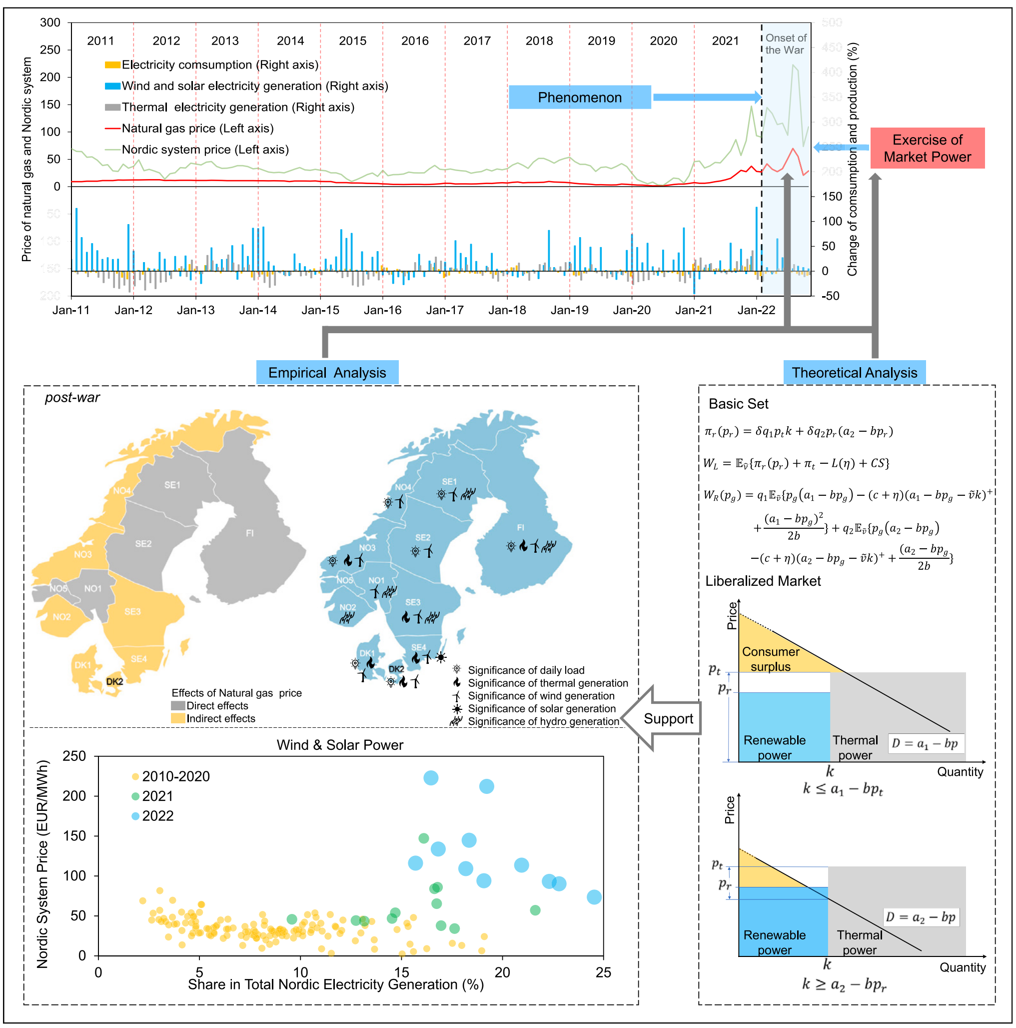

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Highlights

Reasons behind rising Nordic electricity prices after the onset of war are explored

Transmission paths of natural gas price are empirically identified

Market power of non-gas generators is theoretically demonstrated

The study supports regulator's policy intervention during energy transition

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Unpacking the effects of natural gas price transmission on electricity prices in Nordic countries

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SUMMARY

Since the Russia-Ukraine war in February 2022, European electricity prices have experienced considerable turbulence, primarily attributed to a shortage in the natural gas supply. We investigate the relationship between natural gas prices in the European continent and electricity prices in Nordic countries before and after the outbreak of war. Despite the low proportion of natural gas electricity generation, the empirical analysis reveals both direct and indirect transmission paths for natural gas prices in Nordic countries. Meanwhile, the theoretical analysis demonstrates how Nordic renewable (wind and solar) and other non-gas generators exercise market power through price bidding in the anticipation of an increase in gas prices or a shortage of gas supply, which results in higher electricity prices. Understanding the underlying factors and dynamics driving substantial price fluctuations in the Nordic electricity market is essential for comprehending the intricate interconnections within the European energy landscape.

INTRODUCTION

Historical experience shows that certain external shocks, such as geopolitical conflicts, can have significant impacts on energy markets. Natural gas is in high demand in Europe, where it is used in large quantities for electricity generation. In 2021, the EU's natural gas import dependency ratio was 83%.[1] Moreover, benefiting from abundant natural gas reserves and close location, Russia has been Europe's largest source of natural gas imports. Huge imports from a single country are certainly of concern since natural gas price volatility tends to spill over into the electricity market.[2] However, during the past 20 years, the European gas industry has gradually transformed from domination by state-owned monopolies and rigid bilateral contracts to a more competitive market in response to regulatory, technological, and industrial dynamics.[3] This also facilitates the integration process of the electricity markets, and the more integrated markets are, the higher the volatility transmission among them.

The Russia-Ukraine war that began in early 2022 has clearly affected the supply of gas to Europe. An unusual phenomenon is that, along with the Russia-Ukraine war, not only have the electricity prices on the European continent been affected by the shortage of natural gas but also the electricity prices in Nordic countries (Table S1), where the proportion of natural gas electricity generation is fairly low. Denmark, Finland, Norway, and Sweden are less dependent on imported energy products for domestic electricity supply than Germany, the Netherlands, and Italy. The former four Nordic countries together with Germany and the Netherlands are in a unified cross-border electricity trading market, i.e., Nord Pool. Taking the Nordic system price as an example, which is calculated based on the intersection of the aggregated supply and demand curves representing all bids and offers in the entire Nordic market and commonly utilized as a reference by the majority of standard financial contracts in the Nordic region, we look back to the data since 2010 (Figure 1). Over the past decade, renewable energy (wind and solar) in Nordic electricity markets has maintained a high growth rate, while thermal generation is decreasing. There exists a huge spike in Nordic system electricity prices during 2021, which has never happened before. The trends of natural gas prices and Nordic system electricity prices basically converged after the onset of the war while electricity prices appeared more volatile compared to natural gas prices. Meanwhile, the electricity consumption in Nordic countries (Denmark, Finland, Norway, and Sweden) does not show significant changes compared to the previous period.

One concept that can be used to explain the similar trends between natural gas prices and Nordic system electricity prices around the onset of the war is the price correlations among different energy markets. Due to global energy market integration, natural gas price

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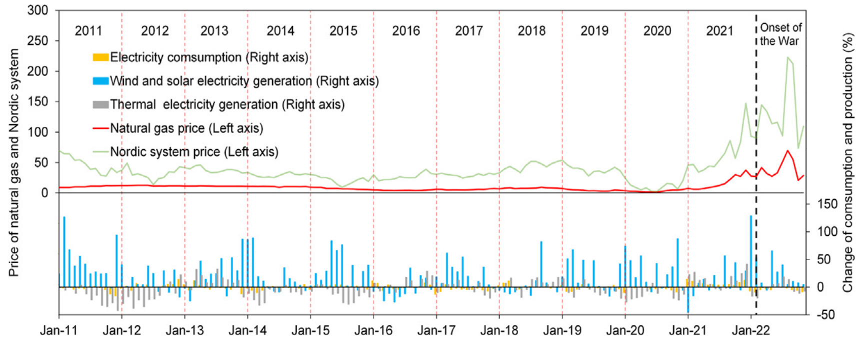

