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Understanding the Relation between Wind Power Output and Strategic Withholding through Production Failures: Evidence from Diversified Producers in Sweden

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Abstract: Previous research provide partial evidence for electricity producers utilizing production failures to disguise the strategic withholding of capacity as well as evidence of diversified electricity producers counteracting the price-reducing effect of the merit order through capacity withholding. In this study, we investigate whether an increased supply of wind power affects the number of reported unplanned production failures among diversified producers in Sweden, thus suggesting this being one of the specific mechanisms with which producers counteract the merit order effect. We use a unique set of local wind speed, plant capacity, and market data to construct variables estimating producer-specific and market total wind power output. With a 2SLS-model, we then examine the effect of wind power on the count of dispatched Urgent Market Messages announcing an unplanned production failure. Our results suggest that a producer's own wind power production has a significant positive effect on the number of reported production failures, while the wind power production of the market has a significant negative effect on the same number. Our results add to the understanding of supply-side strategic behavior in the energy markets.

Keywords: Production Failures, Wind Power, Strategic Withholding, Capacity Withholding, Urgent Market Messages, Electricity Markets, Market Power, Merit Order Effect

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Abbreviations

BRA	Balance responsibility agreement
BRP	Balance responsible party
Ei	Energimarknadsinspektionen – Swedish Energy Market Inspectorate
EUR	Euro
GW	Gigawatt
MOE	Merit order effect
MW	Megawatt
MWh	Megawatt hours
REMIT	Regulation on Wholesale Energy Market Integrity and Transparency
SEK	Swedish krona
SMHI	Swedish Meteorological and Hydrological Institute
Svk	Svenska kraftnät
TWh	Terawatt hours
UMM	Urgent market message

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1. Introduction

The current energy and climate crisis has led to a situation where energy markets receive more attention than ever, and energy politics has become one of the most important topics in both the European Union and Sweden, affecting everyone. The turmoil which the people of Europe have witnessed during recent years has raised concerns with regard to the system's resilience, the functioning of the electricity markets, and the extreme increases in electricity prices. The current situation has put considerable strain on the electricity markets, defined by a complex interplay between supply, demand, pricing, and transmission constraints, of which several are interlinked in the common marketplace Nord Pool.

Ways to resolve the current situation have been debated lively, ranging from reducing energy consumption, and finding new ways of storing energy, to expanding nuclear power production. Another solution that is being proposed as cost-effective and quick to install is to increase the penetration of renewable energy sources, an approach that is becoming increasingly accepted, attracting large interest from both investors and municipalities. For example, the cumulative capacity of Swedish wind power production has increased from 3700 MW to 14 300 MW over the last ten years, an increase of almost 300 percent (Svensk Vindenergi, 2023). Taking this global shift into consideration, identifying, and quantifying the costs and benefits of increased renewable capacity is essential, suggesting several research areas that need further study.

Along with the expansion of wind power capacity and other renewable energy production follows a decrease in the electricity price. The reason is the relatively lower marginal cost of these forms of production in accordance with the so-called merit order effect, MOE. However, there is a risk that electricity producers exercise market power, that is, actively making strategic decisions for the benefit of the firm at the expense of public welfare. This can result in an increase in market price and a counteraction of the MOE. Recent evidence suggests that abuse of market power not only happens in theory but occurs on a regular basis. Up until April 2023, the Swedish Energy Market Inspectorate, Ei, had reported three cases of potential market manipulation to Sweden's financial crime unit. Meanwhile, Denmark's energy regulator reported a Danish power producer for breach of insider trading rules (Montel, 2023).

In this thesis, we examine whether diversified electricity producers counteract the merit order effect through 'strategic capacity withholding,' which means that an electricity producer actively withholds some of its production capacity with the aim of increasing the market price. More precisely, we will investigate the prevalence of strategic capacity withholding through unplanned production failures that are announced as market messages to the electricity exchange Nord Pool in relation to the supply of wind power to the market. We pose the following research question:

How does the output of wind power plants affect a diversified electricity producer's decision to strategically withhold capacity by reporting an unplanned production failure through a UMM for their marginally more expensive means of production, thus counteracting the merit order effect?

This thesis will be outlined as follows: In section two, we provide a background of the electricity market, Nord Pool, and its functioning, and in section three, a literature review with an overview of previous research that is relevant to this study. In section four, we present the economic rationale and an example of capacity withholding. In section five, we present the research question and hypotheses, and in section six, we provide a description of the data used in this thesis. In section seven, we outline the empirical strategy, after which we present the results in section eight. In section nine, we discuss the implications of the results and limitations of the study. Finally, in section ten, we present a conclusion.

2. Background

In this section, we provide a background about the Swedish electricity market and the functioning of the power exchange Nord Pool. We then provide an account of the renewable energy production and characteristics that make electricity markets susceptible to market power.

2.1 The Swedish Electricity Market

The cornerstone of the Swedish electricity market is the high-voltage transmission network operated and owned by the electricity network monopoly Svenska kraftnät, Svk. Being responsible for the electricity distribution in Sweden, Svk's most important role is to ensure a short-term balance between production and consumption in the electricity grid, as well as facilitate the exchange of electricity to neighboring countries. Maintaining a balance with a constant grid frequency of 50 Hz is an ongoing process and a prerequisite for the functioning of the electricity system, which requires a safe and stable supply of electricity every day of the year. The balancing process also involves steps before and after the operational moment, where several electricity producers act as balance responsible parties, BRPs, for their own production or others.' In this crucial part of the process, BRPs make hourly plans for future production and consumption 24 hours a day. These plans are sent to Svk one hour before the operational moment. To actually get into balance, BRPs continuously sell and buy production. (Svenska kraftnät, 2021a & 2023a).

In 1996 Swedish politicians decided to deregulate the electricity market and merge it with the Norwegian power exchange Nord Pool. From this year forward, all electricity produced and traded in Sweden would be exposed to competition on the public market. Following the reform wave that prevailed in Europe, more countries joined and created what today can be called an internal common electricity market (Energimarknadsinspektionen, 2023). The reason for joining a European power exchange was twofold. First, the Swedish power sector had to be made more efficient, especially with regard to the transmission network, sales activities, and to address market concentration following a wave of consolidations. Second, there were several signs of over-investments made during the early 1990s, resulting in an excess supply of electricity in Sweden (Svenska kraftnät, 2021b).

Today, there is trade in both physical and financial electricity. The Swedish electricity market is interconnected with 15 other markets, and large amounts of energy flow through the interconnected power grids. The market is partly deregulated with regard to electricity trading and partly regulated with regard to transmission, governed by Svk. Sweden is a net exporter of electricity for almost the whole year but a net importer of electricity during a few cold winter days (Svenska kraftnät, 2023b).

Since 2011, the Swedish electricity market has been divided into four bidding areas, ranging from north to south. The reason was to account for regional imbalances between production and consumption due to local bottlenecks and a lack of capacity in the old transmission network, built in the 1950s and 1960s. The boundaries of the electricity areas are located where physical constraints limit how much electricity can flow in the transmission network, that is, where there is congestion. The most important implication of the division into electricity areas is that regional prices between areas can vary, something that has led to a lively debate in Sweden. The major driving cause for occurring price differences is that there is more relatively cheap electricity production in the northern parts of Sweden, mainly hydropower (Energimarknadsinspektionen, 2023). Building on this, as Tangerås and Holmberg (2022) write in their report on behalf of the Swedish Riksbank, a purpose of the electricity areas is that different price levels highlight where there is a surplus or deficit, thereby improving the efficiency of the power supply. Any price difference between the two areas is then reduced until flows of electricity match the specified capacity in the transmission network.

2.2 The Functioning of Nord Pool

As mentioned above, Swedish electricity is publicly traded on Nord Pool, a power exchange that offers trading, clearing, settlement, and other services. Nord Pool connects 16 European countries and more than 360 companies. In 2021 a total of 963 TWh of power was traded on this marketplace. There are two primary markets on Nord Pool. On the day-ahead market, trading companies and electricity-intensive industries can buy electricity directly from producers for the next 24 hours every day of the year. Potential buyers of electricity supply bids on how much they are willing to consume at different price levels for every hour of the coming day, while producers specify how much electricity they are willing to sell. Submissions are aggregated in a supply curve where cheaper bids come before more expensive ones, and in an aggregated demand curve, respectively. Before 12 PM, orders are matched in closed auctions with regard to welfare utilization and constraints in the transmission networks. At 1 PM, the resulting intersection for different hours becomes the so-called day-ahead price, or the spot price, a unique area price for each electricity area. The area price represents both the price that consumers are willing to pay for the last kWh of power required to satisfy demand and the last kWh that is produced from the most expensive production source employed to balance the system in the price area (Nord Pool, 2023b).

If conditions change and new information reaches the market, for example, changes in weather forecasts or unplanned production failures, market participants are able to balance their former predictions on the intraday market. Compared to the day-ahead market, the intraday market is similar to a stock market where trading is continuous. It opens two hours after the closing of the day-ahead market, and it closes 60 minutes before the actual operating hour (Nord Pool, 2023a).

A final, important feature of Nord Pool is the REMIT service, meaning Regulation on Wholesale Energy Market Integrity and Transparency. REMIT is a regulatory reporting tool that market participants use to notify the market about expected or unexpected changes to production, consumption, and transmission in order to comply with European regulations. This is actualized through the issuing of Urgent Market Messages, UMMs. Only if a power plant's installed capacity exceeds 100 MW is the responsible market participant required to issue a UMM, in case of a production failure (Nord Pool, 2023c).

2.3 Renewable Energy in the Electricity Market

The Swedish Electricity Mix

Up until the 1990s, when the expansion of renewable energy production started in Sweden, the Swedish electricity market was dominated by hydropower, nuclear power, and some fossil-based thermal power. Today, as shown in Illustration 1 below, almost 98 percent of the electricity produced in Sweden is fossil-free. Hydropower still accounts for the largest share, with 35 to 40 percent of the electricity mix, while nuclear production constitutes around 30 percent. The third largest share, and the share that is also increasing the most, is wind power production, with a current share of 18 to 20 percent. The remaining production methods are mainly fossil-based thermal power and a small but growing share of solar energy.

While solar energy and wind power production come from renewable sources, they are dependent on weather, how much sun there is, and if there is enough wind. Thus, other power sources, such as nuclear and fossil-based thermal power, constitute an important power reserve since their production is possible to plan.

Hydropower is both renewable and adjustable due to the possibility for a producer to choose how much water from the reservoir should be released in production. Producing electricity using hydropower can therefore cover up for fluctuations in other production methods, but water reservoirs are still dependent on an inflow of water from precipitation (Energiföretagen, 2023b).

