# Cournot Competition in Wholesale Electricity Markets: The Nordic Power Exchange, Nord Pool*

Erik Lundin† and Thomas P. Tangerås‡

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**Abstract**

Horizontal shifts in bid curves observed in wholesale electricity markets are consistent with Cournot competition. Quantity competition reduces the informational requirements associated with evaluating market performance because the price-cost margins of all producers then depend on the same inverse residual demand curve instead of one for each firm. We apply the model to the day-ahead market of the Nordic power exchange, Nord Pool, for the years 2011-2013. Results suggest that price-cost margins were around 4 percent.

Key words: Cournot competition, market design, market performance, Nord Pool, Walrasian auction, wholesale electricity market
JEL: D22, D43, D44

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†Research Institute of Industrial Economics (IFN). Faculty affiliate at the Program on Energy and Sustainable Development (PESD), Stanford University. Email: erik.lundin@ifn.se. Website: www.eriklundin.org.

‡Research Institute of Industrial Economics (IFN). Affiliate researcher, Energy Policy Research Group (EPRG), University of Cambridge. Faculty affiliate at the Program on Energy and Sustainable Development (PESD), Stanford University. E-mail: thomas.tangeras@ifn.se. Website: www.ifn.se/thomast

# 1 Introduction

The performance of electricity markets has been a major topic among market monitors and in empirical industrial organization since restructuring of electricity markets began in the 1990s. One reason is the high degree of ownership concentration of generation capacity, which together with a highly price inelastic demand, creates opportunities for exploiting market power. Another reason is the rich set of available data that have created opportunities to estimate less parameterized models than what is usually possible in other markets, where researchers often have relied on the conjectural variations approach developed by Bresnahan (1982) and Lau (1982).

The most notable feature of restructured electricity markets is that wholesale markets typically are organized as Walrasian auctions: Producers, retailers and large industrial consumers submit price-dependent offers or bids to a centralized clearing house, such as a power exchange, that aggregates these offers and bids to obtain market-clearing prices and quantities. On the basis of these bids, supply and demand curves can be separately *derived* rather than *estimated* by means of simultaneous equation methods. It is even possible to calculate a residual demand curve facing each individual firm. The price sensitivity of the residual demand curve measures the firm's ability to influence the wholesale price, i.e. the individual firm-level market power.

The practical applicability of the above approach is limited by the fact that power exchanges often do not give external parties access to bid data at the firm level. Our theoretical contribution in Section 2 is to show that the data requirements are substantially reduced if firms with market power bid their quantities inelastically into the wholesale market at a low price. Under such Cournot competition, firms' market power depends on the properties of the aggregate inverse residual demand curve instead of individual demand curves. This curve can be computed on the basis of aggregate bid data that more often are publicly available. In our theoretical model, exogenous shifts in demand affect the total Cournot output via two additively separable channels. The first is the direct effect of a price change, which is positive when marginal costs are increasing. The second effect only occurs under imperfect competition and works through a change in the slope of the inverse residual demand curve. These theoretical results can form the basis of empirical analyses of wholesale electricity markets characterized by Cournot competition.

We illustrate in Section 3 the usefulness of the approach by an examination of data from the Nordic power exchange, Nord Pool, during 2011-13. This company operates the most important platform for trading wholesale electricity in the Nordic market, the day-ahead market *Elspot*. Our first observation is that the majority of within-week supply bid variation on Elspot stems from horizontal shifts in the supply curve, consistent with large firms competing in quantities. We then use an instrumental variables approach to regress Cournot output on price and a variable that appropriately measures firms' incentive to exercise market power. This variable, the "semi-elasticity" of residual demand, is constructed by multiplying the slope of the aggregate inverse residual demand curve by the Cournot supply net-of-forward market obligations. In particular, we find that the semi-elasticity has a statistically and economically significant negative effect on

Cournot output. This relationship is consistent with firms exercising market power by withholding production from the market, but it is inconsistent with perfect competition. Hence, we reject the hypothesis that Elspot was perfectly competitive during our sample period. Based upon the coefficient estimates, we compute implied price-cost margins of 4 percent. The estimated margins are robust to assumptions about the curvature of the marginal cost functions, as well as assumptions about the firms' financial contracts. When removing outliers in the semi-elasticity variable, estimated markups increase to a level of 16 percent.

The methodology does not require the total demand curve to rotate, unlike in the Bresnahan-Lau framework. Identification of imperfect competition in our context instead relies on the non-linearity of the supply function of the competitive fringe. exogenous variation in the curvature of the (observable) aggregate inverse residual demand curve facing firms with market power. We believe our approach could be fruitfully applied also to other wholesale electricity markets where aggregate bid data are available. Examples include Austria, France, Germany, and Switzerland. These countries are all part of the European Power Exchange, *EPEX*. Visual inspection of bid data from Germany suggests that horizontal supply shifts are important sources of supply variation also here, as depicted in Figure B1. Consistent with this observation, Willems et al. (2009) find a Cournot model to explain short term price variations in the German market just as well as a more complex supply function equilibrium model. It also appears that this bidding behavior is not restricted to the European markets. An example of horizontal supply shifts in the US Midwest market is depicted in Figure B2 adapted from Mercadal (2016). We round off the paper by some concluding remarks in Section 4.

**Related literature** Our paper is among the first to take advantage of novel bid data that have become available in recent years, to assess market performance in the Nordic electricity market. Nord Pool now releases data that enables us to reconstruct aggregate supply and demand bids on the Elspot market. Lundin (2016) uses shifts in the aggregate supply curve to estimate strategic aspects of maintenance scheduling among Swedish nuclear power plants. Tangerås and Mauritzen (2018) exploit differences between the day-ahead and intra-day markets to analyze market power. That method relies explicitly on the inter-temporality of hydro power markets and does not apply directly to thermal markets, contrary to the method in the present paper. Earlier studies, such as Bask et al. (2011), typically are applications of the Bresnahan-Lau model. Damsgaard (2007) and Kauppi and Liski (2008) are exceptions. They build simulation models to account for hydro production. More recently, Fogelberg and Lazarczyk (2014) analyze market power by means of announced production failures. These papers find evidence of market power to varying degree.

Bidding data at the firm level are available in some countries. Notably, Wolak (2003) (California) and McRae and Wolak (2014) (New Zealand) demonstrate that firms submit higher-priced bids when residual demand is less price elastic. Well-known studies of the British market are Green and Newbery (1992), Wolfram (1999), Wolak and Patrick (2001) and Sweeting (2007), all of whom find evidence of market power. Fabra and Toro (2005) find indications of periods with both collusion and price wars in the Spanish market. Ito and Reguant (2016) show that large firms exert market power by shifting output between the day-ahead and intra-day markets.