Figure 1. Changes in price and electricity generation series

The black dashed line represents the time point when the war broke out. The natural gas price and the Nordic system price are marked on the left coordinate axis, while year-on-year changes of the electricity consumption, wind and solar electricity generation, and thermal electricity generation are marked on the right.

volatilities can be transmitted to electricity markets accordingly. Characteristics of price correlation and volatility transmission can be found in the same types of energy markets,[4,5] different types of energy markets,[6,7] and energy-nonenergy markets.[8,9] For instance, oil prices have experienced multiple fluctuations, and the potential reasons for these fluctuations may vary.[10] Unexpected shifts in the global business cycle, global oil production, and inventory demand led to difficulties in anticipating oil price fluctuations. Major fluctuations in oil prices over the past four decades are not alike; changes in supply and demand need to be treated differently.[11] To a large extent, global natural gas trade is similar to that of oil, and thus the same analysis can also be applied to natural gas, especially between European countries and Russia. Political events, geopolitical conflicts or production failures on the supply side led to the reduction or even the cessation of natural gas transportation.[12] However, this time European countries have taken the initiative to break away from the consumption of Russian natural gas, and this trend shows no signs of reversing in the near future. Germany, which depended on Russian natural gas for 55% of its domestic consumption before the outbreak of war, will no longer import Russian natural gas, oil, or coal from 2023 onwards.

In previous energy market studies, at least the following correlations have been determined: 1) Energy trade flows do exist; 2) Targeted energy sources are viewed as international commodities. However, in terms of the natural gas used for electricity generation, the electricity markets of the four Nordic countries do not have a strong gas exchange with the European continent. Given the similar trends in gas prices and Nordic electricity prices, it is worth exploring whether the gas prices indeed affect electricity prices in Nordic countries and why such effects exist since the contribution of natural gas to total electricity generation in 2021 was notably low in Norway (0.19%) and Sweden (0.16%), and comparatively low in Denmark (4.65%) and Finland (5.32%). On one hand, this exploration can shed light on the factors that drive the increase in Nordic electricity prices after the outbreak of the Russia-Ukraine war. On the other hand, it provides decision support for regulators to respond to such a situation, i.e., the fluctuations in fossil energy price can affect electricity prices even with quite low supply levels, which may frequently appear during the transition from fossil to renewables. Moreover, electricity consumption in the Nordic region remains relatively stable compared to renewable and thermal generation (see Figure 1). If there are no apparent issues with demand, it is plausible that an event on the supply side may have occurred.

The large-scale deployment of intermittent renewable energy, such as wind and solar, could be a contributing factor. From a long-term perspective, renewable and thermal generation show the opposite trend, which reflects the energy transition in the Nordic region. From a short-term perspective, despite a decline in hydropower production in 2022 compared to 2021 due to record-low filling levels, the 2.9% decrease in hydropower is compensated by a 2.9% increase in wind and solar generation during our research period. Through policies to promote the utilization of renewable energy, the Nordic countries have been able to develop renewable energy on a large scale and improve energy efficiency.[13] Due to resource endowments, all bidding areas of Norway and *SE1* and *SE2* in the far north of Sweden are mainly dependent on hydropower. However, in Denmark (*DK1*, *DK2*) and southern Sweden (*SE4*), wind energy is the predominant energy source. Overall, except for *NO5*, the share of variable wind and solar energy generation in all bidding areas increased significantly from 2018 to 2022.[14] Previous studies have identified the dampening effect for wind and solar electricity generation that have low or zero marginal costs on the electricity price,[15–19] i.e., the merit-order effect, especially in Germany.[20] Martin de Lagarde and Lantz[19] disentangle the impact of wind and solar generation with a two regime Markov switching model and identify a negative marginal effect from renewable production, which is stronger in regimes of relatively high prices. In addition, in Italy, Clò et al.[21] investigate the non-negligible impact on the Italian wholesale electricity price and find that the increases of wind and solar generation have different degrees of reducing effects on electricity prices, but they also amplify the volatility.

We attempt to investigate what has happened between Nordic electricity prices and European continent natural gas prices since the Russia-Ukraine war. We start our perspective on the price formation of the Nordic electricity market and explore the roles of natural gas prices in the process of Nordic electricity prices before and after the onset of the war. Moreover, we attempt to find the hidden reason, which focuses on the possible exercise of market power through price bidding from Nordic renewable and other non-gas generators. We try to explain this from the perspective of a theoretical model in which we capture the behavioral characteristics of electricity generators under different

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electricity price bidding mechanisms. Additionally, we compare the total social welfare under two structures of electricity markets: liberalized and regulated.

The data are collected from seven European countries (15 bidding areas), among which Denmark (*DK1*, *DK2*), Finland (*FI*), Norway (*NO1* to *NO5*), and Sweden (*SE1* to *SE4*) are Nordic countries, while Germany (*DE*), the Netherlands (*NL*), and Italy (*IT*) belong to the European continent. Bidding areas' codes are consistent with the ENTSOE system. More details about the variables are reported in Table S2. It should be mentioned that, from 2021 onwards, the European gas market began to display distinct characteristics, most notably a sharp increase, compared to 2020 or earlier. The potential ramifications may continue after the outbreak of war. Therefore, to control other unconsidered variables and focus on the impact of the sudden war outbreak, we select the year 2021 as the benchmark for comparison instead of the year 2020 (or earlier). Moreover, electricity production and consumption have high seasonality.[22] To hold the seasonal factor in conducting the comparison of price formulations in pre-war and post-war period, we select the same periods in different years, including *pre-war* (2/24/2021-11/30/2021) and *post-war* (2/24/2022-11/30/2022). And we omit the period from 12/1/2021 to 2/23/2022 to exclude the disturbance of market anticipation before the outbreak of war. If this period is included in the *pre-war* period, the difference in the response to the war between the two periods may be weakened.

The main contributions of the article are as follows: First, our study is among the initial efforts to explore the reasons behind the surge in Nordic electricity prices following the outbreak of the Russia-Ukraine war. Second, we reveal that non-gas generators, particularly solar and wind generators, may exercise market power through price bidding when natural gas prices rise, after conducting analysis from multiple aspects, e.g., electricity price formation, firm-level data, and generation elasticity estimation. Third, we validate the existence of market power under certain conditions, supported by a theoretical model that considers the quotation behavior of market participants. Our analysis offers decision support for regulators to address strategic behaviors from non-gas generators in the face of fossil energy price fluctuations during the energy transition, which arose with the Russia-Ukraine war, and has not previously occurred.

RESULTS

Effect of natural gas prices on Nordic electricity price formation

We investigate the effect of natural gas prices on the formation of electricity prices by incorporating additional variables, such as load, electricity generation, and fluctuations, to construct a regression for electricity prices. The directions of the effects among various price series are illustrated with arrows, and the significance levels of price formation are presented on the direction arrows (Figures 2A and 2B). The effect of natural gas prices on electricity prices among bidding areas consistently exists and is strengthened after the outbreak of war. We identify two transmission paths of natural gas prices to Nordic electricity prices, direct effects and indirect effects. The former mean that the natural gas price is significant within the area's electricity price formation. The latter summarize that, if area *A* is directly affected by the gas price, under the electricity transmission within areas, *A*'s electricity price can affect the electricity price of area *B*. Therefore, the price of natural gas is transmitted by *A* and may have an effect on *B*, which is considered to be an indirect effect.