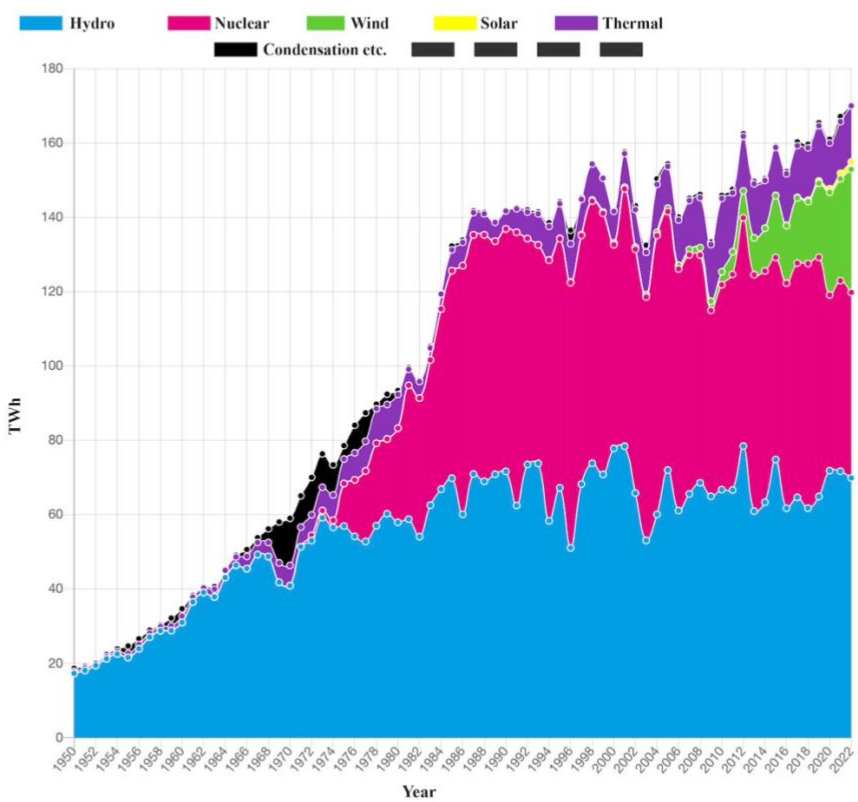

Illustration 1: Sweden's electricity production mix (*Energiföretagen, 2023b*)

The Merit Order Effect

An important mechanism that is relevant to this thesis is the merit order effect, MOE. It depicts price formation in electricity markets in the short term. Aggregate supply is illustrated as the 'merit order curve': a stepped curve that goes from the least expensive production unit, in terms of marginal costs, to the most expensive one. As shown in Figure 2 below, each production method is illustrated as a step that represents the costs and capacities of all generators for a given production type. The broader the step is on the horizontal axis, the higher the aggregate capacity for the specific production method, and the higher the intersection with the vertical axis, the higher the marginal cost of production. The merit order, which is based on marginal costs, is what determines which power is supplied to the market, where the marginally cheapest form of production is the first to be called upon, followed by order of rising costs, and thus also rising prices, until demand is met. The last unit of electricity supplied to the market is also what determines the market price (Krohn et al., 2009).

An illustrative example: baseload production is often used to meet a country's continuous demand for energy as a result of its low marginal costs. Examples of baseload technologies are hydropower and nuclear power, of which both are marginally cheaper than thermal power, which requires an input of relatively more expensive fuels, and therefore they enter the supply curve at a lower level, as seen in Illustration 2 below.

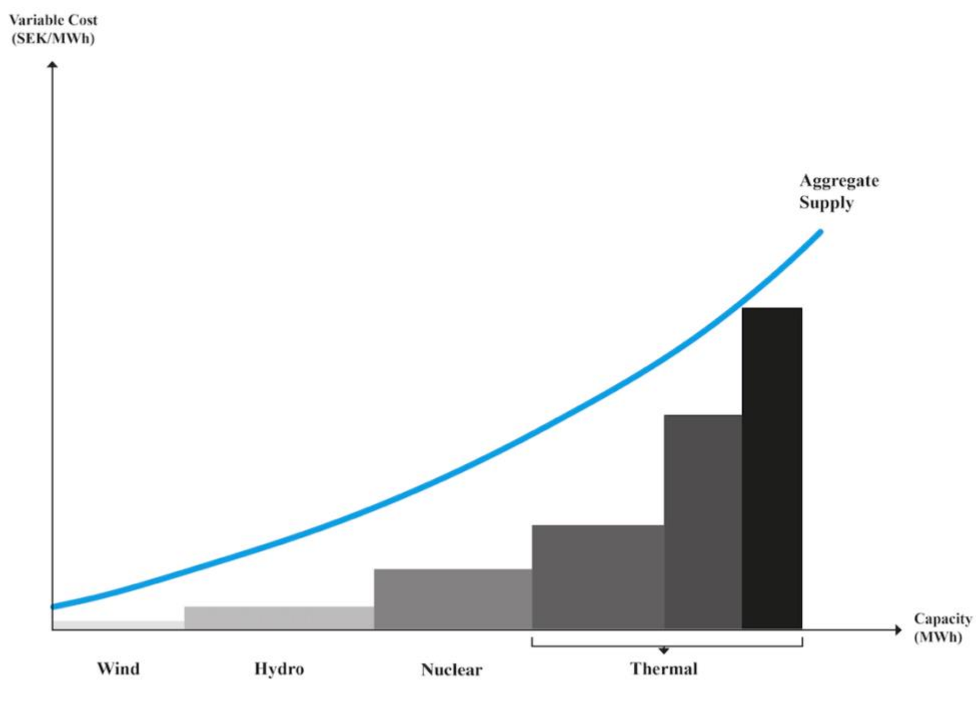

Illustration 2: Authors' own

In theory, the electricity market price should decrease in the long term with a higher share of renewable electricity production because production that is marginally cheaper is offered first, according to MOE. Demand for electricity is almost unchanged regardless of price in the short-term for the reason that it is a necessity for the functioning of society and is therefore said to be inelastic. Due to the inelasticity of demand**,** small changes in electricity supply can result in major price changes.

Wind power production can influence prices in the power market in two ways. First, since wind power has no fuel costs, it has a low marginal cost and therefore enters the bottom of the merit order curve, causing a right-ward shift due to the increased supply. Due to the price inelasticity of demand, this mechanism should result in a lower electricity price. Second, congestion in the transmission system might lead to a separation of a supply area, causing an excess supply of electricity within the area that is now being isolated. Since it is not economically, environmentally, or technologically ideal to reduce wind power generation, conventional production sources might have to reduce production, which could also lower the electricity market price in order to meet the potential excess supply of power (Krohn et al., 2009).

Finally, even if the MOE is a widespread framework, there is criticism. First, it only depicts price formation in the short term as it only considers marginal costs. Second, to capture any long-term development of prices, one would need to include fixed operational costs since no producer will invest in additional power plants if the production that is sold only covers marginal costs. Lastly, the MOE does not take into account factors such as the expansion, deployment, or decommissioning of production plants (Next Kraftwerke, 2023).

2.4 Susceptibility to Market Power

One of the reasons why electricity markets in Europe were deregulated and united in a common market, Nord Pool, was to improve the overall functioning of the market and to avoid any abuse that could occur following a wave of consolidations of electricity producers. However, due to the current characteristics of the electricity market in general and of the Nord Pool exchange in particular, there are still opportunities for participants to exercise market power, in other words, improper exploitation of a firm's market position. Electricity is a homogeneous good, and it is not possible to single out from where certain units are produced. The difference between planned and unplanned ways of producing electricity and the need for expanding and renewing the old transmission network are other features that could create possibilities for exercising market power. Furthermore, due to the mere size of certain market participants, of which some firms control plants in multiple countries, one could argue that with the existence of large electricity producers, there is a susceptibility to market power.

Holmberg and Tangerås (2022) relate resource shortage to market power. If there is not enough local production or capacity in the transmission network in order to meet local demand, there will not be a 'price-cross' on the day ahead market, where aggregate supply and demand intersect. If there is no available power reserve, there is a rationing of electricity where customers must share the available capacity, and the market price is set at a maximum, which is 4000 EUR / MWh (Nord Pool, 2022). However, according to Holmberg and Tangerås, situations with extreme prices are necessary for electricity producers to obtain coverage for their capital costs.

The uniform pricing rule is another feature of Nord Pool that could lead to market abuse. This rule says that the price for all dispatched units is set by the highest-priced dispatched supply bid, the marginal bid. The price that all supplying firms receive is set by the producer that supplies the last dispatched unit of electricity, and all firms whose supply is needed to meet total demand can be said to face a residual demand curve. The important point is that the firm that supplies the last unit of electricity can be seen as a monopolist that sets the price for all participants. Following this rule, a multi-unit generator can achieve a higher market price in two ways. First, it can keep away some of its production from the market by bidding less of its marginally cheaper capacity through physical withholding. Second, a multi-unit generator can bid all of its production above marginal costs, that is, engaging in economic withholding. These strategies decrease aggregate supply, which in turn leads to an increase in the market clearing price if demand is assumed to be constant (Fogelberg and Lazarczyk, 2019, Wolfram, 1999).

On the other hand, there are also traits in the Nordic market that could hinder the exercise of market power. These traits include a healthy business climate, sound values, and a low degree of corruption (Transparency International, 2022). In the case of Sweden, there is also an authority, the Swedish Energy Markets Inspectorate (Ei), that monitors the Swedish energy market in order to uphold transparency and prevent market abuse.

3. Literature Review and Theory

The literature on energy markets and renewable energy sources, in particular, is extensive and growing. In the following sections, we will outline relevant literature, both theoretical and empirical, with regard to our research.

3.1 Market Power

The extensive yet essential matter of market power has been examined by several researchers, all with different approaches. Joskow and Khan (2002) examine price behavior in the wholesale electricity market in California in the year 2000 when the Californian wholesale electricity market faced a sudden but significant increase in electricity prices. The authors conclude that electricity prices exceeded competitive levels due to a significant gap between their calculated benchmark prices and actual prices. Thus, Joskow and Khan find evidence that suppliers withheld supply and exercised some degree of market power.

Tangerås and Mauritzen (2018) examine hydro market power where they analyze the link between real-time and day-ahead competition in a hydro-based wholesale electricity market before and after a major change in the division of electricity areas in Sweden. They look at imperfect competition and analyze aggregate supply and demand, equilibrium prices, and hydro output. Their results indicate that firms exercised some degree of market power on a local level.

Bask et al. (2011) examine whether market participants on Nord Pool have had market power and how it has evolved between 1996–2004, using the Bresnahan-Lau method of weekly data. They get small but statistically significant results and find that electricity suppliers have had market power, but it has decreased as the Nord Pool market has expanded.

3.2 Strategic Withholding

In the electricity markets, market power may be exercised through strategic withholding. Kwoka and Sabodash (2011) analyze conditions that gave rise to unusually high prices during a short period in New York in 2001 and develop an empirical approach for distinguishing between price spikes caused by the abnormal behavior of suppliers and those that are caused by normal supply and demand. They look at unilateral withholding, a kind of strategic withholding where an electricity producer refuses to bid some of its output in order to raise the price so that the remaining output earns more than the loss on the quantity that is being withheld. Kwoka and Sabodash find evidence of abnormal bidding behavior and show that when demand presses on available fixed supply, unilateral withholding can be profitable.