## 2 Theoretical analysis

**The wholesale market** The demand $D(p, \sigma)$ for electricity is a weakly decreasing function of the wholesale price $p$ of electricity and a strictly increasing function of the demand parameter $\sigma$. We treat in this section $\sigma$ as a scalar, but it is relevant to think of it as a vector containing temperature, seasonal variation, and so forth. A subset $K = \{1, ..., k\}$ of the $n \geq k$ generation owners have market power. Each firm $i \in K$ bids its production $q_i$ inelastically into the wholesale market at a positive and weakly increasing marginal production cost $MC^i(q_i)$. In our empirical analysis, a substantial amount of the production capacity is hydro power. Management's decision problem in a hydro power plant is how much of the water reservoir to release through the turbines today and how much to save for the future. The production cost consists mainly of this opportunity cost, the *water value*. If firm $i$'s production comes from hydro power on the margin, then $MC^i(q_i)$ measures the water value of $i$'s marginal hydro plant. All remaining firms $i \notin K$ act as a competitive fringe, bidding in the residual production $q_r$ at positive and strictly increasing marginal production cost $MC^r(q_r)$, where the index $r$ characterizes residual production. The demand function and all marginal cost functions are twice continuously differentiable.

The market-clearing condition

$$P = MC^r(D(P, \sigma) - Q)$$

returns the inverse residual demand $p = P(Q, \sigma)$ facing the $k$ Cournot producers, as a function of the total Cournot quantity $Q = \sum_{i \in K} q_i$ and the demand parameter $\sigma$. The inverse residual demand curve is strictly decreasing in Cournot output (subscripts on functional operators denote partial derivatives throughout):

$$P_Q(Q, \sigma) = \frac{-MC_q^r(D(P(Q, \sigma), \sigma) - Q)}{1 - MC_q^r(D(P(Q, \sigma), \sigma) - Q)D_p(P(Q, \sigma), \sigma)} < 0. \tag{1}$$

**Firm optimization** Firm $i \in K$ enters the production stage with sunk contractual obligations for $f_i$ MWh electricity. This is a composite contract containing forwards and futures of different maturities, bilateral contracts with large industrial customers and direct deliveries to households through vertical integration with electricity retailers, all indexed against the electricity wholesale price $p$. Let $g_i$ be the sunk price of this composite contract.

Cournot producer $i \in K$ maximizes

$$\alpha_i P(q' + Q_{-i}, \sigma)q' - \int_0^{q'} MC^i(z)dz + \alpha_i(g_i - P(q' + Q_{-i}, \sigma))f_i + (1 - \alpha_i) \int_0^{q' + Q_{-i}} P(Z, \sigma)dZ$$

over $q' \geq 0$ taking the production $Q_{-i} = \sum_{j \neq i} q_j$ of all other Cournot firms $j \in K$ as given. The parameter $\alpha_i \in [0, 1]$ represents a trade-off between social welfare and profit in producer $i$'s objective function. The firm is a pure profit maximizer if $\alpha_i = 1$, whereas it behaves closely to that of a central planner if $\alpha_i$ is close to zero. The organization parameter $\alpha_i$ could vary across firms, for instance depending on whether producers are privately owned or (partially) state-owned companies. Such ownership constellations are common in electricity markets.

**Equilibrium** The $k$ first-order conditions

$$P(Q, \sigma) - MC^i(q_i) = \alpha_i(q_i - f_i)|P_Q(Q, \sigma)| \; \forall i \in K \tag{2}$$

characterize the equilibrium quantities $(q_1, ..., q_i, ..., q_k)$ of the firms with market power, where the output $q_i(\sigma, \boldsymbol{f}, \boldsymbol{\alpha})$ of each firm $i \in K$ depends on the demand parameter $\sigma$, the portfolio $\boldsymbol{f} = (f_1, ..., f_i, ..., f_k)$ of contractual commitments and the organization parameters $\boldsymbol{\alpha} = (\alpha_1, ..., \alpha_i, ..., \alpha_k)$.

Equation (2) offers three explanations why a firm with market power would behave competitively. The first is the intensity of competition. A firm will have a small price-cost margin if the price is unresponsive to marginal changes in output, i.e. $|P_Q|$ is close to zero. The second reason is forward contracting and/or vertical integration. A firm has little to gain from increasing the price above the competitive level if it has already sold most of its output up front, i.e. $|q_i - f_i|$ is small. The third explanation has to do with organization design. A firm will exercise little market power if it is set up to take consumer surplus into account, i.e. $\alpha_i$ is small.[1]

The intensity of competition in (2) is defined in terms of the absolute value $|P_Q|$ of the slope of the *aggregate* residual inverse demand curve, unlike in other strategic settings where the residual demand curves at the individual level influence the equilibrium markups. This feature allows us derive a general result concerning aggregate Cournot output (the proof is in Appendix A):

**Proposition 1.** *The effect of a marginal increase in demand $\sigma$ on the total production $Q$ of the $k$ firms with market power equals*

$$Q_\sigma = HP_\sigma + H\lambda P_{Q\sigma} \tag{3}$$

*in Cournot equilibrium, where*

$$\lambda(\sigma, \boldsymbol{f}, \boldsymbol{\alpha}) = \frac{\sum_{i=1}^{k} \frac{\alpha_i(q_i - f_i)}{MC_q^i - \alpha_i P_Q}}{\sum_{i=1}^{k} \frac{1}{MC_q^i - \alpha_i P_Q}} \tag{4}$$

[1] The firm-specific organization parameter $\alpha_i$ and net contract position $q_i - f_i$ are sometimes observable, one can control for them, or they can be estimated. Empirical results reported by McRae and Wolak (2014) can be interpreted in terms of estimates of $\alpha_i$ for the largest firms in the New Zealand wholesale electricity market. Researchers very seldom have access to such exceptional data and therefore must rely on aggregate measures for estimating market performance, such as those we explore in this paper.

*measures market conduct, and*

$$H(\sigma, \boldsymbol{f}, \boldsymbol{\alpha}) = \frac{\sum_{i=1}^{k} \frac{1}{MC_q^i - \alpha_i P_Q}}{1 - \sum_{i=1}^{k} \frac{P_Q + \alpha_i (q_i - f_i) P_{QQ}}{MC_q^i - \alpha_i P_Q}} \tag{5}$$

*is strictly positive if the equilibrium is stable.*

Proposition 1 shows that a marginal increase in demand has two additively separable effects on total Cournot output. A direct price effect makes it more profitable to increase output. This is the first marginal effect in (3). But the change in demand affects also the slope of the inverse demand curve facing firms with market power. Any change in demand that renders the price of electricity more sensitive to changes in Cournot output ($P_{Q\sigma} < 0$) causes firms that exercise seller power to withhold output from the market. This is the second marginal effect in (3). The marginal slope effect $P_{Q\sigma}$ is more important if the incentive to exercise market power measured by the conduct variable $\lambda$, is positive and large. In particular, the slope effect vanishes completely under perfect competition, i.e. when $\lambda = 0$.