(1) Direct effect: Compared to the *pre-war* period, gas prices become significant in the formation of electricity prices in *FI* and *SE2*, while in three areas - *NO2*, *NO4*, and *SE3* - the phenomenon is reversed. In southern Norway (*NO1* and *NO5*) and SE1, gas prices are significant in both periods. In addition, in several representative countries of the European continent, natural gas prices consistently show significant positive impacts on their respective electricity prices. One observation is that for Nordic bidding areas where natural gas prices have a direct impact on their electricity price formation, the shares of natural gas generation during regression periods are quite low or close to zero (Figure S1), except for *FI*, where the natural gas generation share is approximately 2.6% since its natural gas is increasingly sourced as LNG from May 2022. In the areas where natural gas prices change from significant to insignificant (i.e., *NO2*, *NO4*, and *SE3*), electricity prices interact with each other due to the existence of electricity transmission, which leads to the indirect effect of natural gas mentioned in the next paragraph.
(2) Indirect effect: Although the natural gas prices in both periods of the *DK1* and *DK2* areas in Denmark are not significant, the German (*DE*) electricity price is consistently significant and has a large effect, which is further strengthened after the outbreak of war. For *DK1*, the regression coefficient of the *DE* electricity price increases from 0.66 in *pre-war* to 0.70 in *post-war*, which suggests that an underlying 1% rise in electricity prices in Germany may lead to a 0.70% rise in *DK1* (Figure 2C). For *DK2*, the regression coefficient of the *DE* price increases from 0.21 in *pre-war* to 0.64 in *post-war*. From the perspective of correlations, the electricity prices in Denmark, especially *DK1*, also show closer links to gas prices after the outbreak of war (Figure 2D). However, only approximately 5% of Denmark's electricity is generated by natural gas. This can be attributed to Denmark having the largest electricity transmission capacity to Germany among Nordic countries. Meanwhile, within the Nordic region, electricity prices in neighboring bidding areas also have significant effects since there are close electricity transmissions among them, such as northern bidding areas in Norway (i.e., *NO3* and *NO4*) and Sweden (i.e., *SE1* and *SE2*). The electricity prices in *NO3* and *NO4* are closely linked to *SE1* and *SE2*, which are both affected by the natural gas price in *post-war*. Thus, although the effect of natural gas prices on the electricity prices of these two Norwegian areas is not significant in *post-war*, with the extension of the time interval, the effect of natural gas prices will still be indirectly transmitted from *SE1* and *SE2* to *NO3* and *NO4*. In summary, with the outset of the Russia-Ukraine war, electricity prices in the Nordic bidding areas are directly or indirectly affected, and the interaction of electricity prices is strengthened. Meanwhile, there has been no significant change in the daily average amount of electricity transmitted among these areas (see Figure S1).

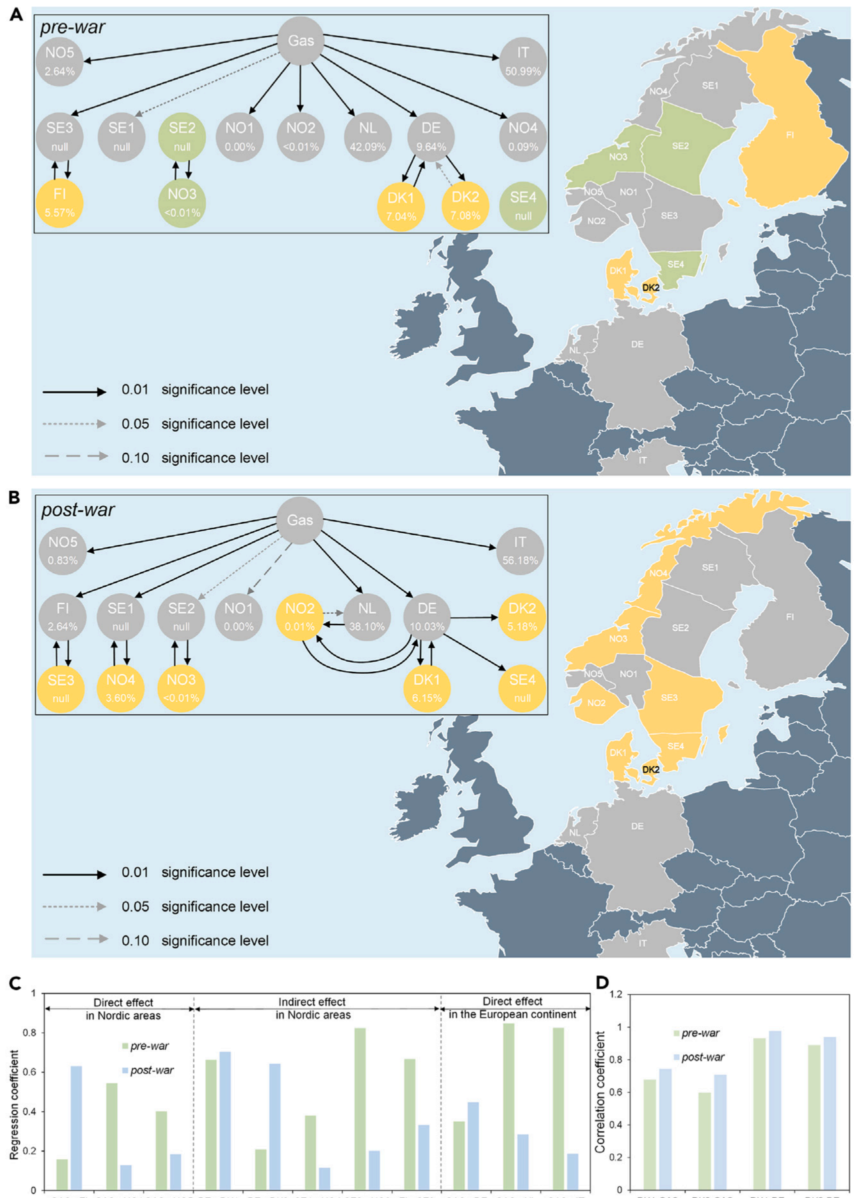

Figure 2. Area location and the effect direction in electricity prices formation

(A and B) Location of bidding areas and the effect direction in electricity prices formation of *pre-war* and *post-war*. The gray color represents areas directly affected by natural gas prices, while the yellow color represents recipients of indirect effects. The green area is the rest of the focused areas in this paper. The percentages under the area code represent the share of natural gas electricity generation in the total generation during the respective period.

(C) Comparison of the direct and indirect impact of the two periods. The symbol "->" on the horizontal axis represents the direction of impact.

(D) The correlationship in price series of *pre-war* and *post-war*.

Effect of variables from the demand and supply sides on price formation

Although the shares of Nordic electricity production generated from natural gas are low, natural gas prices still affect the electricity prices. Apart from natural gas prices, on the demand side, daily load also contributes to price formation in both Nordic and European continent countries which remains basically unchanged in *pre-war* and *post-war* (Figures 3A and 3B). Meanwhile, on the supply side, the affecting factors are diversified after the outbreak of war. Thermal generation, to a large extent, determines the electricity price of European continent countries during the regression period. Hydropower, which experienced record-low filling levels in 2021 and 2022, is still significant in the Nordic region's electricity generation. In terms of intermittent renewable energy, wind generation plays a greater role in electricity price formation in Nordic countries compared to solar generation. Compared to that in Germany, the total shares of wind and solar generation in Finland, Sweden, and Norway are all much lower. During the period of *post-war*, the total shares of wind and solar generation in Finland, Sweden, and