Fogelberg and Lazarczyk (2019) investigate the occurrence of capacity withholding disguised as production failures using an instrumental variable approach and show that marginal producers in the Swedish electricity market in part base their decisions to report a production failure on daily spot prices, put differently, the price that electricity companies pay for electricity, thus indicating that some strategic withholding exists. Their data set permits the examination of how market prices affect the decision about issuing urgent market messages in case of production failures and how it varies by generator type. Their results indicate that, on an aggregate level, a 1 EUR increase in price is associated with a 1.3 percent increase in the number of issued UMMs. They found no significant results of spot prices on the number of reported failures for the baseload technologies, nuclear and hydro.

Similar to Fogelberg and Lazarczyk, Patrick and Wolak (2001) study the strategic use of capacity availability declarations from two national operators in England and Wales. These declarations are used to compute the expected reserve margin for each load period. The strategic use of the declarations is a kind of market power activity, and Patrick and Wolak find that the two national operators earned revenues above their cost of production for shorter periods. They set available capacity and prices to yield prices in excess of the marginal cost.

Wolfram (1999) also investigates the electricity markets in England and Wales. She estimates duopoly power and considers price-cost markups to evaluate outcomes in the combined spot market. Wolfram finds that generating firms appeared to alter their pricing behavior in response to actions taken by the regulator, such as price caps.

3.3.1 Merit Order Effect

Scholars have studied and confirmed the existence of the MOE in several markets, that is, that prices of electricity in deregulated markets decrease with an increase in wind power capacity or other renewable energy sources. Pereira and Saraiva (2013) examine the Iberian power market, specifically Portugal and Spain, and the subsequent impact of an increase in the number of wind farms. Using a system dynamics-based model, they estimate the evolution of the electricity market price based on different shares of installed wind power capacity. Their results indicate that an increase in wind power capacity of 25 percent should lead to a reduction of around 4.5 EUR / MWh in both Portugal and Spain.

Sensfuss et al. (2008) explore the price effect of renewable energy generation on the German market and find that there is a considerable reduction in price: for 2006, the unweighted average reduction in price reached 7.8 EUR / MWh. Moreover, they found two driving factors for the merit order effect. The first one regards the growing renewable electricity penetration, and the second one regards the volatility of fuel prices, of which gas price is the most important factor.

In a rather novel study, Tselika (2022) confirms that the merit order effect occurs in both Denmark and Germany using a panel approach with hourly data to account for hourly-specific effects. She examines the impact of renewable generation on the distribution variability of electricity prices and finds that both solar and wind energy have diverse effects on the distribution of electricity prices, where wind generation reduces price variability for high demand levels and increases price variability for lower and intermediate demand levels.

Finally, Würzburg et al. (2013) present an overview of past research results on the effect of renewable energy on price. They find that the size of the merit order effect varies depending on region and assessment method, but they also identify common patterns and trends in terms of this effect. However, their research does not cover what causes lay behind the price effect. Würzburg et al., therefore, write that further research could include patterns of peak hours and fuel costs as potential causes.

3.3.2 Counteraction of the Merit Order Effect

Despite the fact that there are several studies confirming the negative impact of increasing renewable energy capacity on energy prices through the merit order effect, there is literature that claims the opposite. Ben-Moshe and Rubin (2015) study an oligopoly market, and account for the reality that generating firms may have both conventional power sources as well as wind power. In their numerical example, they explore whether an increase in the penetration rate of wind power will bring market prices down, as shown by a number of researchers. Their results indicate that when diversified producers own most of the wind power capacity, prices may increase with a high renewable energy penetration rate. In their numerical study of five diversified producers, Ben-Moshe and Rubin show that market prices can increase if a producer owns more than 60 percent of the wind power capacity in a certain region.

In a paper from 2017, Acemoglu et al. relate to the research conducted by Ben-Moshe and Rubin when studying the effects of the diversification of energy portfolios on the merit order effect in an oligopolistic energy market. Acemoglu et al. show that producers with a diversified energy portfolio, that is, a market participant controlling some or all of the renewable energy production within a certain region as well as other means of production such as thermal, strategically reduce conventional energy supplies to offset the price declines due to the merit order effect. This is the case when the renewable energy supply is high, and the consequence is a complete or partial neutralization of the merit order effect. Acemoglu et al. emphasize that for this reason, diversified energy portfolios could be welfare-reducing, as they may help to maintain higher prices.

3.4 Our Contribution

As studied in the review of previous literature, several different papers have established that electricity producers possess and exercise market power in different forms when provided with the opportunity. A common method of doing so which has been addressed in previous studies, is through capacity withholding, either by refusing to bid on some available capacity or by declaring capacity unavailable. Further, as the existence of the merit order effect has been proven by researchers investigating an array of different markets, there is also evidence of a conscious counteraction of the same effect in order to maintain a relatively higher price level.

While one can conclude that the exercising of market power and strategic behavior is related to the merit order and its counteraction, the exact nature of the relationship between these fields of research and the incentives guiding the actions of suppliers is not yet determined. Thus, with special consideration to the study of capacity withholding through production failures in the Swedish electricity market by Fogelberg and Lazarczyk (2019) and the study concerning diversified producers' action to counteract the merit order by Acemoglu et al. (2017), we intend to investigate if the mechanism by which the merit order is counteracted is through production failures, specifically. That is, whether the incentive to withhold capacity through production failures is motivated by an increased supply of wind power and, subsequently, whether such withholding strategies are motivated by an intention to counteract the price-decreasing effect of the merit order. In doing so, we hope to contribute to a more holistic understanding of supply-side strategic behavior in the electricity market.

4. Economic Rationale for Withholding Capacity

In this section, we will further explain the rationale for engaging in strategic withholding of capacity from an economic perspective, and specifically, we will address capacity withholding through production failures. We will do so using a graphical example supported by previous research and a closer description of the price-determining mechanisms of Nord Pool.

4.1 Withholding Capacity through Production Failures

The exercise of market power and supply-side strategic behavior in the electricity market may occur in different forms, either through economic withholding or through physical withholding, but the common incentive of doing so is to increase company profits. A prerequisite for capacity withholding, in general, is the inelasticity of demand. This means that demand is almost always constant, and fluctuations are rare. An implication of this is that small changes in electricity supply can result in major price changes. A particular form of physical withholding, capacity withholding through production failures, which was studied by Fogelberg and Lazarczyk (2019), suggests that instead of a producer refraining from bidding all of its available capacity – which may openly be identified as exercising market power – the producer decides to report an unplanned production failure through a UMM for some generating unit which allows the producer to withdraw its production from the market. The result is virtually the same, the producer keeps some production away from the market, thus tightening supply and subsequently increasing the market price, but it is not recognized as manipulative because the producer announced the reason to be some sort of production failure. This form of physical withholding is sensible as we assume that it lies in the interest of all market participants to conceal strategic behavior, and this practice allows them to claim that they are providing their best effort in delivering electricity under the current situation. Since this form of strategic behavior has only been occasionally investigated and due to the difficulty in proving it, we have identified it as a particularly interesting topic to study further.

4.2 An Example of Capacity Withholding through Reporting a Production Failure

Consider a scenario in an arbitrary electricity day-ahead market as depicted below in Illustration 3. The horizontal axis shows the quantity of electricity demanded by the market measured in MWh. The vertical axis shows the variable cost of supplying one additional unit of electricity in SEK per MWh. The demand curve is represented by curve *D*, and the supply curve is represented by the stepped merit order curve, with one step per fuel type. In this scenario, demand is such that in order for the producers to satisfy demand, all wind power production, all hydropower production, and almost all nuclear power production need to be utilized, as shown by the intersection between *D* and the merit order curve, the so-called 'price cross.' Demand is not yet such that thermal production is required to start, and thus, the last unit of electricity sold in this market setting is produced by nuclear power, and it follows that the market clearing price, the price received for each unit of electricity sold in the market, is determined by the variable cost of nuclear power production. Further, this will continue to be the case as long as no shocks sufficiently large to change variable cost levels at the intersection of the demand and supply curves occur, either to the aggregate of supply or to the aggregate of demand.

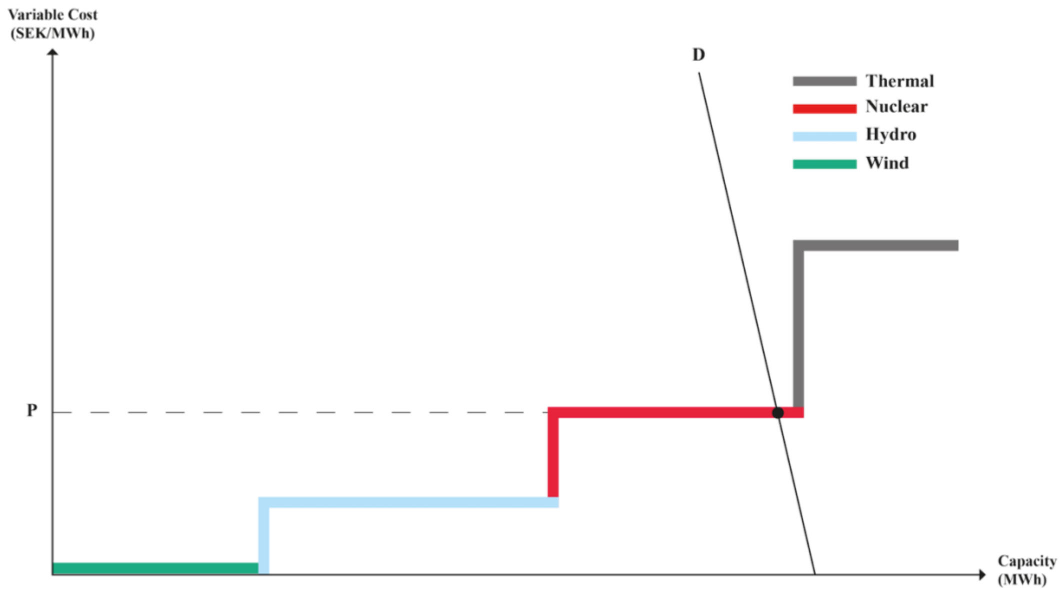

Illustration 3: Authors' own, inspired by Forrest & MacGill (2013)

Now, consider an arbitrary electricity producer in the same market who owns both wind power production and hydropower production. This producer knows that a small shock to the current supply of electricity, reducing either the supply of wind, hydro, or nuclear power, would cause an inward shift of the supply curve. The producer identifies that this would, in turn, cause a need for thermal fuel production to start operating as nuclear power production is already operating at near maximum capacity, setting a new higher market clearing price due to the inelasticity of demand. The producer firm thus decides to withhold part of its hydropower capacity from the market, shifting the quantity of hydropower supplied from Q_1 to Q_2 (Illustration 4) by reporting an unplanned production failure in one of their generators. This reduction of capacity implies that wind, hydro, and nuclear power production in the market is no longer sufficient to meet demand, and thus thermal production is activated. The market clearing price is now determined by the relatively higher variable cost of thermal production, shifting the price level from P_1 to P_2.