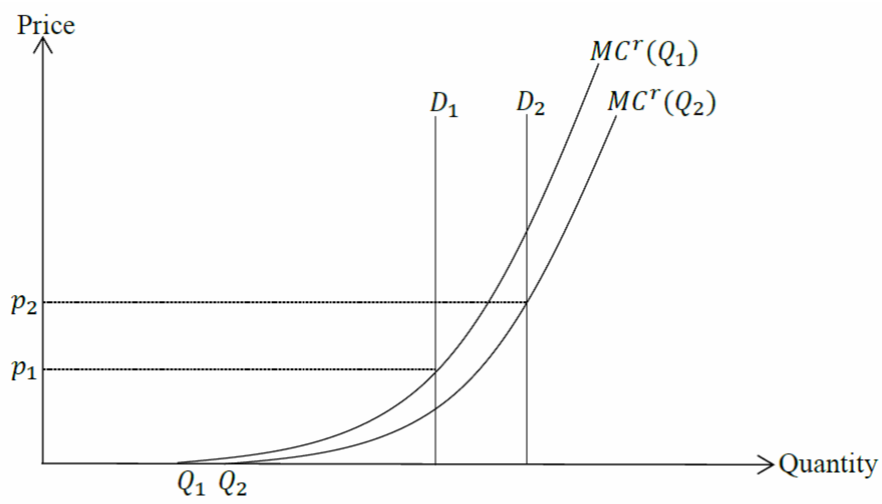
Proposition 1 demonstrates that demand shifters $\sigma$ can be used as instruments to measure market power. In particular, the proposition demonstrates the value of using slope data $P_Q$ in addition to price data $p$ and quantity data $Q$ to assess market conduct. To see this, let $\sigma(\boldsymbol{\xi})$ be a scalar valued function of $L$ different demand shocks $\boldsymbol{\xi} = (\xi_1, ..., \xi_l, ..., \xi_L)$. By this formulation, price and quantity data alone generally are insufficient to identify market power (Lau, 1982). It is impossible to identify market power even on the basis of additional slope data if $P_{Q\sigma} = 0$ because then all variation in Cournot output resulting from variation in demand is independent of market conduct $\lambda$. But slope effects can be non-zero even if demand shocks are scalar valued. Differentiating $P_Q(Q, \sigma)$ characterized in (1) with respect to $\sigma$ yields:

$$P_{Q\sigma} \neq 0 \Leftrightarrow \frac{MC_{qq}^r}{(MC_q^r)^2} + MC_q^r D_{pp} \neq \frac{D_{p\sigma}}{D_\sigma}[1 - MC_q^r D_p].$$

An often-applied and realistic assumption in the analysis of wholesale electricity markets is that total demand is exogenous and completely price inelastic for all prices $p$ below a bid-cap $\bar{p}$. The parameter $\sigma$ then measures total demand, $D(p, \sigma) = \sigma$. All variation in total demand here occurs as vertical shifts in the (flat) demand curve. In particular, there is no exogenous variation that causes total demand to rotate around the price: $D_\sigma = 1$ and $D_{p\sigma} = D_{pp} = 0$. Yet $P_{Q\sigma} \neq 0$ if the supply of the fringe is non-linear, $MC_{qq}^r \neq 0$. The latter property is empirically verified in our sample data. In this example, the elasticity of residual supply provides the slope variation required to identify market power in our model.

Proposition 1 holds generally under Cournot competition. It does not rely on symmetry, nor does it require any functional form assumptions on total demand $D(p, \sigma)$, on the marginal cost $MC^i(q_i)$ of firms with market power or on the supply $MC^r(q_r)$ of the competitive fringe. Estimating market conduct on the basis of $Q$, $p$ and $P_Q$ nevertheless poses problems because $\lambda$ is

Figure 1: Cournot competition with a competitive fringe




a function of two variables, demand $\sigma$ and forward contracts $\boldsymbol{f}$, at least one of which fluctuates over time. To get around this empirical problem, we add more structure to the theory model. Assume that marginal production costs are linear, $MC^i(q_i) = \gamma_i + cq_i$ for all $i \in K$, and that all firms with market power have the same organization parameter $\alpha_i = \alpha$ for all $i \in K$. In this special case, the conduct variable (4) simplifies to

$$\lambda = \frac{\alpha}{k}(Q - F),$$

where $F = \sum_{i=1}^{k} f_i$ is the total contract position of all firms with market power. Substitute the linear marginal cost function into the first-order condition (2), rewrite and sum up over all $k$ firms to get

$$Q = -\frac{1}{c}\sum_{i=1}^{k} \gamma_i + \frac{k}{c}p - \frac{k}{c}\frac{\alpha}{k}|P_Q|(Q - F). \tag{6}$$

This equation establishes the total Cournot quantity $Q$ as a linearly separable function of the equilibrium price $p$ and the semi-elasticity $|P_Q|(Q-F)$, which represents the theoretical foundation for the structural equation (7). This equilibrium relationship and estimated coefficients may change with other specifications of the marginal cost functions. We perform robustness checks in Section 3 below.

**Implications of Cournot competition** Figure 1 is a graphical representation of quantity competition in a wholesale electricity market. Assume that firms supply $Q_1$ MWh electricity to the wholesale market at price zero when total demand is equal to $D_1$. The competitive fringe supplies additional electricity at marginal cost up to the point at which the market clears at price $p_1$. An increase in demand from $D_1$ to $D_2$ increases Cournot supply from $Q_1$ to $Q_2$ upon which the fringe covers excess demand at the market-clearing price $p_2$. Cournot competition with a competitive fringe causes the supply function to *shift horizontally* with changes in the demand for wholesale electricity.

Typically, wholesale electricity market designs allow market participants to submit price-dependent bids. Cournot competition is only a special case of more general bidding strategies. The seminal contribution by Klemperer and Meyer (1989) shows that all supply-function equilibria are located between the Cournot and Bertrand (pure price competition) outcomes. It would be in firms' joint best-interest if everybody placed price-inelastic bids, as this would reduce the price-elasticity of all firms' residual demand curves and drive up the price. If there is little demand uncertainty at the bidding stage, then it is a unilaterally profit maximizing strategy to submit price inelastic bids, which then is a sustainable equilibrium. Figure 1 provides additional information why firms would prefer Cournot competition. Here, the price is always set by the marginal cost of the most expensive unit that produces in equilibrium. Measuring market performance by a comparison of the equilibrium price with the marginal cost of the marginally accepted unit would lead to the conclusion that the market was perfectly competitive. Withholding infra-marginal units thus is a way to mask market power. Finally, technical constraints, such as ramping costs, may create additional incentives to submit low bids to ensure that the unit (for instance nuclear power) is accepted during all hours covered in the trading period.

Strategic behavior other than Cournot competition is also consistent with horizontal shifts in the supply curve. Hortaçsu and Puller (2008) consider supply schedules that are restricted to be additively separable in prices and forward commitments, $S^i(p, f_i) = \beta^i(p) + \eta^i(f_i)$ for all $i \in K$. Short-term variations in forward contract commitments then induce horizontal shifts in the equilibrium supply functions. As Hortaçsu and Puller (2008) recognize, such supply functions need not be optimal from the viewpoint of firms. Moreover, we argue in Section 3.1 that short-term variations in forward commitments are unlikely to be the source of the observed variation in our sample data. It is possible that firms with market power supply both price independent (Cournot) and price dependent bids in a way that is consistent with Figure 1. We consider this possibility in Appendix A, where we assume that firms supply $q_i + \lambda MR^r(\hat{q}_i - q_i)$ MWh electricity to the wholesale market, where $\hat{q}_i$ is firm $i$'s total production. The resulting equilibrium condition is essentially the same as in equation (2). In particular, the incentive to exercise market power depends on the aggregate slope $|P_Q|$. Hence, Proposition 1 can be extended also to strategies that encompass price-dependent bids. From the results in Klemperer and Meyer (1989), it follows that Cournot bidding is the least competitive equilibrium consistent with unilateral profit maximization. From that perspective, estimated price-cost margins should be interpreted as upper bounds to the markups in the wholesale market.