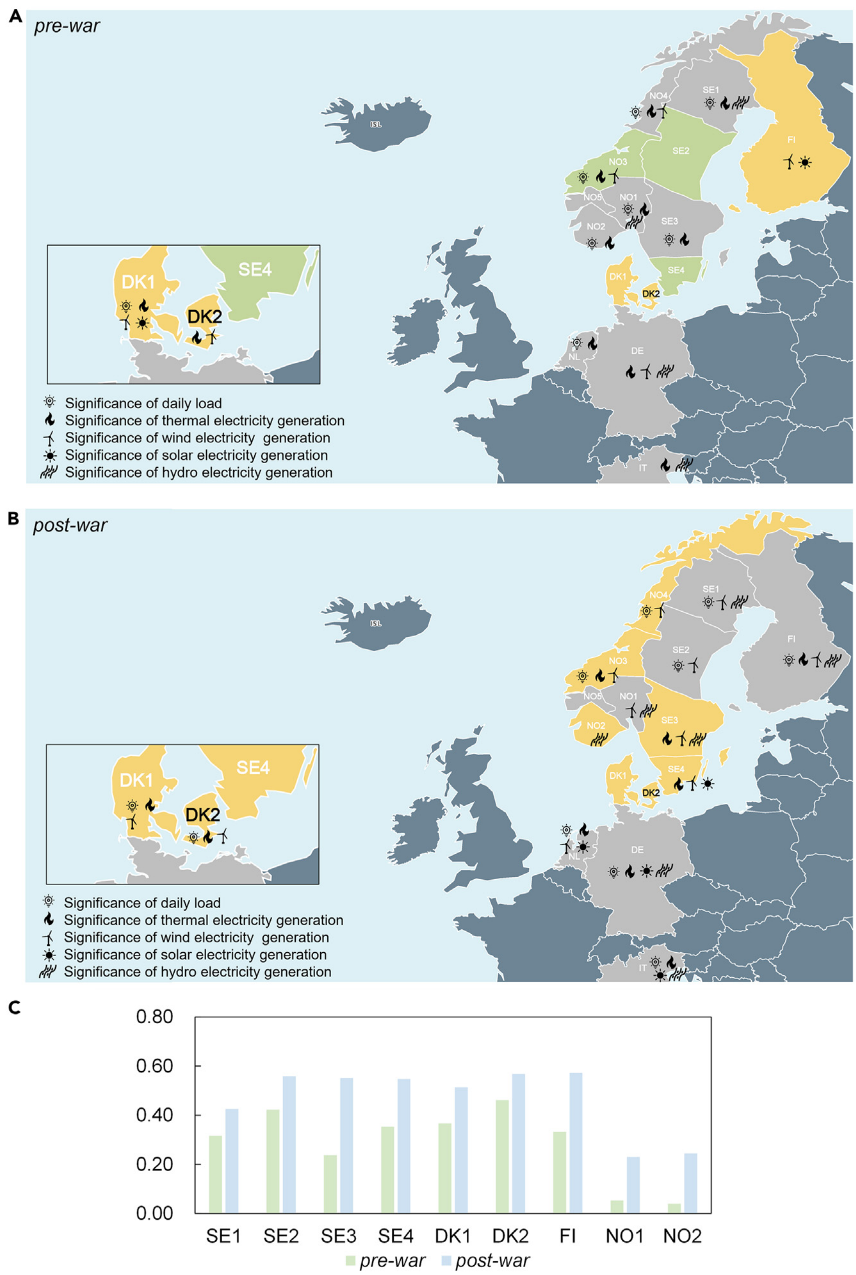

Figure 3. Factors of electricity price formation in different areas

(A and B) Important factors of electricity price formation during *pre-war* and *post-war*. When a certain symbol appears in the area, it means that the factor represented by the symbol is significant in the price formation in the current area.

(C) Absolute values of correlation coefficient between wind generation and regional electricity prices.

Norway are 16.9%, 20.2%, and 9.9%, respectively, while the share is 34.9% in Germany. In all bidding areas of Sweden, Denmark, and Finland, as well as parts of southern Norway (i.e., *NO1* and *NO2*), the correlations between wind generation and regional electricity prices have strengthened significantly (Figure 3C).

Possible exercise of market power from Nordic generators

From the regression model of price formation, we draw the following conclusions: First, despite experiencing record-low filling levels in 2021 and 2022, hydropower remains significant to the Nordic region's generation. Second, since the outbreak of the war, the wind and solar generation have become more significant across several bidding areas. Meanwhile, during our research period, the decrease in hydropower

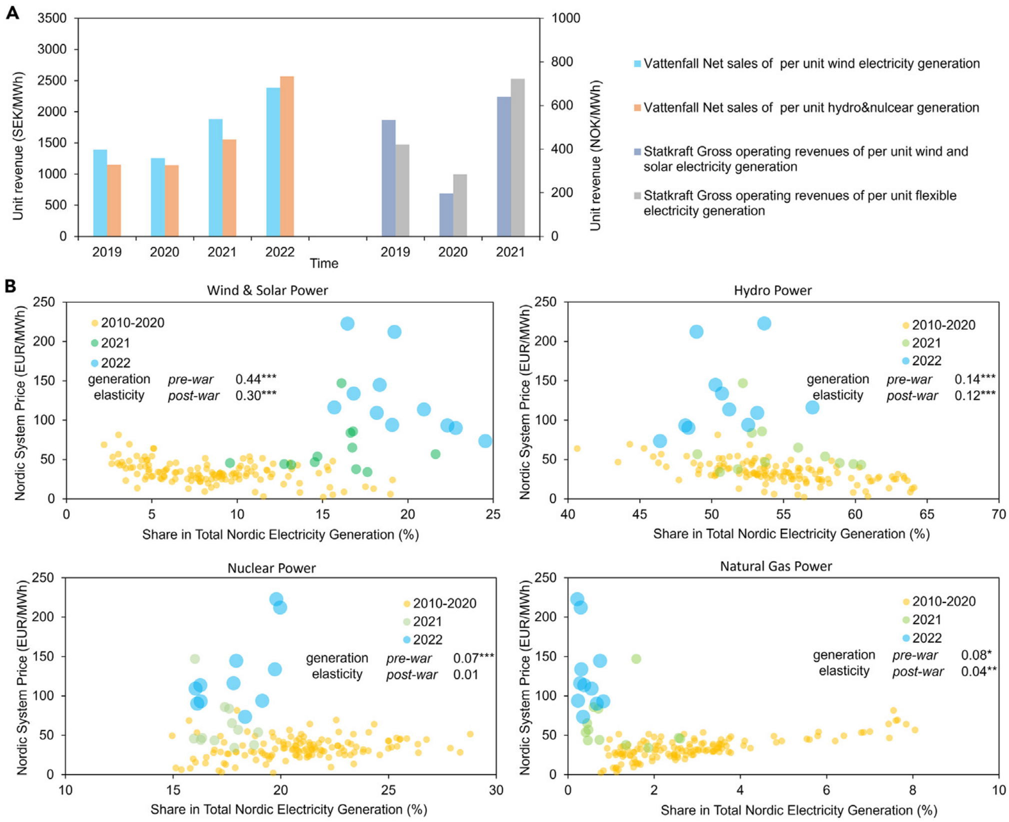

Figure 4. Unit revenue of major Nordic generators and share of wind & solar generation

(A) Unit revenues under different statistical methods of two major Nordic generators for electricity generation. It should be noted that Statkraft adjusted its format for data disclosure, making it no longer possible to calculate its gross operating revenues per unit of wind & solar generation for 2022. The financial data is sourced from the annual reports available on the websites of the two firms. Vattenfall, https://group.vattenfall.com/investors and Statkraft, https://www.statkraft.com/IR/results-reports-and-presentations.

(B) Nordic system prices and shares of different electricity source in total generation. For values of generation elasticity, * denotes significance level 10%, ** denotes significance level 5%, and *** denotes significance level 1%.

(2.9%) is compensated by an increase in wind and solar generation (2.9%). In the following analysis, we take wind and solar together as "wind & solar" because of the dominance of wind relative to solar in the Nordic. For hydropower, nuclear, and wind & solar generation, whose marginal costs remain relatively stable, their revenues rose sharply. Operational data of non-gas electricity generation from two major Nordic electricity generators, Vattenfall and Statkraft, reveal that both companies recorded large increases in per-unit revenues (Figure 4A). So there is the possibility of raising prices to ensure income among these generators, which is achieved through the exercise of market power. It should be pointed out that excluding pre-contracted transactions, all electricity suppliers and consumers in the trading market will face the same clearing price, thus the annual differences between wind/solar and other technologies are similar.