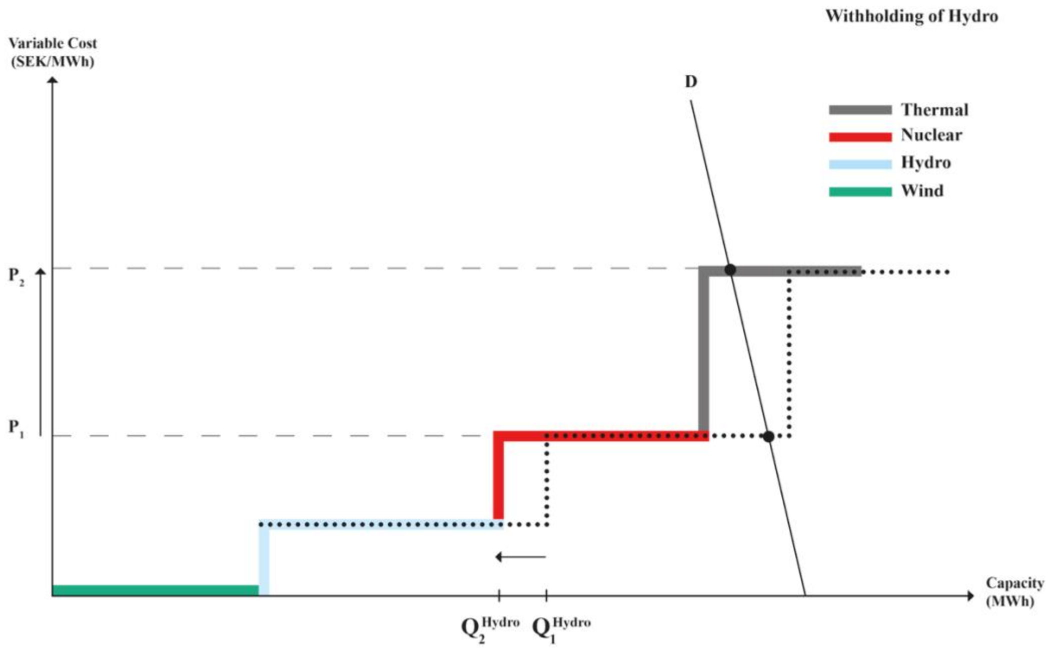

Illustration 4: Authors' own, inspired by Forrest & MacGill (2013)

From an economic, profit-maximizing perspective, this decision is rational as long as the increased profit received from the plants still providing electricity to the market following the price increase is greater than the loss of profit incurred from reducing the overall capacity provided. This can also be shown numerically. If we assume that the producer owns 1000 MW of total capacity and that the price at P_1 is 400 SEK / MWh, the producer receives revenues of 400 000 SEK. We assume that the producer needs to withhold 100 MW in order to achieve the change in price from P_1 to P_2. It thus follows that P_2 would have to be at least 444.44 SEK / MWh in order for the producer to receive the same revenue as under the initial state of the market.

4.3 Incentive to Withhold Capacity in Relation to Wind Power Production

As discussed in previous sections, it follows from the MOE that the supply of wind power production is the first to be used in a market, following from its virtually zero marginal cost. As is also previously discussed, the price-determining mechanism of Nord Pool, in essence, a uniform price auction granting the same price to all producers, implies that it is the price of the last unit of electricity dispatched which determines the market price. These two factors combined imply that as the share of electricity supplied by wind power increases, either through an increase in plants or through increased output of existing plants, the supply curve shifts outwards, and the last unit of electricity supplied will be supplied by a production unit occupying a lower step of the merit order curve. This is the essence of the MOE. However, as shown numerically by Acemoglu et al. (2017), an increased share of supply coming from wind power production causes an incentive among diversified producers to withhold some of their other production in order to counteract the MOE. The rationale is similar to what has been explained in our example above. Doing so will cause the market price to be determined by production occupying the higher end of the merit order curve, increasing total profits. The reason why wind power is not the production being withheld also stems from profit maximization, as its low marginal cost implies higher profits for all prices relative to all other means of production, and thus it should be dispatched under the vast majority of market conditions (Forrest and MacGill, 2013). With the same logic, it should not only be the output of a firm's own wind power production which affects the decision to withhold capacity – but the aggregate of the market, as an increase in the wind power output of a competitor will have the same decreasing effect on the market price. In this context, however, it is important to recognize that information asymmetry concerning the anticipated production and bidding strategies of other firms may diminish the willingness to engage in strategic behavior based on the output of others.

5. Research Question and Hypotheses

With regard to the economic rationale of withholding capacity through production failures which we have presented, and the effect of wind power on the incentive to engage in withholding strategies, we seek to investigate whether capacity withholding through production failures is the mechanism with which the MOE is counteracted. In order to do so, we have formulated the following research question and hypotheses:

Research Question

How does the output of wind power plants affect a diversified electricity producer's decision to strategically withhold capacity in the Swedish market by reporting an unplanned production failure through a UMM for their marginally more expensive means of production, thus counteracting the merit order effect?

Hypothesis 1

An increase in the output of wind power plants owned by a diversified electricity producer increases the likelihood of the same producer to strategically withhold capacity in the Swedish market by reporting an unplanned production failure through a UMM for its marginally more expensive production, thus counteracting the merit order effect.

Hypothesis 2

An increase in the output of all wind power plants in Sweden, excluding a producer's own wind power plants, increases the same producer's likelihood to strategically withhold capacity in the Swedish market by reporting an unplanned production failure through a UMM for its marginally more expensive means of production, thus counteracting the merit order effect.

6. Data

In the following section, we will describe the data used in our thesis, how it was retrieved, and the constraints applied to the data collection with regard to the research scope and availability of appropriate data. Summary statistics of all data are available in appendices A and B.

6.1 Input Data Selection

Time Span

In determining the time span of the data used in this thesis, the number of observations of each variable on a yearly basis has been a more significant factor than the theoretical arguments for limiting ourselves from including additional years. The majority of the variables which we use in our estimation of wind power production or in our regressions are observations made on an hourly basis for each day of the year for several different locations, implying that each additional year included in our study gives rise to a substantial increase in additional data points. However, the response variable in this study, the number of dispatched urgent market messages announcing an unplanned production failure from one of the diversified producers, which we include in our study, is scarcer. Following this, we have decided to use data covering 2020/01/01–2022/11/15 in order to ensure a satisfactory number of observations and to keep the data set at a workable size. The cut-off date is chosen based on the availability of local wind speed data, specifically. With these specifications, we have a total of 25 200 hours observed in this study.

Electricity Producers

The main scope of interest in this thesis consists of electricity producers that are diversified, which we define as owning both wind power plants and some other form of power plant, either thermal (including gas, coal, oil, and biomass-fueled plants), hydro, or nuclear plants. These plants must have an installed capacity of at least 100 MW in order to be obliged to report UMMs in case of a production outage according to the rules of Nord Pool, as previously stated. It should be mentioned that many producers might not own any wind power plants or other power plants with a capacity exceeding 100 MW, even though they could control the output of such facilities through a balance responsibility agreement, BRA. These agreements apply between Svenska kraftnät and a given producer, which becomes the BRP of the facility, and thus also becomes the party trading the electricity produced. However, as conclusive information concerning BRPs is not publicly available, our set of diversified producers becomes dependent on ownership (Svenska kraftnät, 2023c).

Through open-source data that can be accessed from the Swedish Energy Agency, we retrieved information about all firms in Sweden that own wind power production (Energimyndigheten, 2023). The wind power plant ownership data was then cross-checked with all market participants that published UMMs on REMIT Nord Pool regarding production failures concerning thermal, hydro, or nuclear production. From this, we created a unique set of diversified producers that fulfills our requirements in the Swedish market, and which consists of Vattenfall, Statkraft, and Fortum. Further, we assess that these producers also have a sufficient degree of market power in order to actually have the capability to successfully engage in strategic capacity withholding in the electricity market, given the total installed capacity of their production units in the Nordics, as shown in Table 1. The raw data set used in our research is structured as one coherent set of panel data with the same number of hourly observations for each of the diversified producers included.

Additionally, as we are interested in the aggregate of wind power production in the Swedish market, we also identified two additional firms, Jämtkraft and Skellefteå Kraft, which do not fulfill our requirements to be included in the set of diversified producers but own several wind power production facilities of considerable capacity. The reason is that we want our constructed variable for market production to incorporate a greater share of the actual production. The estimated wind power output of these two firms is included in our coming calculations of the total wind power output in the market but is otherwise not observed.

The six largest electricity producers in the Nordics, Production, TWh					
	2004	2008	2012	2016	2020
Vattenfall	70,9	73,5	76,6	65,8	64,7
Statkraft	26,2	41,9	49,2	45,9	54,9
Fortum	50,7	49,9	47,4	43,4	43,9
Uniper (Sydkraft)				23,7	21,3
Skellefteå Kraft	3,5	3,8	4,2	4,1	3,9
E.ON	34	30,2	28,4	1,3	
Sum	185,3	199,3	205,8	184,2	188,7
Share of total	48,9%	50,1%	50,6%	46,6%	45,7%
Total production	379,2	397,5	406,4	395,6	413,1

Table 1: Authors' own, created with data from Energiföretagen (2023a)

6.2 The UMM Data

We retrieved data of UMMs issued for our defined time span on Nord Pool's site *REMIT*. Given the prevailing regulations with regard to the obligations to report failures and our set of diversified producers, all of them are required to report unplanned production failures through this system for generating units with an installed capacity exceeding 100 MW.

In order to find the UMMs that are relevant for this study, we filtered UMMs issued during the time period to include all messages announcing unplanned production failures for all production units except wind power plants in the four Swedish electricity areas. This means that we excluded messages pertaining to transmission failures and consumption failures as these are not reported by the electricity producers, nor are they able to influence their occurrence. We also excluded planned production failures that were known in advance, for instance, due to planned maintenance, as these are already known by the market, and thus their effect on the market clearing price will already have been accounted for. In total, 897 UMMs were retrieved for the time period and then manually cleansed with regard to the duration of the failure given our definition of a strategic failure, further explained in section 7.1, and ownership of the facility as we are only interested in UMMs dispatched by our set of diversified firms. This resulted in a final set of 570 UMMs dispatched by our identified set of diversified producers during the chosen time period.

Ideally, the UMMs should also have been sorted by messages announcing a new failure or messages prolonging an existing failure, following the results of Fogelberg and Lazarczyk (2019), which showed that electricity producers put more emphasis on the prolongation of existing outages compared to strategically timing them or announcing them for the first time. However, REMIT does not enable sorting on new outages and prolongation of existing ones but rather merges and updates the message with any additional information submitted. It would be possible to retrieve this information directly from Nord Pool's File Transfer Protocol server, FTP, but the raw data on UMMs which is uploaded there is not sorted by countries nor by type of UMM but includes all messages for all participating markets amounting to more than 300 000 separate text files per year, requiring significant computing power to process and which lies beyond the scope of this study. This is also the reason why the UMMs in our study were retrieved directly from REMIT and not from Nord Pool's FTP server.

6.3 The Wind Speed and Wind Power Plant Data

Given our research question, data on the wind power production output of individual firms and of the market in Sweden are essential to our study. However, this data is not available at the plant level but only on an aggregate price-area level for all producers in the area, and thus we were required to construct a variable that captures this output in order to identify the change in output of our set of diversified firms. This could be done through estimation using power curves and different equations from the field of engineering, as those presented by Lydia et al. (2014). However, their method requires extensive data on the technical specifications of each individual plant and of local weather, making it inappropriate for this study as our primary interest is not the exact precision of our estimate of wind power production but rather the effect of increasing output. Therefore, instead of performing such an estimation, we constructed a proxy for wind power production, with general specifications of wind turbines and data which are directly related to the wind power output and available on a plant level. In doing so, we used local wind speed data, which is strictly exogenous, and wind farm-specific capacity data.