## 3 Empirical analysis: The Nordic wholesale electricity market

**Institutional background** The national electricity markets in the Nordic countries were deregulated one after the other during the 1990s and integrated to create a common wholesale electricity market for Denmark, Finland, Norway and Sweden. This Nordic market was later expanded to include Estonia, Latvia, and Lithuania. Full market coupling with continental

Europe was recently implemented.

The main trading platform for physical energy is the day-ahead market, *Elspot*, operated by the Nordic power exchange, *Nord Pool*. Elspot trades more than 80 percent of all electricity produced in the region, and is the market we analyze in this paper. It works as follows. Every day at noon, market participants submit bids to Nord Pool for each of the 24 hours of the following day. Each participant can submit hourly bids consisting of at most 62 quantity/price pairs up to a bid cap.[2] Nord Pool connects all quantity/price pairs by linear interpolation to create hourly *system* supply and demand curves. The intersection of these curves is the aggregate market-clearing price, the so-called *system price*.[3] The system price is calculated by setting all transmission capacity within and between Denmark, Finland, Norway and Sweden to infinity. Trade flows between the Nordic region and Germany/the Baltic countries are counted either as price inelastic supply (imports), or as price inelastic demand (exports). Net exports account for 6 percent of the total cleared volume. In the empirical analysis, we use the system price as the price variable.

The equilibrium price that market participant meet equals the system price if there are no network constraints in the system. But if the transmission capacities reported by the system operators are insufficient to handle the trade flows necessary to clear the market at the system price, then Nord Pool is obliged to recompute the market. Elspot can then be partitioned into as much as 15 different price areas with local market clearing, the geographical borders of which are illustrated in Figure B4. The clearing procedure applied by Nord Pool implies that the slope of the residual demand function facing any given firm is always well defined for every hour, unlike in many other electricity markets. The price area configuration itself may change over time. For instance, Sweden went from being one single price area, to having the four price areas depicted in the figure in November 2011. The system price is the reference price for the main financial products. Thus, if a producer has sold a futures contract for 1 MWh at a price of 10 EUR and the day-ahead price is realized at 9 EUR/MWh, the producer receives a payment of 1 EUR from the buyer of the contract. Vertical integration has a similar effect, although retail contracts are physical instead of financial. Primarily, the firms' hedged power consists of futures traded on the Nasdaq Commodities trading platform and retailing obligations to deliver power to end consumers at predetermined prices.[4]

The production mix for the whole market is depicted in Table 1. The two major energy sources are

[2] The bid cap was 2000 EUR/MWh in our sample, but increased to 3000 EUR/MWh in 2015. Historically, prices have never risen to the level of the bid cap.

[3] Participants also have the possibility to submit *block bids* in addition to the above *regular bids*. A block bid differs from a regular bid in two respects. First, it is tied across two or more consecutive hours. Second, a block-bid is either accepted or rejected in full. Nord Pool applies an iterative algorithm to find a combination of block bids that maximizes total market surplus. The volume of accepted block bids enters as one single inelastic bid in the computation of the hourly market clearing system price. On average, 5 and 1 percent respectively of the accepted sell- and buy volumes in our sample data are block bids.

[4] See Wolak (2007) for an empirical examination of the competitive effects of forward contracting in the Australian electricity market, and Bushnell et al. (2008) for the competitive effects of vertical integration in three electricity markets in the U.S.

Table 1: Production mix in the Nordic market

| Production type | Percentage of production |
|---|---|
| Hydro | 49 |
| Thermal (non-nuclear) | 19 |
| Nuclear | 27 |
| Wind | 5 |

Note: This table depicts market shares by energy source for the Nordic market during 2011-2013.

Table 2: Market shares of the largest firms

| Firm | Percentage of production |
|---|---|
| Vattenfall | 19 |
| Statkraft | 14 |
| Fortum | 12 |
| E.ON | 7 |

Note: Market shares of total Nordic production for the largest firms 2011-2013.

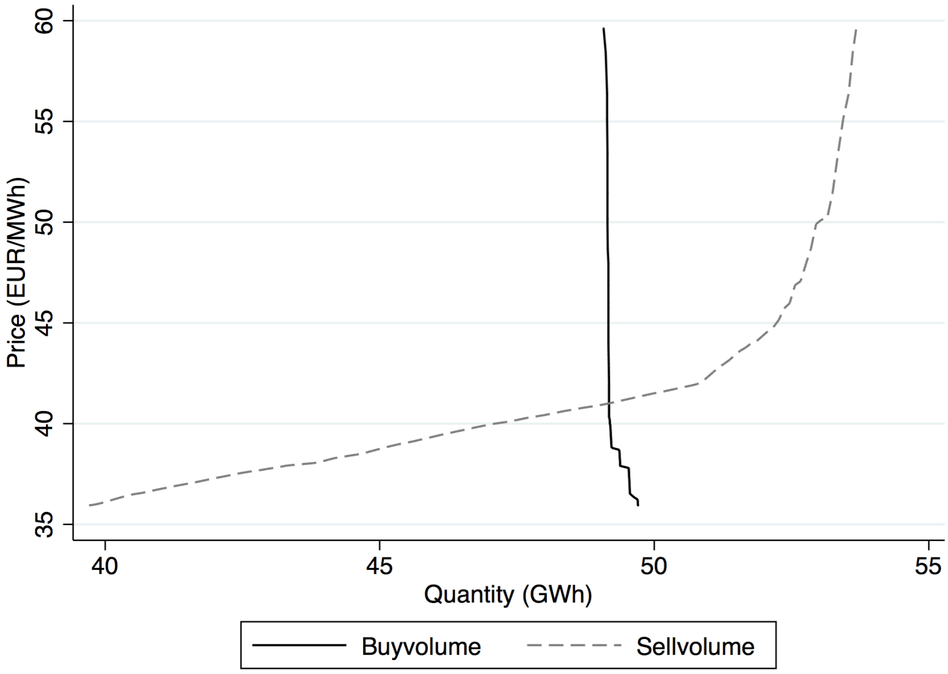
hydro power (49 percent) located in Norway and Sweden and nuclear power (27 percent) located in Finland and Sweden. The market is fairly concentrated, with market shares displaying little annual variation during the sample period. The firm with the largest share of total production is the Swedish state-owned firm Vattenfall (19 percent), followed by the Norwegian state-owned Statkraft (14 percent). The third largest producer is Fortum (12 percent), which has the Finnish state as the majority owner, followed by the German private energy firm E.ON (7 percent).

**Data** System supply and demand curves, net exports, volumes of accepted block bids, and the demand forecast have been downloaded from the Nord Pool FTP-server.[5] Based upon this bid data we can exactly reproduce the final step of Nord Pool's clearing algorithm and replicate all hourly system prices in our sample. Figure 2 depicts an example of a supply and demand function. The hourly system supply and demand curves contain around 600 quantity/price pairs each. The demand function is highly inelastic, except at low prices. The supply elasticity varies more. Nuclear and hydro power provide base load production, and are usually supplied at low prices. As demand increases, more thermal production is dispatched and the supply curve becomes steeper. As a result, the supply elasticity is generally lower in peak (08:00-20:00) than off-peak hours. The average price during peak hours is 30 percent higher than the average price during off-peak hours, which is comparable to the price difference in the winter compared to the summer.