Moreover, the share of wind & solar in Nordic generation and the system price both showed significant upward trends since 2021 and became more pronounced in 2022 (Figure 4B), which is different from the other three electricity sources. The trends appear to be a result of the increased generation of wind & solar in Nordic countries during 2021 as the production of thermal (including natural gas) began decreasing. It is hard to obtain detailed quotation data from Nord Pool that distinguishes between electricity sources (e.g., wind, solar, or thermal), which limits our analysis on the behavior of different generators (e.g., Lundin and Tangerås[23]). Therefore, we employ a proxy indicator, namely, generation elasticity, which is estimated using the generation of different technologies and system price data. The generation elasticity differs from the traditional concept of price elasticity of supply, in which the latter uses cross-sectional data for estimation, while the former employs time series data. However, both indicators share a commonality in reflecting the sensitivity of generation to price changes. The greater is the supply elasticity of competing firms, and the greater is the constraint that these firms place on a firm trying to raise price above marginal cost.[24] In contrary, we can infer that, given a generator in an imperfect competitive electricity market, the greater the generation elasticity is, the greater the market power would be if the generator were to raise the price. And wind & solar has the largest price elasticity of generation among the four electricity sources (Figure 4B). So wind & solar is more suspected.

Inspired by Jónsson et al.,[15] we conduct an analysis of the distribution of electricity prices with different levels of wind & solar penetration at an hourly resolution. According to the average penetration rate, the data subset of a certain area is divided into two intervals, i.e., low

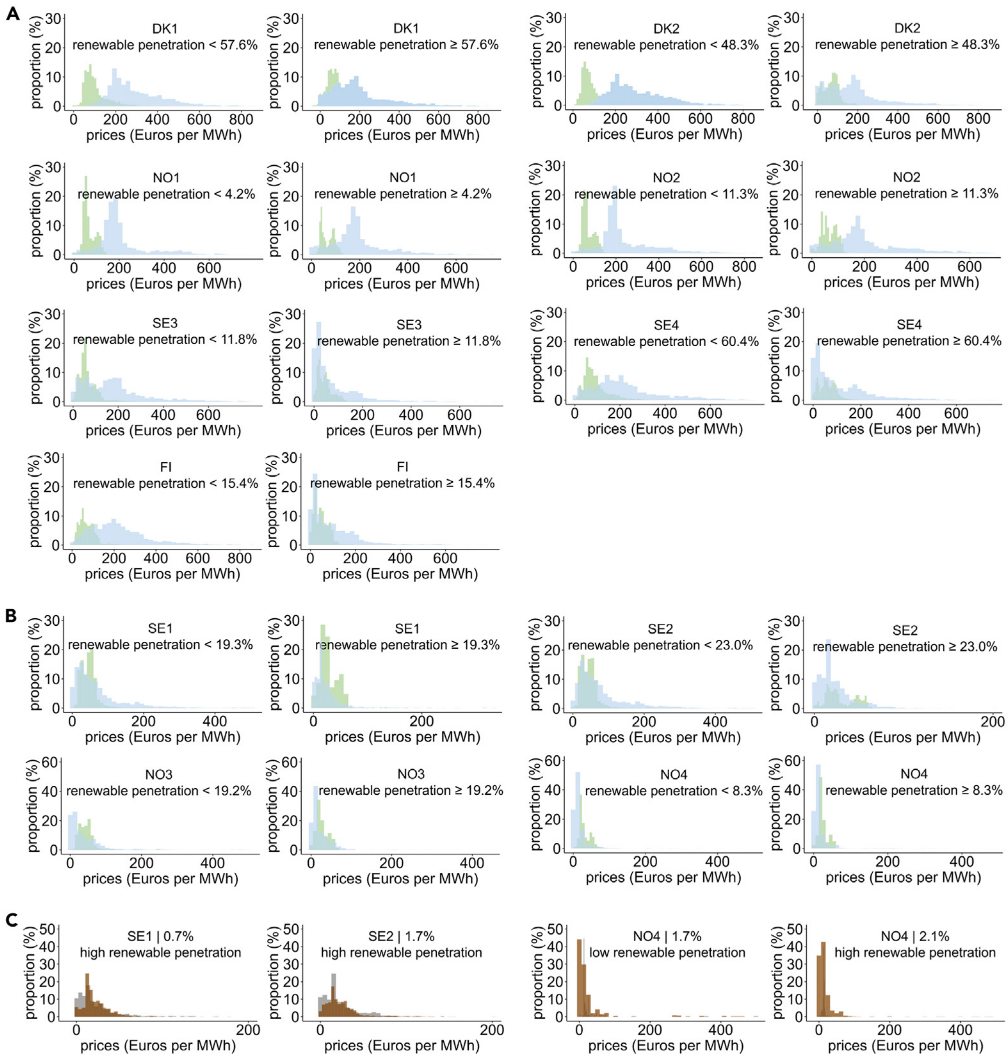

Figure 5. Distribution of electricity prices with different levels of wind & solar penetration

(A and B) For each area, the left subgraph represents the *pre-war* (green histogram) and *post-war* (blue histogram) price distributions at a low renewable penetration range, and correspondingly, the right subgraph represents a high renewable penetration range. The average penetration rate, i.e., the division value (to the right of the zone code) between low and high penetration range is the average value of the daily proportion of renewable energy generation during the full research period.

(C) The distribution of *post-war* electricity prices in the low thermal (natural gas) generation penetration range (gray histogram) and the high penetration range (brown histogram) under a specific range of renewable penetration. The division value to distinguish thermal (natural gas) generation ranges is calculated in the same way in Figures 5A and 5B. The percentage to the right of the area code is the division value.

penetration range (from 0% to the average penetration rate) and high penetration range (from the average penetration rate to 100%), and both of them includes approximately 6720 pairs of values of the renewable penetration and the electricity price. There are two main findings. First, when the same period is selected (*pre-war* or *post-war*), Denmark, southern Norway, southern Sweden, and Finland (i.e., *DK1*, *DK2*, *NO1*, *NO2*, *SE3*, *SE4*, and *FI*, see Figure 5A) exhibit lower average electricity prices in the high penetration range compared to the low penetration range. This indicates that higher renewable penetration indeed contributes to lowering electricity prices within the same period, aligning with previous literature findings. Second, when the same penetration range is selected, average electricity prices in *post-war* are higher than those in *pre-war*. In other words, it is precisely after the war outbreak that average electricity prices rise in all seven aforementioned areas within the same penetration range. This may result from that non-gas generators, especially wind and solar generators, tend to raise electricity prices as natural gas prices rise.

The areas with different results are *SE1*, *SE2* and *NO3*, *NO4* (Figure 5B). For northern Sweden, i.e., *SE1* and *SE2*, the difference between these two areas and the aforementioned seven areas is that the average electricity prices in *post-war* show a trend of decrease in the high renewable penetration range. Then, for the high penetration range, we add the gas electricity penetration ranges for additional analysis

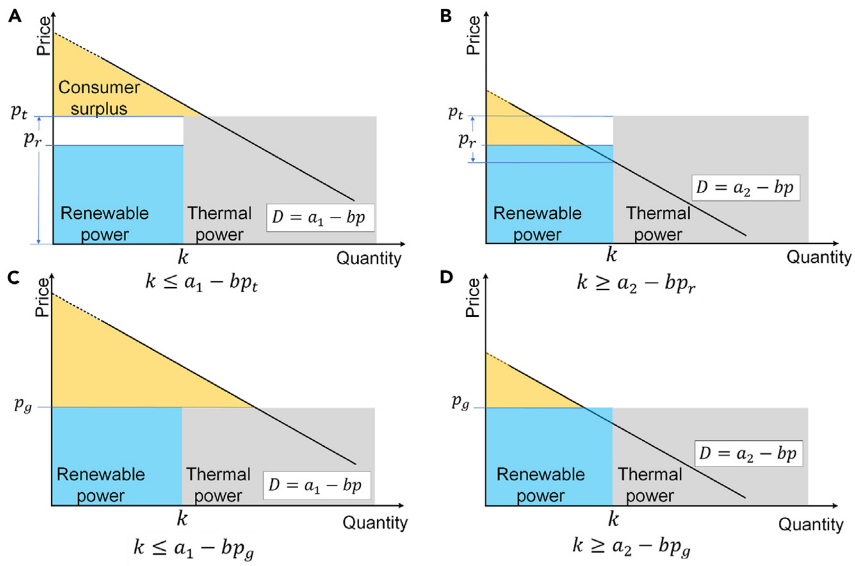

Figure 6. Illustration of quoted price in a liberalized market and a regulated market

(A) Quoted price in a liberalized market with high demand. It is necessary to introduce the thermal generator to satisfy the demand together when the renewable generator has utilized the available capacity.