Initially, we identified 21 wind farms owned by our set of diversified firms and by the two additional large wind power producers, Jämtkraft and Skellefteå Kraft, which were included to increase the share of the total market which we proxy for in the methodology section. We then cross-checked the total capacity for each wind farm through the producers' own websites, what was given on the market intelligence service company The Wind Power, and what was provided to the Swedish Energy Agency. From these sources, we were also able to check the commissioning dates to ensure the operability and to verify that the capacity of each wind farm remained constant for the entire time span of our study, thus providing us with a single consistent capacity value for each wind farm. Then, we retrieved the exact coordinates for each wind farm, again from The Wind Power, but as these coordinates do not coincide perfectly with weather stations, the rule of proximity had to be used. Therefore, wind farms were matched with the closest weather station given by SMHI. Finally, for each of these identified weather stations, historical meteorological observations on hourly wind speeds for our time span were extracted and combined in a single data set.

6.4 Forecasted Consumption and Electricity Spot Price Data

Market factors, specifically the electricity spot price of the day-ahead market on Nord Pool and consumption, affect the incentive to engage in strategic withholding, as explained in previous sections of this thesis. Hence, we need to include this data in order to be able to control for their respective influence on a producer's eventual decision to withhold capacity.

Forecasted hourly consumption in Sweden is supplied by Svenska kraftnät but retrieved from Nord Pool and is based on the BRPs' prognosis of the amount of electricity in MW which will be consumed on an hourly basis in each electricity area (Svenska kraftnät, 2023b). Typically, these forecasts exhibit great precision and are close to realized consumption, following the relatively predictable demand, as exhibited in Figure 5 below. An important characteristic of this data is its cyclicality stemming from the changing of the seasons and the increase in electricity consumption during the cold months due to the increased need for heating, as also can be seen graphically when comparing Figure 5 and Figure 7. This further suggests that including this data also provides a control for any effects of seasonality on supply-side strategic behavior.

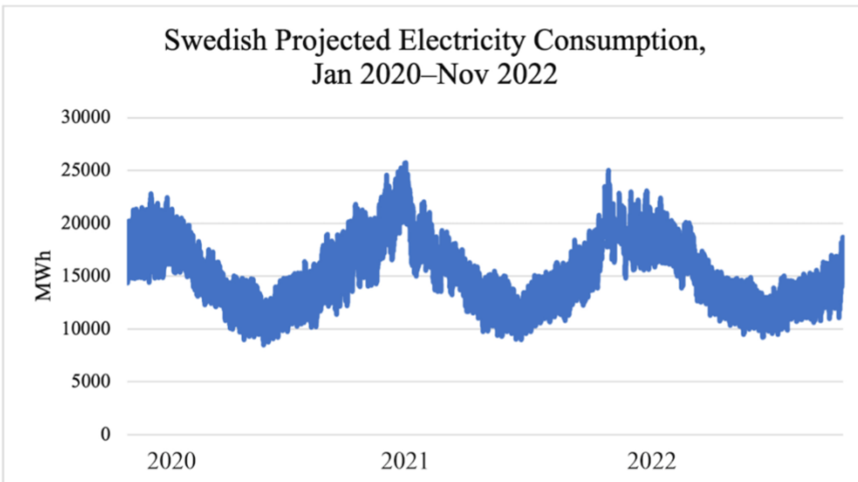

Figure 5: Authors' own, created with Nord Pool data

The hourly electricity spot price data for each electricity area was retrieved from the Nord Pool FTP server. The relevance of price on the incentive to withhold capacity has been established in previous literature and in our theory section, both due to its direct effect on the decision to withhold capacity and through its correlation with other market factors which affect the same decision, such as congestion in the electricity grid. It follows that we want to remove this effect in order to arrive at an unbiased estimate of the effect of wind power production on the same incentive.

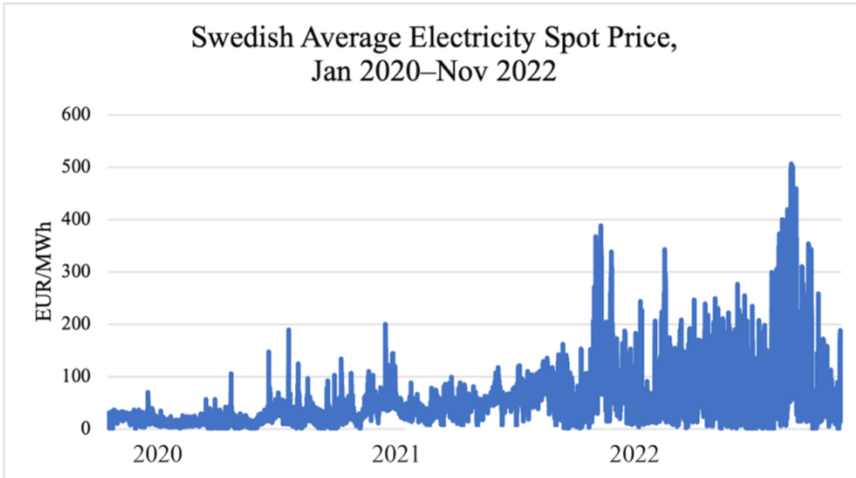

Figure 6: Authors' own, created with Nord Pool data

6.5 Weather Data

Changes in the weather are of great relevance for the electricity market, as renewable energy production such as hydro, wind, and solar are dependent on weather, and thus also supply, while demand is dependent on factors such as the need for heating. This especially holds true in Sweden, given the share of wind and hydropower production in the energy mix and a relatively cold climate. This implies that the weather affects the electricity spot price, and subsequently, this data becomes important as it will allow us to instrument for the price later in our methodology.

From a three-dimensional data set containing grid data for the entirety of Sweden, given by SMHI's PTHBV database, average precipitation levels and temperature on an aggregated Swedish level were retrieved using the programming language Python. The database is specialized in hydrological model calculations and contains the daily average of both temperature and precipitation levels rather than the hourly, as in the case of wind speed. The data is calculated using all available observations from SMHI's weather stations. Through geostatistical interpolation, observations are assigned to each of the grids in the database with consideration to factors such as topography, wind direction, and measurement losses of precipitation (SMHI, 2023). The temperature data is given in degrees Celsius, while the precipitation level data is presented in kg/m^2 – equivalent to millimeters. As this data provides the daily average, each hourly observation from the same day is attributed the same value of temperature and precipitation, respectively.

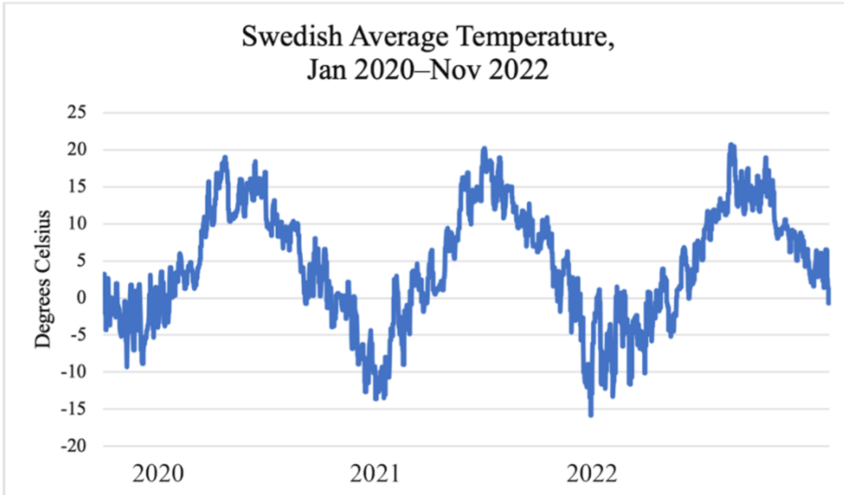

Figure 7: Authors own, created with SMHI data

6.6 Missing Values

There are several missing values in the wind speed and forecasted consumption raw data set. There are 3033 missing values in the data set on wind speeds across all examined wind farms, with no explanation provided but potentially due to technical failures of the weather stations. For the variable forecasted electricity consumption, there are 1755 missing values in daily clusters. Again, there is no explanation provided other than that the forecasts for those particular days are not available for downloading through Nord Pool, potentially, as there were no forecasts submitted. In terms of the wind speed values, the number of missing values is relatively small in relation to the total amount of observations of wind speed, 25 200 at 21 different locations. We assess that the loss of statistical power and the threat of distorted patterns is negligible. The number of missing values of forecasted consumption is a greater concern. While this could be addressed through interpolation or imputation, it is associated with a risk of uncertain estimates and wrongful assumptions concerning the distribution of the data being interpolated – especially given that forecasts respond to shocks and signals from both producers and consumers to the market, and that the lack of actual forecasts could follow from the uncertainty of day-ahead demand. Thus, we accept that these values are missing as well and subsequently remove the hourly observations with missing values from our regressions.

7. Empirical Strategy

In this section, we will present our empirical strategy and methodology. We will start by further describing our response variable as well as the method and reasoning behind the construction of our predictor variables. Then, we will present the first stage regression and the two different model specifications for the second stage regression before finally addressing our identifying assumptions.

7.1 The Response Variable

The response variable used in our methodology is *(failure)*, representing hourly count data of UMMs dispatched by our three diversified firms, which announces unplanned production failures. This variable includes failures of all generating units except wind power production plants, as it is the effect of these units' output on the incentive to withhold production which we are interested in, and as explained in section 4.3, it is assumed that it is not rational for a diversified firm to withhold wind power production from a strategic perspective.

The response variable is intended to capture strategic failures, that is, intentional shutdowns of production aimed at increasing the market price of electricity, reported as real production failures. In doing so, we assume that a strategic failure will have a duration between one hour and 24 hours. The reasoning is that a shorter failure would be unlikely to impact the market price of electricity, as it would be resolved before it influenced any predictions of the day-ahead production, and thus also, the electricity spot price. At the same time, a failure exceeding 24 hours would be longer than necessary to achieve an effect on the same price and would prevent the generating unit from generating profits for longer than is rational. Hence, we exclude failures shorter than one hour and longer than 24 hours.

7.2.1 The Predictor Variables

We will use two different predictors in our regressions in order to answer our research question. The first one is the aggregate hourly wind power production output of the individual firms, which we define as diversified and of interest, and which will help us test the first hypothesis. The second one is the aggregate hourly wind power production of the market, excluding the firm which is being observed, and which intends to help us test the second hypothesis.