Table 3 reports summary statistics. We define the Cournot quantity as bids below 5 EUR/MWh that are not accounted for as imports. Such bids will in practice always be accepted because the daily system price exceeded 5 EUR/MWh for the entire sample. We only want to include

[5] Access to the Nord Pool FTP-server is subject to a subscription fee. But most of data are also available free-of-charge for manual downloads at the Nord Pool downloads center (www.nordpoolspot.com/download-center/). Bid data at individual firm or area levels are currently not publicly available.

Figure 2: System supply and demand




Note: Note: This figure depicts the system supply and demand functions on the Nordic day-ahead market during 2-3 pm, January 19, 2013.

Table 3: Summary statistics

| | Mean | Sd | Min | Max |
|---|---|---|---|---|
| Cournot quantity | 21.6 | 2.9 | 13.6 | 31.7 |
| Equilibrium quantity | 35.9 | 7.3 | 19.9 | 58.2 |
| Price (p) | 38.8 | 14.3 | 1.4 | 225.0 |
| Semi-elasticity ($\|P_Q\|(Q-F)$) | 21.5 | 104.7 | 0.0 | 2204.3 |
| Demand forecast ($\sigma_1$) | 43.8 | 8.9 | 25.8 | 69.0 |
| Wind output ($\sigma_2$) | 2.3 | 1.5 | 0.0 | 8.6 |
| Temperature | 8.9 | 7.4 | -15.4 | 30.2 |

Note: Quantities are expressed in GWh, price in EUR/MWh, and temperature in Celsius. $N = 26304$.

strategic Cournot bids, and therefore subtract bids that are likely to come from wind power. Since the marginal cost of wind power is zero or even negative (because of the production subsidies), we assume that wind power is supplied inelastically. When regressing the Cournot quantity (prior to netting out wind power) on the wind power variable, the estimated coefficient is 0.99 and precisely measured (the standard error is 0.016), consistent with this assumption. The mean Cournot quantity is 21.6 GWh, accounting for 60 percent of the mean cleared equilibrium quantity. Figure B3 depicts the Cournot quantity and the cleared volume as a function of time, demonstrating that the two variables follow each other closely, with a correlation of 0.62.

To compute the slope of the residual demand function facing the Cournot players, we take a quantity window of 0.5 GWh on each side of the market clearing point and interpolate prices at these points, to obtain two quantity/price pairs $(Q_1, p_1)$ and $(Q_2, p_2)$. As described above, this interpolation procedure is identical to the clearing algorithm used by the auctioneer (given the volume of accepted blockbids and net exports). The (absolute) slope is then computed as $|P_Q| = |\frac{p_1 - p_2}{Q_1 - Q_2}|$. We also computed the slope by instead using windows of 0.25 and 1 GWh respectively. The correlations between all slope measures are above 0.9, confirming that the size of the window is not crucial. The mean slope is 2.59, meaning that a one GWh contraction of the Cournot quantity will result in a 2.59 EUR/MWh increase in the equilibrium price. The mean of the corresponding elasticity, $|P_Q|\frac{Q}{P}$ (where $Q$ is the Cournot quantity and $P$ is the equilibrium price), is 1.5. The mean of the corresponding semi-elasticity, i.e. $|P_Q|(Q - F)$ , is 21.5. Since this variable is highly skewed with a few exceptionally large outliers, we also conduct sensitivity analysis by gradually removing all observations above the $96^{th} - 99^{th}$ percentile.

The mean of the demand forecast is 43.8 GWh, around 20 percent above the Elspot equilibrium quantity. This difference occurs because some of the electricity consumed is traded outside of the day-ahead market. The demand forecast is published by the national transmission system operators (TSOs) at 11:00 the day before delivery, whereas bids can be submitted until noon.

Wind output has been downloaded from the Swedish and Danish TSOs, Finnish Energy (an umbrella organization for Finnish energy producers), and Statistics Norway. Statistics Norway only publishes wind output on a monthly basis. In the baseline analysis we assume that the within-month variation in Norwegian wind output is directly proportional to the wind output in rest of the Nordic region. We also perform a robustness test where we instead keep Norwegian wind production constant during each month. Since Norwegian wind production accounts for less than 8 percent of total wind output, the choice of method should only have a trivial impact on the results. The Danish TSO also submits day-ahead wind power forecasts, which perhaps is more appropriate in our context since bidding is done the day before delivery. Therefore we also conduct sensitivity analysis by replacing (Danish) observed wind power by its corresponding day-ahead forecast.

Temperature data were provided by the Swedish Meteorological and Hydrological Institute. In contrast to regions with milder climate, air conditioning is not used in the Nordic region, so the relationship between temperature and demand is always negative. The hourly realized temperature is measured in Stockholm, which is the largest metropolitan area in the region and located approximately at the centroid of the Nord Pool market.

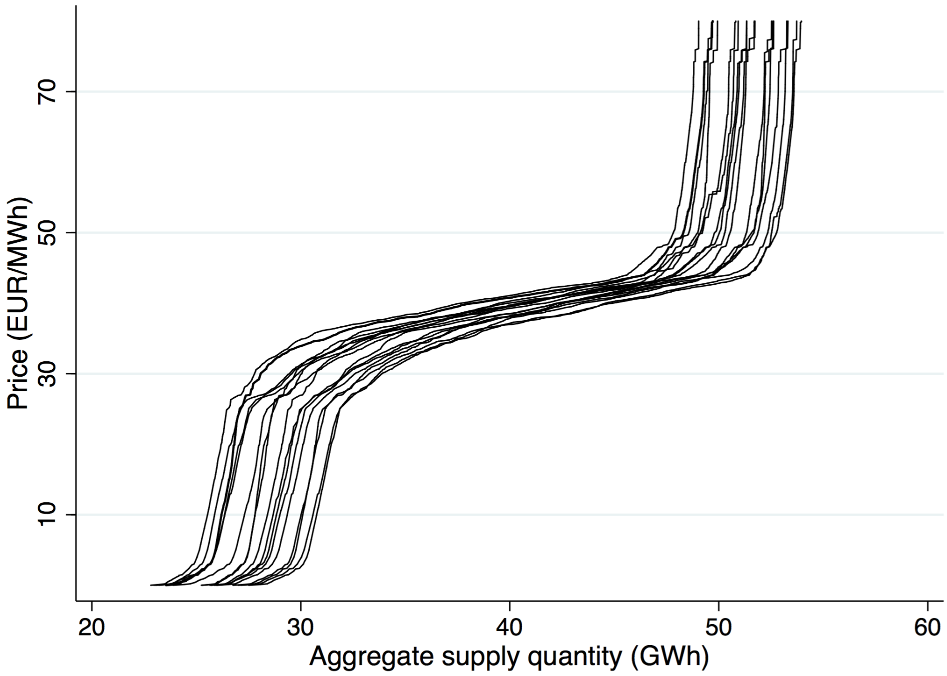
We do not have any direct information about firms' forward obligations at each point in time. Instead, we base our estimate on the yearly hedging ratios reported by several of the large firms in their annual reports (Vattenfall, 2013; Fortum, 2013; E.ON, 2014). The hedging ratio is hedged energy measured as a share of the expected physical output for the upcoming year. Hedging ratios differ only slightly across firms and years. To compute the relevant estimated volumes of forward obligations, we sum the observed Cournot quantities each year and multiply by the mean reported hedging ratio (which is 70 percent). Using this figure, we allocate contracts within each year. The most liquid product traded on the Nasdaq platform is yearly futures, where the seller commits to delivering 1 MW electricity each hour of the year. In the main specification we assume that Cournot firms have signed enough of these contracts so that their net position is non-negative for the hour with the lowest Cournot bid in the sample (which is 13.6 GWh). This means that 90 percent of all forward obligations are covered by yearly contracts. We assume that the remaining ten percent are load-following retail contracts. This figure may appear comparatively low, but retail prices are unregulated in the Nordic region and are often set as a markup over the mean day-ahead price for a certain period. Hence, any price increase in the spot market is passed on directly to consumers. We also perform robustness tests by varying both the hedging ratio and the share covered by load-following retail obligations.[6]