(B) Quoted price in a liberalized market with low demand. The renewable generator can conquer the demand alone with a probability of δ.

(C) Spot price in a regulated market with high demand. (D) Spot price in a regulated market with low demand. Notes: p_r is the quoted price for renewable; p_t is the quoted price for thermal; p_g is the spot price determined by the government. The meanings of other notations are presented in STAR methods and Note S3 parts, respectively.

(the available Swedish electricity data does not distinguish between specific natural gas generation, so we use thermal generation in *SE1* and *SE2*), it is found that the average electricity price in *post-war* of *SE2* is higher at high thermal penetration range than at low thermal penetration range, while *SE1* remained basically unchanged. As for area *NO3* and *NO4*, the average electricity prices in *post-war* are lower than the *pre-war* prices within both high and low renewable penetration ranges. And the same additional analysis is applied to *NO4*, while *NO3* has only one record of natural gas generation data in our research period. It is also found that, in *NO4*, the average electricity price in *post-war* could be higher in the high natural gas penetration range with both of the two renewable penetration ranges (Figure 5C). Although electricity prices in these areas have decreased since the outbreak of war, we can speculate that wind and solar generators can drive up electricity prices through higher penetration of natural gas.

Given that the marginal generating costs of wind, solar, and other non-gas generation are much lower than those of natural gas, this provides generators with more flexibility in electricity price bidding. Taking the most suspected wind and solar generators as an example, a conjecture can be inferred: wind and solar generators in Nordic countries have already attempted to raise electricity prices based on their increasing production in 2021. The expected increase in gas prices or gas supply shortages due to the conflict between Russia and Ukraine may have been used as an excuse for this attempt.

A transparent theoretical analysis

Analysis in the previous section suggest that rising electricity prices may be a reflection of unexpected market actions from non-gas generators, especially wind and solar generators, in Nordic electricity markets. To analyze the market power of non-gas generators in raising prices, we establish a simple and transparent model to investigate the optimal quoted price for generators in a regional electricity market within either liberalized or regulated structures. The theoretical model considers the behavior of the suppliers in the electricity market. This allows us to explore how generators may quote under different cases, as well as demonstrate the potential for renewable or other non-gas generators to exercise their market power in price bidding.

The simplicity of the theoretical model serves a dual purpose. First, it is designed to closely mirror the operational mechanisms of the Nordic electricity market, where electricity with lower marginal costs is preferentially allocated to the grid, known as the merit-order effect. Second, it retains a degree of universality. Therefore, we depict the most representative technologies in both new and traditional energy, with a specific focus on renewable and thermal generation, to reflect the competition and collaboration during the energy transition. Specifically, we consider two types of markets: a liberalized market and a regulated market where difference lies in the mechanism determining the clearing electricity price (see Figure 6). In the liberalized market, the renewable generator determines its quoted price and submits to the gird, which then dispatches electricity to satisfy the demand in ascending order after receiving the quoted prices. While in the regulated market, the final spot price is determined by the government. The main results are presented in Table 1. The model is effective since it reveals a counter-intuitive result that the renewable generator can follow the thermal generator's quotation.

Table 1. Results of theoretical model

Liberalized market	Renewable generator's quotation mechanism	
i. $\frac{a_2}{2b} < \frac{a_2 - k}{b}$	$p_r^* = \frac{a_2 - k}{b}$	Independent quotation
ii. $\frac{a_2 - k}{b} \le \frac{a_2}{2b} \le p_t$	$p_r^* = \frac{a_2}{2b}$	
iii. $p_t < \frac{a_2}{2b}$	$p_r^* = p_t$	Follow the thermal generator's quotation
Regulated market	Regulated electricity price $p_g^* = (1 - \delta q_2)(c + \eta)$	
Market Comparison	If the renewable generator bid at the same quoted electricity price to that of thermal generator (iii), the total social welfare in a regulated market is always higher than that of a liberalized market ($W_R \ge W_L$).	

Demand is assumed as $D = a_1 - bp$ with probability q_1 or $D = a_2 - bp$ with probability q_2, in which a_1 is much larger than a_2. The intermittency of renewable output follows a two-point distribution with probability δ. In the liberalized market, p_r is the quoted price for renewable generator and p_t is the thermal's quoted price. p_r^* represents the optimal quoted price for the renewable. In the regulated market, the spot price p_g^* is optimal price determined by the government. η represents the amount of environmental damage per unit of electricity. W_L is the total social welfare in a liberalized market; W_R is the total social welfare in a regulated market.

In a liberalized market, the thermal generator determines a quoted price defendant on the gas price and the renewable generator tries to optimize its price to maximize the profit. Both renewable and thermal capacity needs remain in the electricity system to satisfy the social electricity demand together. We prove that, dependent on the demand characteristics, installed capacity, and thermal generator's quoted price, the renewable generator's quotation mechanism can be divided into two categories, one is independent of thermal generator's quoted price, and the other is to follow the thermal generator's quotation.

The quoted price of the thermal generator is positively correlated with the unit cost of electricity generation, where the price of natural gas constitutes a significant portion of the unit cost. Therefore, in the case of following the thermal generator's quotation, rising gas prices can raise quoted price of both the thermal and renewable generator. When the output of renewable generators meets demand, compared to the situation of quoting with a fixed profit rate, the clearing price increases, which can be seen as a form of market power in price bidding. Looking back at the reality of rising electricity prices, the results obtained by the theoretical model support that the expected gas price increases or gas supply shortages could serve as a convincing excuse and would result in a rise in electricity prices.

Meanwhile, when comparing total social welfare in the case of following the thermal generator's quotation, a regulated electricity market always yields higher total social welfare than a liberalized market. Although such theoretical results contradict the intuition, it supports the regulator's policy intervention in electricity prices under specific conditions, such as a sharp rise in fuel prices.

Conclusion and discussion

In summary, although natural gas generation in Nordic countries is fairly low, the results of the empirical model still highlight the significance of natural gas prices in the European continent for Nordic electricity price formation in which the direct effects and indirect effects of natural gas prices are identified. Moreover, we also determine the significance of non-gas generation, especially wind & solar generation, in the formation of Nordic electricity prices. And the proposed theoretical model reveals the existence of an optimal strategy that renewable generator's quoted price is to follow the thermal generator's quotation. Combining empirical and theoretical analysis, the results suggest that the sharp rise in electricity prices in Nordic countries may be a collateral affair in which Nordic renewable and other non-gas generators take advantage of natural gas price fluctuations to raise Nordic electricity prices.

This study tends to shed light on a phenomenon where, under certain conditions, wind and solar, or other non-gas generators, can exercise market power through price bidding as natural gas prices rise. With the increasing shares of wind and solar generation in electricity systems, more unknown phenomena may emerge in the electricity market. Lessons learned from the Nordic electricity price changes around the Russia-Ukraine war can help regulators prepare for and improve energy market regulation with a high proportion of wind and solar generation, especially the suppression of electricity price fluctuation on the generator side. It is the insight that we wish to convey to readers and that regulators need to pay attention to during the process of energy transition.