7.2.2 Implementing a Proxy for Our Independent Variable Wind Power Production

In the construction of our proxy for wind power production, as previously mentioned, we will have to consider several factors and use both weather and technical data. First, we use hourly SMHI data for local wind speed (*speed*) for each of the municipalities where we have identified wind power production facilities owned by one of our diversified firms or by Jämtkraft and Skellefteå Kraft. This variable is strictly exogenous and has a clear causal relation to the output of wind power plants as it, by design, is the variable input that determines the output in MWh that a wind power plant produces (EWEA, 2016). However, in order to use this variable in making a reliable estimate of wind power production, we are required to make a few simplifying assumptions with regard to technical specifications and operability:

- Concerning technical specifications of the generating units, in order to interpret (*speed)*, we will assume that the design and type of plant do not have a significant impact on the reliability of our use of wind speed in the proxy for plants' output.
- We assume that maintenance, production failures, or other potentially disrupting events do not impact wind power production, as we have to assume that wind power farms are always operational for the sake of the validity of the proxy.
- We assume that wind power plants are not subject to significant curtailment due to grid constraints or other factors, nor that the distance to the transmission line significantly impacts their output in order to simplify our model.

The additional variable which is determining the output of a wind power plant and which must be included regardless of the previous assumptions is the capacity of the production plants (*capacity*), which will interact with our variable (*speed*). Neglecting the difference in capacity between plants would render us unable to appreciate the difference in actual output and, thus, also the effect on our dependent variable, which is the high wind speed at a larger wind power plant facility relative to a small one. The capacity of each facility is also constant over the entire time period, which we observe and is primarily determined by the number of generating units rather than the technical differences of plants. Besides this interaction term and the aforementioned assumptions, we will have to account for the range of wind speeds which wind power plants actually operate within and when they produce at maximum capacity. In order to do so, the following specifications are made to the proxy:

- Wind power plants are only operational when wind speeds are between approximately three and a half and 25 meters per second (Vattenfall, 2023). This means that for wind speed values above 25 meters per second, the output of a wind power plant is, in reality, zero rather than at maximum because the plant shuts down due to safety reasons, and for values below three and a half meters per second, the plant is not operating because the wind speed is not sufficiently strong to start it. This issue will be addressed by creating a dummy variable (*limit*), taking the value one when $3.5 \leq (speed) \leq 25$, and zero otherwise, which interacts with the (*speed*) and (*capacity*) variables.

1. $(limit) = \{1 \; if \; 3.5 \leq (speed)_{it} \leq 25, 0 \; otherwise\}$

- We must also regard the fact that wind power plants reach maximum production capacity at wind speeds of approximately 13 meters per second and remain at maximum until the wind speeds reach 25 meters per second or more (Vattenfall, 2023). That is, for wind speeds above 13 meters per second, wind power output exhibits zero marginal return.
- Lastly, we make the assumption that actual production increases cubically with the variable *speed* when $speed \leq 13$, as this is the case according to the International Renewable Energy Agency (IRENA, 2022). We account for this and the maximum capacity threshold by introducing the variable (*max*), taking the value $(speed)^3$ when $speed \leq 13$, and 13^3 otherwise.

2. $(max) = \{(speed)^3 if \; (speed) \leq 13, 13^3 \; if \; (speed) > 13\}$

Our proxy for wind power production thus becomes:

3. $(proxy)_{it} = (max)_{it} * (capacity)_i * (limit)$

Where (*max*) is the wind speed, with regard to the limitations mentioned, at plant $_i$ at time $_t$. $(capacity)_i$ is the production capacity at plant $_i$. (*limit*) is an interaction variable representing the range in which wind power plants are operational within, equal to $\{1 \text{ if } 3 \leq (speed)_{it} \leq 25, 0\}$. It is also important to note that the value of the variable (*proxy*) cannot be interpreted as the output in units of MWh, which wind power production is, in reality, measured in. Rather, the variable assumes a value of an arbitrary unit that is positively correlated with actual wind power production rather than directly representing the precise MWh output value.

Finally, in order to be able to incorporate the effect of wind power production on the number of dispatched UMMs announcing an unplanned production failure in our regression and to answer our research question, we construct two variables from our proxy:

4. $(productionind)_{it} = \sum_{i=1}^{n}(proxy)_{it}$

Which represents the aggregate value of (*proxy*) for all wind power plants at locations *i* owned by firm *i* at time *t*, and:

5. $(productionothers)_{it} = \sum_{i=1}^{n}(proxy)_{it} - (productionind)_{it}$

Which represents the aggregate value of (*proxy*) for all wind power locations $_i$ owned by other firms than the firm $_i$ observed in the market. Ideally, this variable would include observations for all participants in the market owning wind power production, but as this is beyond the scope of our study, we have restricted ourselves to using data from our diversified producers constructed as per the methodology above as well as adding corresponding observations for the wind power production owned by Skellefteå Kraft and Jämtkraft.

These variables allocate the correct observations of (*proxy*) to the corresponding observations of the dependent variable in the panel data. Specifically, (*productionind*) captures the effect of a firm's own wind power production on the number of dispatched UMMs announcing an unplanned production failure from the same firm for any of their other means of production, while (*productionothers*) captures the effect of the aggregate wind power production of other firms in the market on the same number. Summary statistics of the constructed variables can be found in Appendix C.

7.3 Firms’ Own Wind Power Production

We test our hypotheses by conducting a two stage least square (2SLS) regression similar to that of Fogelberg and Lazarczyk (2019). We set unplanned production failures (*failure*) reported through UMMs by our diversified firms, excluding failures of wind power plants, as our dependent variable and our constructed variable (*productionind*), the proxy for wind power production, as the independent variables.

Another important factor in determining the incentive to engage in strategic withholding of production is the market demand for electricity and the size of the market. High demand, or an increase in demand, suggests that additional generating units are required to operate and that the market clearing price of electricity is determined by production occupying the higher levels of the merit order, and thus that prices increase. Simultaneously a small inward shift of the supply curve in such a scenario would result in an even higher equilibrium price, as the demand curve will be relatively steep and as the demand for electricity is inelastic in the short term. This suggests that at times of high demand, the incentive to withhold capacity increases following demand-side inelasticity. Given the fact that our research question is about supply-side strategic behavior, we want to remove this effect. However, actual demand as such cannot be measured, and instead, we proxy for it using data on aggregate Swedish electricity consumption. An additional consideration that is necessary when using consumption as a proxy is that of reverse causality because, albeit demand is inelastic, it is not perfectly inelastic. Realized electricity consumption thus becomes dependent on price and subsequently on the strategic behavior of the electricity producers. Hence, we will use forecasted consumption data for our control variable hourly aggregate Swedish electricity consumption (*consumption*), which previously has been expected to be of relevance to the price-determining mechanism in electricity markets (Forrest & MacGill, 2013). These forecasts are presented at 11:00 AM one day ahead (Nord Pool, 2023b) and should be exogenous to firms' strategic behavior while still capturing the effect of electricity demand on the number of producer-dispatched UMMs announcing an unplanned production failure.

Additionally, as addressed in preceding sections, previous studies have researched and found a significant effect of the electricity spot prices (*price*) on the number of dispatched UMMs concerning unplanned production failures (Fogelberg & Lazarczyk, 2019, Bergler et al., 2016), and it becomes important to control for this effect in order to avoid omitted variable bias and to ensure an unbiased estimate of the effect of wind power production on our dependent variable. Given the design of the day-ahead electricity market, with a market clearing price being set on the previous day and prices being correlated over time as the next day's price would be the same as today in the absence of any shocks, we assume a producer who wants to impact the spot price by reporting a production failure will do so with regard to the current price. Thus, we match each observation of our dependent variable with the corresponding daily average Swedish electricity price – calculated as the average of the spot price in electricity areas SE1, SE2, SE3, and SE4. However, there is a significant risk that electricity spot prices are correlated with additional omitted variables, such as the producers' bidding strategies or with actual production failures, and thus the variable electricity spot prices may cause a problem with endogeneity. In order to account for this, we will instrument for spot prices in the first stage of our 2SLS regression.

Already addressed in section 6.5, demand in the Swedish electricity market is closely related to temperature – demand increases as the temperature decreases – and the domestic supply in the Swedish electricity market is dominated by hydropower plants as the primary source of baseload production, in turn, dependent on precipitation, as this impacts both the water level and the flow of the rivers. As the market clearing electricity spot price is determined by the supply and demand of electricity, we estimate that temperature (*temp*) and precipitation (*precipitation*) are suitable instruments, especially given that they are also strictly exogenous – and thus, like Fogelberg and Lazarczyk (2019), we will use them as instruments for electricity spot prices in the first stage of our 2SLS regression.

Given our hypothesis that the number of reported unplanned production failures increases when wind power production is high, we assume that the variance of the standard errors should increase with our proxy for wind power production, suggesting that we may have a problem with heteroscedasticity. It is also reasonable to assume that a large share of the reported unplanned production failures is not a result of strategic behavior but of actual failures. When this is the case, it is also reasonable to assume that certain production units could experience failures more frequently as a result of previous incidents, suggesting that our dependent variable is influenced by its own past values, which means that we have a risk of autocorrelation. Both of these two assumptions are also relevant with regard to the first stage regression, as fluctuations in temperature and precipitation increase price volatility and thus could lead to heteroscedasticity, and supply-shocks, market trends, and seasonality, respectively, may cause autocorrelation if the effects persist. In order to address these concerns, we will use heteroscedasticity and autocorrelation consistent (HAC) standard errors in all of our regressions, also known as a Newey-West estimator. Finally, given that our data is longitudinal by nature and that our dependent variable is the count of UMMs sent by a defined number of firms, we will use Poisson regressions for our 2SLS regression, as these are appropriate for dealing with count data in a panel data setting.

Our 2SLS thus becomes:

First stage:

6. $(price)_t = \beta 0 + \beta 1(temp)_t + \beta 2(precipitation)_t + \epsilon$

Second stage:

7. $(failure)_{it} = \beta 0 + \beta 1(productionind)_{it} + \beta 2(consumption)_t + \widehat{\beta} 3(price)_t + \epsilon$

Where $(failure)_{it}$ is the number of reported unplanned production failures reported by firm i at time t. $(productionind)_{it}$ is our proxy for the aggregate wind power production of firm i being observed at time t. $(consumption)_t$ is the forecasted aggregate hourly Swedish electricity consumption in MWh at time t. $(price)_t$ is the estimated average Swedish electricity spot price from the first stage regression at time t, and ϵ is the HAC-standard error term.

7.4 Introducing Other Firms' Wind Power Production

In the final step, we use the same first stage regression and conduct the same regression as in the previous second stage, but add the predictor variable (*productionothers*), the proxy for wind power production in the market. This regression is intended to also capture the effect of the total wind power production supply available to the market, excluding the observed firm's own supply, on the number of reported unplanned production failures from the observed firm. All other model specifications remain unchanged. Our second Poisson-regression thus becomes:

8. $(failure)_{it} = \beta 0 + \beta 1(productionind)_{it} + \beta 2(productionothers)_{it} + \beta 3(consumption)_t + \hat{\beta} 4(price)_t + \epsilon$

Where $(failure)_t$ is the number of reported unplanned production failures reported by firm i at time t. $(productionind)_{it}$ is our proxy for the aggregate wind power production of firm i being observed at time t. $(productionothers)_{it}$ is our proxy for the aggregate wind power production of the market excluding firm i being observed at time t. $(consumption)_t$ is the forecasted aggregate hourly Swedish electricity consumption in MWh at time t. $(price)_t$ is the estimated average Swedish electricity spot price from the first stage regression at time t, and ϵ is the HAC-standard error term.