### 3.1 Inelastic bids are the main source of supply variation on Elspot

Bidding on Elspot features precisely those horizontal supply shifts in Figure 1 that are associated with Cournot competition. Figure 3 displays a sample of hourly bid curves of a representative week on Elspot that illustrate this behavior. Cournot bids account for the majority of accepted bids and also represent the main source of supply *variation* on Elspot. In fact, the clearing prices within any given week can be accurately replicated using static representations of the elastic portion of the supply functions, so that the only variation comes from Cournot bids (including wind power). We construct these approximations by first fitting the supply functions in increments of 0.1 EUR/MWh. After netting out the Cournot quantity associated with each bid, the mean weekly bid quantity is computed for each price level. In the last step, we fit the supply functions using a lowess smoothing filter. We interpret this supply function as an approximation of the marginal cost curve of the competitive fringe for that week. Figure 4 depicts an example of such a supply function, together with the data points used to construct it. We then add the Cournot bids and wind power output to each weekly supply function and re-clear the market. The predicted prices are very close to the observed prices, with a median

[6] A hedging ratio of 70 percent could be an upper bound to forward commitments as firms have an incentive to overstate their positions. Willems et al. (2009) estimate 50 percent hedging in an analysis of the German wholesale electricity market. The symmetric duopoly model by Allaz and Vila (1993) generates 50 percent hedging in equilibrium.

Figure 3: Horizontal supply shifts on Nord Pool Elspot



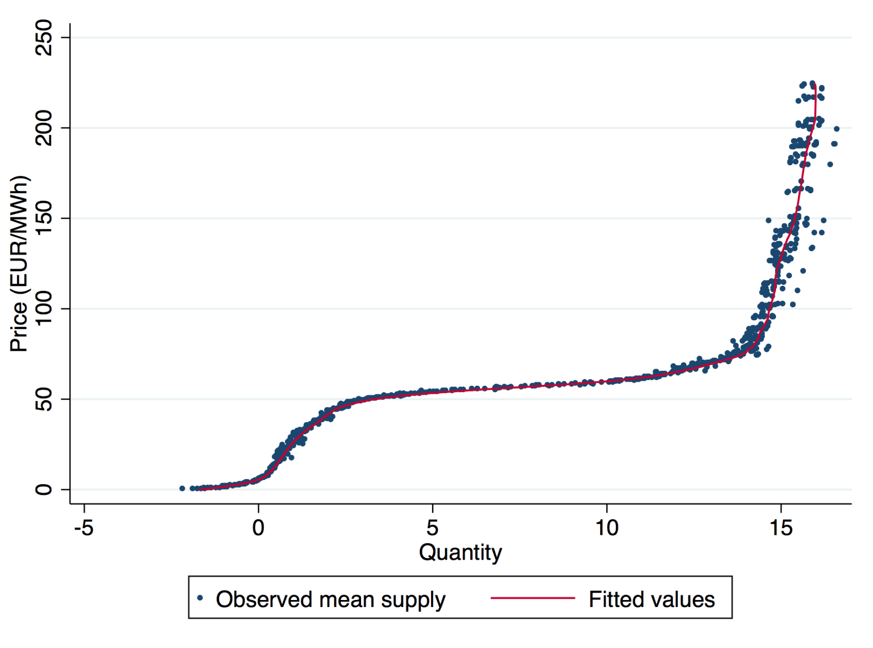

Note: The figure shows aggregate supply bids in the Nordic day-ahead market for a random set of hours March $1-7$, 2013.

within-week correlation of 0.96. Figure 5 displays the observed versus predicted prices for one sample week. Hence, even though we use the observed hourly elastic supply functions of the competitive fringe to compute the residual demand functions facing the Cournot producers, this exercise demonstrates that the essential within-week supply bid variation comes from inelastic bids.

Horizontal shifts have previously been found to be an important source of supply variation also in other wholesale electricity markets, for instance the Midwest market (Mercadal, 2016). Figure B2 depicts a set of supply functions in that market for one firm, that appear to be parallel shifts. Hortaçsu and Puller (2008) argue that variation in short-term forward contract obligations can explain such horizontal supply shifts. The financial products most common in the Nordic market are standardized forward contracts that clear against the monthly, quarterly, or yearly system price. Due to negligible liquidity (Nordreg, 2016), there is not enough variation in shorter-term forward contracts in the Nordic region to explain the large variation in supply shifts *within* months.

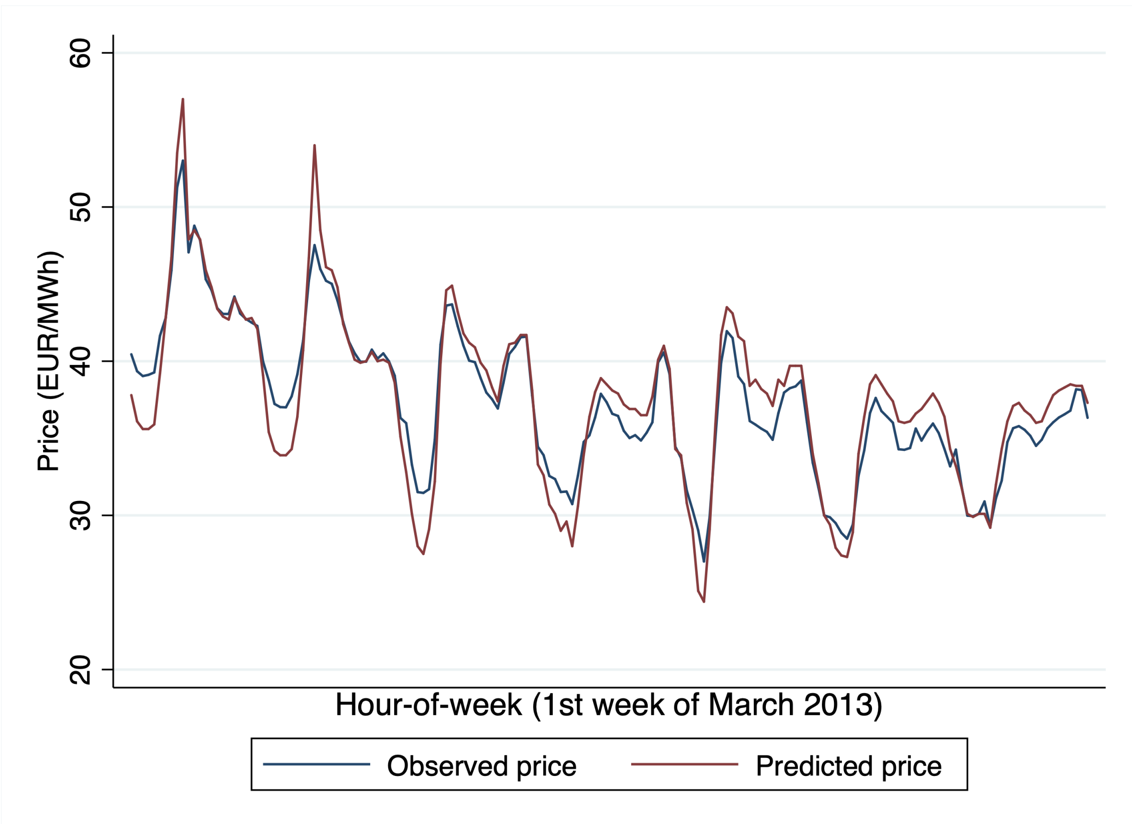
Although consistent with Cournot competition, horizontal supply shifts are not direct evidence of firms with market power bidding in Cournot fashion on Elspot. But regardless of the underlying strategic interaction, the key to estimating market performance on Nord Pool lies in understanding the variation in the supply of inelastic bids, because the observed variation in elastic bids is close to negligible. Given the additional data requirements necessary for uncovering the finer