Although the degree of market power has been reduced since the covering area of Nord Pool has expanded,[25] it is still found that flexible producers with perfect forecasts can also increase its profit in both the day-ahead and intraday market by coordinating its offer.[26] The current stage of energy transition from fossil to renewables in European countries and the absence of significant changes in electricity demand leave room for strategic actions in price bidding not only from flexible producers, but also from wind and solar generators. When renewable energy penetration is increasing toward an aim (such as carbon neutrality), its intermittent output and marginal cost close to zero bring uncertainty to both the electricity systems and market prices.

It is believed that improving the interconnection of electricity trading markets, the extension of the transmission grid, and combination of flexible generation and energy storage capacities can all contribute to stabilize the volatility of renewables integration. However, these options can do nothing in mitigating possible exercise of market power through price bidding from renewables. Thus institutional innovation or regulatory intervention in the electricity market is needed. Our theoretical model also shows that a regulated electricity market can lead to higher social welfare than that of the liberalized market under certain conditions if intermittent renewables and the thermal generation capacity remain to meet the demand together, which also highlights the necessity of regulatory intervention when unexpected situations occur in the electricity market, although it is often argued that liberalized competition in electricity markets is efficient in allocating resources. In addition, the council of the EU approved a temporary windfall tax in October 2022, to curb surplus profits of electricity producers (including low-cost producers such as wind and solar) made in 2022 or 2023 and the obtained "solidarity contribution" in the regulation will be used in support of final electricity customers, which is an example that echoes our conclusion.

Limitations of the study

Our study is not without flaws. In the results, we do not distinguish in detail the different effects that wind and solar may have, although in the empirical model two kinds of electricity generation are included separately. In fact, in the Nordic region, wind generation has always occupied a larger share than solar. However, the installed capacity of solar generation in the Nordic region has grown rapidly in recent years. Meanwhile, in the theoretical model, we simplify the number of participants and sketch a simple two-point distribution for the intermittent description of renewable energy generation, which may not be able to perfectly capture the reality.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

- KEY RESOURCES TABLE
- RESOURCE AVAILABILITY
  - Lead contact
  - Materials availability
  - Data and code availability
- METHOD DETAILS
  - Selected variables in the empirical model
  - Regression for the empirical model of electricity price formation
  - Calculation of the generation elasticity
  - Basic set and conclusions of the theoretical model

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2024.109924.

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AUTHOR CONTRIBUTIONS

Supervision: J.Y.; conceptualization: J.Y. and L.Z.; methodology: LZ.Z., J.L., W.Z., and Y.B.; data collection: LZ.Z.; writing-original draft: L.Z. and LZ.Z.; writing-review and editing: J.Y., L.Z., and H.Z.; visualization: L.Z.Z. and H.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author(s) used Microsoft Copilot in order to improve the grammar and readability. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited data		
Electricity prices and load of different technologies in bidding areas	ENTSOE	https://transparency.entsoe.eu/dashboard/show
Energy production of different technologies in bidding areas except for Sweden	ENTSOE	https://transparency.entsoe.eu/dashboard/show
Nordic system price	Nord Pool	https://data.nordpoolgroup.com/auction/day-ahead/system?deliveryDate=latest&currency=EUR
Energy production of different technologies in Sweden	Svenska-Kraftnät	https://mimer.svk.se/ProductionConsumption/ProductionIndex
Natural gas prices	ICE Endex	https://www.ice.com/products/27996665/Dutch-TTF-Natural-Gas-Futures/data
Electricity transmission across different areas	Nord Pool	https://www.nordpoolgroup.com/en/Market-data1/Power-system-data/Exchange1/
Software and algorithms		
R	R 4.1.3	https://cran.r-project.org/bin/windows/base/
Eviews	Eviews 10.0	https://www.eviews.com/

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Jinyue Yan (j-jerry.yan@polyu.edu.hk).

Materials availability

The study did not generate new materials

Data and code availability

- Data: The corresponding descriptions of data are listed in the key resources table.
- Code: The codes used for data processing are available upon reasonable request from the lead contact.
- Any additional information required to reanalyze the data reported in this paper is available from the lead contact upon request.

METHOD DETAILS

Selected variables in the empirical model

Given that both demand and supply play significant roles in price formation, we construct a regression model of electricity prices for each area, taking into account factors such as load, renewable generation, conventional thermal, and hydro generation. The renewable energy we consider consists of wind and solar energy, which is prevalent in the literature.[27] The fluctuation of intermittent renewable energy feed is characterized by intraday variance in the model, as well as the load. Another important factor that determines the price of electricity is the transmission of electricity between areas. The electricity resources of each bidding area vary. However, the construction of transmission capacity improves the regional liquidity of electricity. Similar to transmission, we also consider the impact of electricity prices in neighboring areas. Additionally, our model incorporates our variable of interest: natural gas prices.

Regression for the empirical model of electricity price formation

The basic model is specified as follows:

$$pe_{it} = \alpha_0 + \alpha_1 pe_{i\ t-1} + \alpha_2 png_{i\ t-1} + \alpha_3 pe_{it}^{n} + \alpha_4 LOAD_{it} + \alpha_5 IRE_{it} + \alpha_6 CONV_{it} + \alpha_7 TRANS_{it} + u_{it} \qquad \text{(Equation 1)}$$

where pe_{it} is the day-ahead electricity price (the explained variable) for area i at day t, α_0 the intercept, α_j the respective coefficients and u_{it} is the disturbance term. Equation 1 employs a simple regression composed of the lag term of electricity price $pe_{i\ t-1}$ and natural gas price $png_{i\ t-1}$.

Considering that electricity prices may not respond so quickly to changes in natural gas prices, we use the first-order lag term of natural gas prices $png_{i\,t-1}$. pe^{n}_{it} is a vector composed of electricity prices in area i's neighbors. $LOAD_{it}$ is a two-dimensional vector consisting of daily load *load* and its variance *loadvar* (derived from hourly data). IRE_{it} is a four-dimensional vector containing renewable-related control variables: daily electricity generation of wind *wind* or solar *solar* and their variance *windvar* and *solarvar*, respectively (also derived from hourly data). $CONV_{it}$ is a vector composed of conventional daily generation variables: conventional thermal generation $thermal_{it}$; hydro generation $hydro_{it}$; nuclear generation $nuclear_{it}$ if any. $TRANS_{it}$ means daily inter-regional export electricity *export* or import electricity *import*, which depends on whether the country generally exports or imports electricity. Specifically, the transmission variable $TRANS_{it}$ is excluded in the regression for continental European countries since the data for daily electricity transmission we use are obtained from the Nord Pool website. The specific data processing required to obtain these final variables can be seen in Note S1. We estimate regression coefficients within the period *pre-war* and *post-war* separately. The regression is based on ordinary least squares. The results of unit roots tests and the cointegration tests are reported in Tables S3 and S4, respectively. Detailed results of regressions are in Table S5. Visualization and discussion in the paper and the Supplemental Information are based on results of Table S5. Meanwhile, Table S6 reports the results of regression using natural gas price data without lag terms.

Calculation of the generation elasticity

We calculated the generation elasticity of the Nordic system electricity price with respect to the generation volumes of various types (hydro, nuclear, natural gas and wind & solar). We only consider generation technologies and the price, since the uniformity of the additional explanatory variables in the calculation of elasticity for different generation technologies is difficult to guarantee, and with the same time period, the interference of external factors is consistent. Specifically, we take the logarithm of each variable and fit it according to the following formula,

$$\ln p = m_i + n_i \ln Q_i + \varepsilon_i \qquad \text{(Equation 2)}$$

which includes the system price p, intercept m_i, generation elasticity n_i, generation Q_i, and error term ε_i of technology i.

Basic set and conclusions of the theoretical model

We conduct a simple and transparent model, assuming a regional electricity market that consists of two generators with renewable and thermal energy separately. Generators are tasked with satisfying electricity demand with striving to maximize their profits. The demand is assumed as $D = a - bp > 0$, where p is the spot price for electricity market, b is a exogenous constant determined by market property. We use probability to capture different levels of demand functions, specifically, $a = \begin{cases} a_1 \text{ with probability } q_1 \\ a_2 \text{ with probability } q_2 \end{cases}$ in which a_1 is much larger than a_2.