7.5 Identifying Assumptions

In order to infer a causal relationship between our dependent and independent variables, we assume that our proxy for the independent variables of firms' individual wind power production and the aggregate wind power production is exogenous to strategic failures, an assumption which aligns with the previous assumptions made concerning wind power production. More precisely, this means that we assume that wind power production is not utilized in any withholding strategies through production failures but rather that it is always non-strategically supplied – an assumption whose rationale is explained through the merit order effect.

Concerning our proxy for wind power production, we have implicitly assumed that the only factors of relevance are local wind speed, the capacity of the generating units, and general specifications concerning operationality, which we have implemented for all wind power plants regardless of the specific turbines used, in order to create our proxy. This is a rather strong simplifying assumption, as, in reality, the radius of the rotors, the height of the plant, and other technical specifications will also impact the actual output of a wind power plant. However, these omitted factors remain consistent over time, and as wind speed is the exogenous input determining the effect of a wind power plant, our proxy should capture variations in the output sufficiently well.

Finally, as we are using an instrument for the variable electricity spot prices, it is essential that our instruments, temperature, and precipitation, are not correlated with the error term of our model. This requirement should be satisfied as both of these variables are strictly exogenous. We also need to assume that the instruments used only affect our response variable through the treatment – that is, through their effect on prices – and that they do not influence the number of strategic failures in other ways directly or indirectly. This is done in order to ensure that our instrument leads to an unbiased estimate of the effect of the electricity spot price on strategic failures.

8. Results

In this section, we present the results of our methodology with a focus on the relationship between wind power production and UMMs announcing unplanned production failures. We will start by presenting the first stage regression and the instrumental variable approach. Then we will present the result of our second stage regression with producers' own wind power production as the predictor variable, followed by our second stage regression including both producers' own wind power production and the wind power production in the market as predictor variables.

8.1 Instrumenting for Price

The results of the first stage regression, which will apply to both specifications of the second stage regression, investigate the relationship between daily average temperature and precipitation with the Swedish average hourly electricity price. The results are presented in Table 2.

First stage regression: Instrumenting for prices

Variable	Estimate	Std. E (HAC)	Z value	Pr(>IzI)	Significance
temp	0,33682	0,55453	0,6074	0,5435954	
precipitaiton	-4,32885	1,14668	-3,7751	0,0001603	***

Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 2

The coefficient for the variable (*precipitation*) suggests that a one-millimeter increase in average daily precipitation is associated with a 4.33 EUR decrease in price. This relationship aligns with what we would expect, as the Swedish energy supply is largely hydro-based, and thus an increase in precipitation should result in increased output of hydro-plants, suggesting that supply increases and prices decrease. This relationship is statistically significant at a 0.1 percent significance level, indicating that it is highly unlikely to occur by chance. This result, along with the underlying theory, suggest that precipitation, indeed, is a valid and strong predictor of the electricity price.

The coefficient of the variable (*temp*) suggests that a one-degree increase in temperature is associated with a 0.33 EUR increase in the price of electricity, contrary to what would be expected in the Swedish market as demand increases when the temperature decreases. However, this result is not statistically significant, which further implies that temperature is not a suitable instrument for electricity price – at least not given our data. It is also contrary to the result of previous research which successfully used it as an instrument (Fogelberg and Lazarczyk, 2019) and to the information presented by Energimarknadsinspektionen (2023), the Swedish Energy Market Inspection Agency, concerning price-determining factors, suggesting that temperature, in theory, should be a strong predictor.

What is interesting to note is that the initial results of the regression, prior to the implementation of HAC-standard errors, indicated that the effect of temperature on electricity prices also was significant at a 0.1 percent level. However, after performing a Durbin-Watson test which with a DW-statistic of 0.06 suggests strong evidence for autocorrelation, and a Breusch-Pagan test which with a BP-statistic of 349.54 (see Appendix D) suggests strong evidence for heteroscedasticity, it is apparent that the use of HAC-standard errors is appropriate. Another potential reason why temperature is not a suitable instrument for our particular data set is the significant shock to electricity prices that occurred in 2022 following the Russian invasion of Ukraine and the subsequent disruption of the gas supply to European markets, which the Swedish market is interconnected with. As this effect prevailed throughout the entire year of 2022, it may have disrupted the usual and expected relationship between temperature and electricity price. Regardless, given the statistical significance of precipitation as a predictor of the electricity price and as the range, the mean, and the median of the predicted values of price from the first stage regression are close to those of the actual price (see appendices A and C), we assess that the predicted values of our model are still valid and suitable as an instrument for the electricity price.

8.2 Individual Wind Power Production

The results from the second stage regression using HAC-standard errors investigate the relationship between firms' own wind power production and the number of UMMs dispatched reporting an unplanned production failure. The results are presented in Table 3. As the range of values for the different variables in the model differs significantly, the coefficients have been rescaled for interpretability, as described in the table. Further information concerning the constructed variables can be viewed in Appendix C.

Initially, we note that forecasted consumption does not have a significant effect on the number of dispatched UMMs in our model, suggesting that this form of demand-side behavior does not influence the decision to engage in strategic withholding through production failures. The estimate of price consisting of the fitted values from the first stage regression does, however, provide a significant effect at a 5 percent level. The interpretation is that a 1 EUR increase in the price of one MWh of electricity is associated with a 0.017 increase in the number of reported unplanned production failures. This result is aligned with findings of previous research.

Second stage regression 1: Producers own wind power production

Variable	Estimate	Std. E (HAC)	Z value	Pr(>IzI)	Significance
productionind	0,008112	0,000458	17,712	<2e-16	***
estimatedprice	0,016921	0,00663	2,553	0,01068	*
consumption	-0,0011173	0,00016	-0,702	0,48265	

Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 3
Note: The variable (productionind) has been rescaled to represent a 1000-unit change, the variable (consumption) has been rescaled to represent a 100-unit change in MWh, and the variable (estimatedprice) has not been rescaled and represents a one unit change in EUR per MWh.

The effect of interest in this study, that of a diversified firm's own wind power production on the number of dispatched UMMs announcing an unplanned production failure for their other means of production, is estimated at 0.0081 while controlling for the effect of forecasted electricity consumption and electricity price. This suggests that for a 1000-unit increase in their own wind power production, a firm is expected to report an additional 0.0081 production failures. While this effect is small in absolute numbers, it is important to note that this variable assumes values ranging from zero to 453 666 and that its observations have a standard deviation of 48 722 (see Appendix C), indicating that a unit increase in the wind power production of a firm equivalent to one standard deviation is associated with an expected increase in the number of reported production failures with 0.39. This effect is statistically significant at a 0.1 percent level, indicating that it is highly unlikely that the observed effect has occurred by chance, but rather that there indeed is a positive relationship between the predictor and response variables of our model. These results thus provide support for our first hypothesis, that an increase in a firm's own wind power production will have a positive effect on the number of reported production failures, for the same firm.

8.3 Adding the Markets' Wind Power Production

The results from the second stage regression using HAC-standard errors, using both firms' own wind power production and the wind power production of the market as predictor variables, are presented in Table 4. Just as in the former section, the coefficients have been rescaled.

With this specification, the effect of forecasted electricity consumption on the response variable remains insignificant. The effect of price decreased slightly in magnitude compared to the model without the market's production of wind power, while its p-value increased. However, these are of such a marginal magnitude that the change in explanatory power is negligible.

Second stage regression 2: Producers own and the markets wind power production

Variable	Estimate	Std. E (HAC)	Z value	Pr(>IzI)	Significance
productionothers	-0,001979	0,000735	-2,6938	0,007065	**
productionind	0,008024	0,000486	16,498	<2,2e-16	***
estimatedprice	0,016235	0,0072447	2,241	0,025028	*
consumption	0,0003812	0,0016199	0,2353	0,813949	

Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Table 4
Note: The variable (productionind) and (productionothers) have been rescaled to represent a 1000-unit change, the variable consumption has been rescaled to represent a 100-unit change in MWh, the variable (estimatedprice) has not been rescaled and represents a one-unit change in EUR per MWh.

A firm's own production of wind power remains significant at a 0.01 percent level, and its effect on the number of production failures only decreases by 0.00088. This indicates that the introduction of wind power production in the market only has a weak attenuating effect and that the individual production of a firm still has a notable impact on the response variable. The effect of the wind power production of the market, excluding the observed firm's own production, on the response variable is significant at a 1 percent level. Its coefficient suggests that for a 1000-unit increase, the number of reported production failures decreases by 0.002. While this is also a number of a small magnitude, this variable assumes values ranging from zero to 1 273 401, suggesting that as is the case with firms' own production, the effect is not necessarily small as we may expect large unit increases and decreases to occur.

In contrast to our second hypothesis, that the wind power production of the market would have a positive effect on the number of reported production failures for the observed firm, this model provides support for the opposite. This result indicates that firms are neither acting strategically in response to the aggregate of wind production nor are they passive but rather consciously refrained from engaging in strategic withholding when the total supply of wind power in the market increases.

9. Discussion

In the following section, we will discuss the results of our empirical strategy in relation to our previously stated hypotheses and theory, as well as some limitations which we have identified with regard to our methodology and data collection.

9.1 Discussion of Results

The results presented in the preceding section provide both support and opposition to our hypotheses. As we hypothesized, the effect of a firm's own wind power production on the number of reported production failures was both significant, meaningful, and aligned with our anticipated result. That is, we find support for the hypothesis that an increased share of wind power supplied by a diversified firm increases the number of unplanned production failures reported by the same firm concerning their other means of production – while controlling for the effect of demand through forecasted consumption and for the effect of the electricity price through an instrumental variable approach. This suggests that as a diversified firm supplies more electricity at zero marginal cost and thus contributes to the merit order effect, the firm is more likely to withhold the capacity of its conventional, marginally more expensive production. Supposedly, this is done with the intention of counteracting the price-reducing effect that the increasing supply of wind power has on the market price of electricity while simultaneously increasing the profits of both the observed firm and other suppliers in the market. Consequently, this is an indication that the public welfare benefit following the merit order effect is at least partially destroyed by supply-side strategic behavior.

Applying the same logic, it would seem rational from an economic, profit-maximizing perspective to respond similarly to an increase in the total output of wind power in the market. Because essentially, in a situation where short-term demand is inelastic and simultaneously satisfied through the supply of wind power and baseload production, the decision to withhold a sufficient amount of capacity to shift the intersection of the demand and supply curves to a higher step of the merit order and thus increasing the price, should primarily be affected by whether, the additional profit from the increased price is greater than the lost profits of the withheld capacity. Naturally, the incentive increases with the share of wind power output currently supplied, as this will yield greater infra-marginal profits, but being the owner should not be an absolute condition, but rather that a firm has a sufficient degree of market power to be able to influence the price. However, our results of the model, including the wind power production of the market, indicate the opposite, namely that an increased share of wind power supplied by the market as a whole has a negative meaningful, and significant effect on the number of reported unplanned production failures of diversified producers. At the same time, the significant and positive effect on the number of reported production failures from a firm's own wind power production remains. This implies that while a diversified firm's decision to strategically withhold capacity is subject to a positive effect from their own supply of wind power, it is partially mitigated by the relatively weaker negative effect given by the total wind power production in the market. This is the opposite of our second hypothesis, as we anticipated the effect of the total market supply of wind power to further increase the number of reported unplanned production failures.