Figure 4: Constructing a representative supply function for one week




Note: The figure shows a representative supply function in the Nordic market during one week, including the raw data consisting of each bid during that same week (excluding Cournot bids).

Figure 5: Observed vs predicted prices using representative weekly supply functions




Note: This figure depicts observed vs. predicted prices in the Nordic day-ahead market during one week. When determining the predicted prices, within-week variation in the supply bids comes from inelastic Cournot bids (including wind power) only.

details of strategic interaction in the Nordic electricity market, we maintain that the theoretical analysis in Section 2 provides a useful foundation for an empirical analysis of inelastic bidding on Nord Pool.

### 3.2 Estimation

In light of equation (6) following Proposition 1, we want to estimate

$$Q_t = \beta_0 + \beta_1 p_t + \beta_2 |P_Q^t|(Q_t - F_t) + \beta_3 X_t^S + v_t + \varepsilon_t, \tag{7}$$

where index $t$ refers to the sample hour. The $\beta_1$ estimate measures the effect of an increase in the wholesale price $p$. The $\beta_2$ estimate measures the market power effect on Cournot output working through the semi-elasticity of the net-of-forward market obligations inverse demand curve. In the below specifications, we simply refer to $|P_Q|(Q - F)$ as the "semi-elasticity". The vector $X_t^S$ controls for exogenous supply shocks, and $v_t$ is a vector of time fixed effects. $\varepsilon_t$ is the econometric error term, capturing both optimization errors and unobserved supply shocks, such as plant failures. Estimated standard errors are robust and clustered by week-of-sample.

**Fixed effects** As electricity consumption is cyclical, we acknowledge that each observation $t$ belongs to a certain hour of the day $h$, day $d$, and sample week $w$. In the main specification we therefore add fixed effects for each hour-of-the-day, day-of-the-week, and week-of-sample. We also estimate the model by substituting the week-of-sample fixed effects by a set of day-of-sample fixed effects.

**Controls** As a supply control we add temperature, since it may have an effect on the failure frequency of certain power plants.

**Instruments** Due to reverse causality, the model cannot be estimated using OLS. Contracting Cournot output will always have a positive effect on the price independent of the shape of the residual demand function. When the residual demand function is convex, there is also a positive effect on the (absolute) slope, while the opposite is true when the residual demand function is concave. Proposition 1 shows that the marginal effect of an increase in the demand shifter $\sigma$ is additively separable in price and slope, so it is convenient to use demand shifters as instruments. Since we have two endogenous variables, we need two instruments that are not perfectly correlated, $\sigma_1$ and $\sigma_2$. We use forecasted demand and wind power output.

Forecasted demand has previously been used as an instrument for price by e.g. Kim and Knittel (2006). The demand forecast does not take price into account. Otherwise, the exclusion restriction would be violated since the demand forecast would suffer from reverse causality (since variations in the Cournot quantity affect the price and thereby also demand). Instead, it is determined by indicators of weather and economic activity. The demand forecast is a very strong determinant of the actual quantity cleared in the spot market with a within-year correlation of above 0.95, confirming that the short run price elasticity of demand is very low. Another presumption is that the Cournot quantity responds to the demand forecast only through its effect on the price and the slope. That is, firms' mapping of how variations in demand affects equilibrium outcomes has to be accurate and cannot not follow some simplified rule of thumb. Since the rules of the day-ahead auction have not changed notably since the turn of the century, this means that there have been more than 100 000 similar auctions prior to the ones analyzed in the present study. Hence, participants' should have close to perfect knowledge of how demand affects equilibrium outcomes.

Wind power is essentially negative demand, as discussed in the data section above. It is important that all bids coming from wind power are netted out when computing the Cournot quantity. Otherwise, the effect of wind output on the Cournot quantity could be due to a positive correlation between the observed and unobserved wind output.

**Marginal cost function** In the main specification we assume that the marginal cost function is linear, but also provide sensitivity analysis with regard to the curvature of the marginal cost function.

### 3.3 Results

The results from our main specification are in Table 4. Since the relationship between the instruments and the price is non-linear, we square the instruments before estimating the first stage regression. The Cragg-Donald F-statistics are consistently very high throughout all specifications, confirming that instruments are strong. In specification (1), we estimate the model without controlling for temperature. Both variables are measured precisely and have the expected signs. A larger semi-elasticity $|P_Q|(Q-F)$ leads to a contraction of Cournot output, consistent with the exercise of market power. A higher price is associated with an expansion of Cournot output, consistent with increasing marginal costs. We add the temperature variable in specification (2). In column (3), we include day-of-sample fixed effects. The magnitudes of the effects are only trivially affected by these modifications.

We reject the null hypothesis of perfect competition because the estimated $\beta_2$ coefficient is negative and statistically significant in each specification (1)-(3). These negative estimates are consistent with firms exercising market power by withholding production from the day-ahead market when day-ahead prices are more sensitive to reductions in output. Under perfect competition $\beta_2$ would be insignificantly different from zero. Our model delivers in the parametric case a structural estimate of market performance instead of being a purely diagnostic test of whether the market is competitive, because we can use the functional form assumptions to quantify the implied price-cost margins. Sum up the first-order condition (2) across all $k$ firms with market power to get

$$L = \frac{p - \frac{1}{k}\sum_{i=1}^{k} MC^i(q_i)}{p} = \frac{\alpha}{k}\frac{|P_Q|(Q-F)}{p} \tag{8}$$

under the assumption that $\alpha_i = \alpha$ for all $i \in K$. The left-hand side of this equation is the Lerner

Table 4: Results from the main specification

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| Price (p) | 0.84*** | 0.84*** | 0.97*** | −0.055*** |
| | (0.0968) | (0.0979) | (0.127) | (0.00667) |
| Semi-elasticity ($\|P_Q\|(Q-F)$) | −0.066*** | −0.066*** | −0.073*** | 0.0037*** |
| | (0.0109) | (0.0109) | (0.0114) | (0.000297) |
| Temperature | | −0.014 | 0.038 | −0.019** |
| | | (0.0317) | (0.0309) | (0.00758) |
| Demand forecast$^2$ ($\sigma_1$) | | | | 0.00075*** |
| | | | | (0.0000880) |
| Wind output$^2$ ($\sigma_2$) | | | | −0.080*** |
| | | | | (0.00297) |
| Lerner index | 3.74 | 3.77 | 3.63 | |
| Fixed effects | Week | Week | Day | Week |
| Cragg-Donald F-stat | 136.9 | 137.6 | 63.2 | |
| N | 26304 | 26304 | 26304 | 26304 |