The thermal generator has ample capacity to cover the peak demand and its capacity can not be expanded any further. We represent the unit variable cost including fuel and operating cost by $u_i, i \in \{r, t\}$. We assume that $u_r = 0$, since the operating and fuel cost of the renewable is negligible, and $u_t = c > 0$, implying that the unit cost of electricity is larger than that of the renewable and positioning gas generation at the upper end of dispatch order. Moreover, to represent the intermittency of renewable technology, we use a random variable $\tilde{v} \in [0, 1]$ which means the installed capacity k can only generate $\tilde{v}k$ unit of electricity. To capture the intermittency feature while maintaining the workability and intelligibility of the model, we assume that the intermittency $\tilde{v}$ follows a two-point distribution with probability δ: $\tilde{v} = \begin{cases} 1 \text{ with probability } \delta \\ 0 \text{ with probability } 1 - \delta \end{cases}$.

Faced with electricity demand, the grid delivers generation of different technologies to consumers based on the dispatch order. The renewable is dispatched with priority by the grid due to its lower marginal cost and lack of emissions. When total demand exceeds renewable generation ($D > \tilde{v}k$), the thermal generation is dispatched as a backup energy source. We consider two types of markets: a liberalized market and a regulated market. Their distinction lies in the mechanism determining the final electricity price. In the liberalized market, the renewable generator determine its quoted price and submit to the gird, which then dispatches transmission to satisfy electricity demand in ascending order of these quoted prices, with the highest being the final spot price. We assume the quoted price p_r for renewable is always lower than that for thermal p_t (p_r^* represents the optimal quoted price for the renewable generator). While in the regulated market, the spot price p_g is determined by the government (p_g^* is the optimal price). Also, we assume that a_1 is large enough and a_2 is small enough so that $\frac{a_2 - k}{b} \leq p \leq \frac{a_1 - k}{b}$ always holds.

In a liberalized market, we assume that two generators are rational and have full information about both technologies. The thermal generator set a quoted price p_t while the renewable generator anticipates the additional willingness to pay of consumers (consumer surplus) due to the price difference. When $\tilde{v}k$ satisfies $\tilde{v}k \geq a_2 - bp_r$, the grid only dispatches renewable generation; when $\tilde{v}k$ satisfies $\tilde{v}k \leq a_1 - bp_t$, the grid will dispatch thermal generation to satisfy surplus demand (see Figures 6A and 6B). In Figure S2, we show a case that is graphically feasible but actually covered by the cases shown in Figures 6A and 6B. The profit function of the renewable generator is presented below:

$$\max_{0 \leq p_r \leq p_t} \pi_r(p_r) = \mathbb{E}_{\tilde{v}}\left\{q_1\left[p_t \tilde{v}k\right]\mathbb{I}_{\tilde{v}k \leq a_1 - bp_t} + q_2\left[p_r\left(a_2 - bp_r\right)\right]\mathbb{I}_{\tilde{v}k \geq a_2 - bp_r}\right\} \qquad \text{(Equation 3)}$$

where $\mathbb{I}_{\{\cdot\}}$ is the indicator function. The following proposition characterizes the equilibrium of the game.

Proposition 1

The optimal quoted price of the renewable generator are as follows.

(i) When $\frac{a_2}{2b} < \frac{a_2 - k}{b}$, $p_r^* = \frac{a_2 - k}{b}$
(ii) When $\frac{a_2 - k}{b} \le \frac{a_2}{2b} \le p_t$, $p_r^* = \frac{a_2}{2b}$
(iii) When $p_t < \frac{a_2}{2b}$, $p_r^* = p_t$

Proposition 1 suggests that, dependent on the demand characteristics, installed capacity and thermal generator's quoted price, the renewable generator's quotation mechanism can be divided into two categories, one is to quote independently (i.e., $p_r^* = \frac{a_2 - k}{b}$ or $p_r^* = \frac{a_2}{2b}$), and the other is to follow the thermal generator's quotation (i.e., $p_r^* = p_t$).

The total social surplus includes producer surplus, environmental loss and consumer surplus, which is denoted by CS. In the liberalized market scenario, the government is not required to make any decisions, i.e., total social surplus is determined by the Nash equilibrium behavior of two generators:

$$W_L = \mathbb{E}_{\tilde{\nu}}\{\pi_r(p_r) + \pi_t - L(\eta) + CS\} \quad \text{(Equation 4)}$$

where $L(\eta) = q_1\eta(a_1 - bp_t - \tilde{\nu}k)\mathbb{1}_{\tilde{\nu}k \le a_1 - bp_t} - q_2\eta(a_2 - bp_t - \tilde{\nu}k)\mathbb{1}_{\tilde{\nu}k < a_2 - bp_r}$ is used to capture the loss from carbon emissions, in which η represents the amount of environmental damage per unit of electricity generated. Recall that the loss is linearly increasing in emissions intensity, with the attention given to carbon emissions in most countries and regions, the assumption is reasonable. We then characterize the total social surplus in the liberalized market in case(iii):

Proposition 2

In the liberalized market, when the renewable generator should set $p_r^* = p_t$, the total social surplus is:

$$\begin{aligned} W_L = & \frac{1}{2b}\left[q_1(a_1 - bp_t)^2 + q_2(a_2 - bp_t)^2\right] + q_2(a_2 - bp_t)[p_t - (1-\delta)(c+\eta)] \\ & + q_1\{p_t(a_1 - bp_t) - (c+\eta)(a_1 - bp_t - \delta k)\} \end{aligned} \quad \text{(Equation 5)}$$

Besides, we consider a regulated market in which the government determines the electricity price to maximize the total social welfare (Figures 6C and 6D). For a given electricity price p_g, $\tilde{\nu}k$ is first produced by renewable capacity and the unsatisfied demand $(D - \tilde{\nu}k)^+$ is covered by thermal generation. So the welfare function of the society in a regulated market is as below:

$$\begin{aligned} \max_{p_g \ge 0} W_R(p_g) = & q_1\mathbb{E}_{\tilde{\nu}}\left\{p_g(a_1 - bp_g) - (c+\eta)(a_1 - bp_g - \tilde{\nu}k)^+ + \frac{(a_1 - bp_g)^2}{2b}\right\} \\ & + q_2\mathbb{E}_{\tilde{\nu}}\left\{p_g(a_2 - bp_g) - (c+\eta)(a_2 - bp_g - \tilde{\nu}k)^+ + \frac{(a_2 - bp_g)^2}{2b}\right\} \end{aligned} \quad \text{(Equation 6)}$$

Proposition 3

In the regulated market, the welfare function of the society in a regulated market is:

$$\begin{aligned} W_R(p_g) = & \frac{1}{2b}\left[q_1(a_1 - bp_g)^2 + q_2(a_2 - bp_g)^2\right] + q_2(a_2 - bp_g)[p_g - (1-\delta)(c+\eta)] \\ & + q_1\{p_g(a_1 - bp_g) - (c+\eta)(a_1 - bp_g - \delta k)\} \end{aligned} \quad \text{(Equation 7)}$$

Proposition 4

In the regulated market, the optimal electricity price is $p_g^* = (1 - \delta q_2)(c + \eta)$.

We then turn to the market comparison. It is believed that the pricing mechanism of liberalized market will bring higher social welfare compared to a regulated market. However, based on the above model settings, we obtain different results: social welfare in a regulated market can always be higher than that in a liberalized market.

Theorem 1

If the renewable generator bid at the same quoted electricity price to that of thermal generator (iii in **proposition 1**), the following inequality for total social welfares in two different markets always holds: $W_R \ge W_L$.

Detailed proof can be found in Note S3.