These findings, in relation to our theory, may, however, be explained by further considering the implications of a larger total share of wind power supplied for a single diversified firm and its opportunity to exercise market power. As the total share of wind power supply increases, the supply curve shifts outwards, and subsequently, the intersection with the demand curve will occur at a lower step of the merit order – causing lower prices and an incentive to withhold some production. However, if this outward shift is relatively large, the amount of capacity which would need to be withheld in order to instigate a need for marginally more expensive production to start operating, increases. Thus, in a situation of a high total supply of wind power, the capacity which a firm unilaterally would need to withhold in order to achieve an increased price in the market also increases. In this case, it is likely that the capacity which would need to be withheld is of such volume that the loss incurred from the lost production supersedes the additional profits generated by the remaining production supplied to the market. This suggests that while a large share of total wind power in the market creates a situation where a profit-maximizing firm, in theory, should have the incentive to withhold production in order to increase the market price, the firm may not be able to unilaterally do so at a profit.

From interpreting our results and carefully considering the underlying market mechanisms, one may thus conclude that we find support for the hypothesis that a diversified firm's decision to withhold capacity through the reporting of an unplanned production failure is subject to a positive effect by the same firm's own output of wind power – given the opportunity to recover any losses of withheld production through their remaining operational production through infra-marginal profits and the counter-action of the merit order effect. Simultaneously, we do not find support for the hypothesis that the decision to withhold capacity through the reporting of an unplanned production failure is subject to a positive effect on the total wind power output in the market. Rather, our results indicate that the decision to withhold capacity through unplanned production failures is subject to a negative effect on the total output of wind power, potentially because a larger share of wind power supplied increases the volume of capacity, which unilaterally would need to be withheld in order to achieve a counter-acting effect to the merit order.

9.2 Limitations

Wind Speed

A potential limitation of our results lies in the precision of the estimation of wind power production, which is necessary given the aforementioned lack of actual output data. Regardless of the method applied in conducting such an estimation, the calculation of wind power production is dependent on wind speed as its exogenous input. However, the most accurate wind speed data available is measured at the height of approximately ten meters (SMHI, 2021), and the closer to the ground the measuring point gets, the more the wind decreases. Meanwhile, the hub height for an average wind turbine is between 90–100 meters, with rotors able to capture the stronger winds at 120 meters height and above (Statkraft, 2023). The result of this is that we expect our wind speed observations to be of a systematically smaller magnitude than the actual wind speed affecting the rotors of the turbines. The main limitation posed by this fact does not lie in the systematically smaller values observed, as our constructed variables are not interpreted in MWh and as they still capture the change in output sufficiently well, but rather that we are likely to observe a disproportional share of observations with a wind power output of zero, as the wind speeds at ten meters height more frequently fail to exceed the operational threshold of 3.5 meters per second. In order to address this, one could potentially also estimate the wind speed at the height of the turbine, something which we, however, assess would be associated with a greater uncertainty with regard to the precision of the estimate of wind power production.

UMMs

Urgent market messages play a vital role in this thesis since we examine whether strategic withholding of capacity comes into play through the reporting of unplanned production failures issuing UMMs. However, all capacity withholding through production failures is not necessarily captured by UMMs since the threshold for being required to report a production failure through the REMIT system is that the relevant facility has an installed capacity exceeding 100 MW. This indicates that, for example, diversified producers owning several different facilities and who would decide to withhold 50 MW of production through production failures could do so by announcing a failure at a facility with an installed capacity lower than 100 MW, making this unobservable by the market. However, to the best of our knowledge, there is no available data concerning operational plants at large, at a given time, and it is thus unlikely that there is a variable that could capture strategic withholding through production failures more accurately than the UMM data in the REMIT system.

Unobserved Production

A final limitation regards unobservable control of electricity production due to the system with balance of responsible parties. While all of the diversified firms included in this study are the BRPs of their own production, they may also act as the BRP for other production facilities which they themselves do not own, but which means that they are the trading party for the output generated at Nord Pool (Svenska kraftnät, 2023a). This suggests that the market power of a firm, and the share of wind power that they control, may be greater than what we can observe. This implies that including a control variable for production that a firm controls through a BPA might contribute to a more precise explanation of the relationship between wind power production and the incentive to engage in strategic withholding of capacity. Data on which firms act as BRPs in some capacity is provided by eSett (2023), a company providing settlement services for the Nordic electricity market. However, the information about who is a BRP for which plant is not publicly available, and upon request to Vattenfall, Statkraft, and Fortum, all three firms declined to share the information. Further, as far as we know, the effect and implications of BRP agreements concerning production owned by others have not been addressed in previous research concerning strategic withholding.

10. Conclusion

In this thesis, we have aimed to contribute to the existing research concerning strategic withholding, counteraction of the merit order effect, and market power in the electricity market. More specifically, we have investigated the effect of wind power production output on strategic capacity withholding through the reporting of unplanned production failures by large, diversified electricity producers in an effort to provide an increased understanding of the price mechanisms and strategies used by such producers to extort influence over prices in response to the price decreasing effect of the merit order in Sweden. To this end, we have specified a 2SLS-regression model, instrumented for the electricity price and constructed two variables for firms' individual wind power output and the total wind power output in the market, respectively, using a unique data set containing local wind speed data, firm-specific wind power plant capacity and an array of the electricity market and weather data.

With this model, we have tested our hypotheses that diversified firms will be more likely to announce an unplanned production failure when their own wind power output increase and that they are more likely to do so when the total wind power output in the market increase. For the first hypothesis, we received support at a 0.1 percent significance level, suggesting that as a large, diversified firm's wind power output increases, they are more likely to report an unplanned production failure for its other production methods. For the second hypothesis, we received significant results at a 1 percent level providing support for the opposite of our hypothesis, namely that as the total output of wind power increases in the Swedish market, a large, diversified producer is less likely to report an unplanned production failure. These results support our theory that capacity withholding through announcing unplanned production failures is a strategy used by producers to counteract the price-decreasing effect of the merit order through increased wind power output, under the assumption that they will be able to recover greater infra-marginal profits for their remaining operational production. The results in this thesis are partially aligned with previous literature, as we do find some evidence of strategic behavior and extortion of market power, albeit the exact phenomena of strategic withholding through production failures are inherently difficult to observe.

With regard to the contemporary situation in the European electricity markets, being subject to constraint due to the war in Ukraine and the foreclosure of nuclear power plants while simultaneously experiencing increased investments in wind power, we believe that continued research concerning strategic withholding and the counteraction of the merit order is of importance. Specifically, as the Swedish electricity supply is largely given by state-owned electricity producers, it would be of relevance to investigate how the likelihood of engaging in strategic withholding differs in a market that is dominated by private firms. Further, we also suggest investigating the effect of BRP agreements in relation to the incentives to engage in strategic withholding, as it will provide greater insights regarding the distribution of market power.

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Appendix

Appendix A: Control Variables Data

Variable	Daily/hourly	Mean	SD	Median	Min	Max	SE
UMM	Hourly	0,01	0,08	0	0	1	0
Temperature	Daily	4,49	7,79	4,05	- 15,85	20,72	0,03
Precipitation	Daily	2,36	2,02	1,86	0,01	13,87	0,01
Consumption	Hourly	15 192,33	3 208,18	14 715,00	8 415,00	25 745,00	12,10
Price	Hourly	52,52	54,56	35,99	- 2,08	506,50	0,20

Note: UMM is reported in the number of UMMs dispatched, the temperature in degrees Celsius precipitation in millimeters, consumption in MWh, and price in EUR/MWh. UMM, Consumption and Price data were retrieved from Nord Pool, weather data was retrieved from SMHI.

Appendix B: Wind Speed Data

Wind speed at	Daily/hourly	Mean	SD	Median	Min	Max	SE
Juktan	Hourly	2,37	1,82	2	0	12	0,01
Stor-Rotliden	Hourly	1,85	1,3	1,7	0	9,4	0,01
Klaliden Fäbodberget	Hourly	1,85	1,3	1,7	0	9,4	0,01
Högabjär-Kärsås	Hourly	2,72	1,57	2,4	0	12,4	0,01
Hjuleberg	Hourly	2,72	1,57	2,4	0	12,4	0,01
Högre väg	Hourly	2,6	1,62	2,5	0	11,2	0,01
Lillgrunds	Hourly	6,72	3,17	6,4	0	22,3	0,02
Stamåsen	Hourly	2,19	1,49	1,9	0	10,9	0,01
Mörtjärnberget	Hourly	1,18	1,37	0,8	0	9,7	0,01
Björkhöjden	Hourly	1,66	1,54	1,3	0	11,4	0,01
Ögonfägnaden	Hourly	1,48	1,05	1,3	0	7,2	0,01
Mullberg	Hourly	4,8	2,49	4,2	0	18,2	0,02
Sjisjka	Hourly	3,45	2,42	3	0	17	0,02
Kyrkberget	Hourly	2,2	1,69	1,9	0	12,8	0,01
Hornberget	Hourly	2,15	1,79	1,9	0	11,9	0,01
Almåsa	Hourly	2,43	1,89	2	0	13,9	0,01
Solberg	Hourly	1,48	1,05	1,3	0	7,2	0,01
Uljabouda	Hourly	1,91	1,45	1,8	0	8,8	0,01
Jokkmokksliden & Storliden	Hourly	2,15	1,79	1,9	0	11,9	0,01
Bureå	Hourly	3,42	1,93	3	0	15	0,01
Blaiken	Hourly	2,37	1,82	2	0	12	0,01

Note: All statistics pertain to the measurement of wind speed per second in meters. Wind speed data was retrieved from SMHI.

Appendix C: Constructed Variables Data

Variable	Daily/hourly	Mean	SD	Median	Min	Max	SE
Estimated price	Hourly	52,52	8,77	54,06	5,16	66,71	0,03
Productionind	Hourly	21 619,00	48 722,51	0	0	453 666,15	18,35
Productionothers	Hourly	84 802,29	101 035,33	48 156,14	0	1 273 401,02	400,07

Note: Estimated price pertains to the predictions from the first stage regression.

Appendix D: First Stage Regression, DW- and BP-tests

First-stage regression: Durbin-Watson test	
DW	0,059127
p-value	<2,2e-16

First-stage regression: Breush-Pagan test	
BP	349,34
df	2
p-value	<2,2e-16

Appendix E: Second Stage Regression 1 DW- and BP tests

Second stage regression 1: Breusch-Pagan test	
BP	240,2
df	3
p-value	<2,2e-16

Second stage regression 1: Durbin-Watson test	
DW	1,9713
p-value	8,169-e05

Appendix F: Second Stage Regression 2 DW- and BP-tests

Second stage regression 2: Breusch-Pagan test	
BP	232,66
df	4
p-value	<2,2e-16

Second stage regression 2: Durbin-Watson test	
DW	1,9664
p-value	1,957e-05