* $p < .10$, ** $p < 0.05$, *** $p < 0.01$

Note: Results from the baseline specification. Hour-of-the-day and day-of-the-week fixed effects are included in all regressions. The price and the semi-elasticity are instrumented using the square of forecasted demand and wind production in all specifications expect for (4), which is estimated using OLS. In this specification instruments are instead included as controls. Standard errors are robust and clustered by week-of-sample.

index, which is a standard measure of market performance. We calculate it here as the difference between the price and firms' average marginal cost, as a percentage of the price. The information we need to be able to estimate $L$ is $\frac{\alpha}{k}$. If we have estimated the coefficients in (7) correctly, then $\beta_1 = \frac{k}{c}$ and $\beta_2 = -\frac{k}{c}\frac{\alpha}{k}$; see equation (6). Substituting them into (8) produces

$$L = -\frac{\beta_2}{\beta_1}\frac{|P_Q|(Q-F)}{p}.$$

We report the sample means of the Lerner index in Table 4. The Lerner index is consistently around 4 percent.

For comparison, we depict OLS estimates in specification (4) of Table 4. Forecasted demand and wind output are now included as controls, and these variables have the expected signs. Increased demand has a positive effect on Cournot output. Correspondingly, the effect of wind output is negative, since wind is essentially negative demand. But the price and semi-elasticity coefficients now change signs, presumably because of reverse causality as discussed above. Consequently, there is no economically meaningful interpretation of the implied Lerner index in the OLS specification.

### 3.4 Sensitivity analysis

We perform sensitivity analysis in a number of dimensions.

**Marginal cost function** Consider a more general marginal cost function than the linear specification. Assume that marginal cost functions are symmetric and of the form $MC^i(q_i) = \gamma + cq_i^\theta$, where $\theta \in [1, 2]$. The main specification assumes $\theta = 1$. By way of the equilibrium relationship

$$Q^\theta = -\frac{k^\theta}{c}\gamma + \frac{k^\theta}{c}p - \frac{k^\theta}{c}\frac{\alpha}{k}|P_Q|(Q - F),$$

we re-estimate the structural equation (7) in the baseline specification (2) from Table 4 with $Q^\theta$ as dependent variable. Results are depicted in Figure B5 for different values of $\theta$. As seen in the figure, both the price and semi-elasticity coefficients are sensitive to the assumed curvature of the marginal cost function. But the estimated markups are robust because they are calculated on the basis of the ratio $-\frac{\beta_2}{\beta_1}$ of the estimated coefficients. The markups remain fairly stable at around 4 percent for all values of $\theta$.

**Wind power definition** We estimate our baseline specification (2) from Table 4 using alternative definitions of the wind power variable. First, we estimate the model using monthly Norwegian wind output directly instead of redistributing output within each month. Second, we estimate the same specification but replace Danish wind output by the corresponding day-ahead forecast at the time of bidding, to reflect that bidders do not have perfect information about day-ahead wind conditions (the corresponding data for Sweden, Finland and Norway are not available, but Denmark accounts for the largest share of wind power in the Nordic region). Results are depicted in Table B1. Naturally, in both specifications we compute the Cournot quantity using the corresponding wind power variable. In both specifications, the implied Lerner indices are only marginally different from the baseline specification.

**Sensitivity to outliers** The semi-elasticity variable is highly skewed with a few extremely steep outliers. To examine whether these outliers drive our results, we re-estimate the baseline specification (2) after removing all observations above the $96^{th} - 99^{th}$ percentile. Results are depicted in Figure B6. As more observations are removed, the (absolute) magnitude of the semi-elasticity coefficient increases, generating higher Lerner indices. When all observations above the $96^{th}$ percentile are removed, the mean Lerner index is around 16 percent, which is approximately 4 times larger than in the baseline specification. This means that our results should be interpreted with care, but the baseline specification does not appear to produce an exaggerated estimate of market power. The mechanism explaining the sensitivity to outliers can be demonstrated using Figure B7. It depicts the predicted semi-elasticity from the first stage regression when including the full sample (triangles), the Cournot quantity, and a regression line (dashed). Also depicted are the predicted values when excluding all semi-elasticity observations above the $98^{th}$ percentile (circles) and the corresponding regression line (solid). Due to the convexity of the residual demand function, extremely high slopes are sometimes realized when demand is high. Our simplified first-order approach then predicts the Cournot quantity to be very low, as that would lead to extremely high prices. However, if the Cournot firms fully responded to these incentives, that would most likely catch the eye of the competition authorities and other market monitoring authorities. Ramping constraints may be another reason why firms cannot always adjust output swiftly as a response to great variations in the semi-elasticity. Further, since these events are rare, firms may not always be able to predict the exact hours in which they will occur. As a result, the Cournot quantity is comparatively high for these extreme slopes, and the corresponding regression line is positive. The regression line for the smaller sample is much more flat. After adding fixed effects and controlling for the price, the semi-elasticity coefficient is negative also for the full sample (as seen in the baseline regression), but much less so in comparison to the results obtained using the small sample.

**Sensitivity to hedging strategies** Figure B8 depicts results when we vary the assumed hedging ratio between 0 and 70 percent while keeping the share of load-following obligations constant at 10 percent. The estimated markups are decreasing in the hedging ratio. When setting the hedging ratio to zero the estimated Lerner index is close to 5 percent, i.e. about 25 percent higher than the baseline estimate, demonstrating the importance of taking forward positions into account when estimating firm behavior. Figure B9 depicts results when varying the share of yearly futures in the firms' hedging portfolio between 50 and 90 percent (where 90 percent is the baseline). Throughout this sensitivity analysis, the aggregate hedging ratio is fixed at 70 percent and all remaining contracts are load-following. From the figure, we see that the estimated Lerner Index is decreasing in the share of yearly futures, again varying between 4 and 5 percent.

## 4 Conclusion

We analyze in a theoretical model wholesale electricity markets characterized by Cournot competition, and formulate an empirical test based on aggregate bid data to evaluate market performance. Cournot competition is consistent with horizontal shifts in bid curves observed, for instance, on the day-ahead market Elspot of the Nordic wholesale electricity market. We apply the method to Elspot and estimate price-cost margins of around 4 percent during our sample period 2011-2013. The estimated margins are robust to assumptions about the curvature of the marginal cost functions, as well as assumptions about the firms' financial contracts. When removing outliers in the semi-elasticity variable, estimated markups increase to a level of 16 percent.

The method can be used to evaluate competition also in other wholesale markets where only aggregate bid data are available provided strategic interaction can appropriately be described in terms of Cournot competition.[7]

We have only been able to test the model on aggregate (system level) data for the Nordic market.

[7] An obvious candidate for this analysis would be the European Power Exchange *EPEX*.

One would expect local variations in supply conditions and market concentration to yield also local variations in competition depending on the country and price area. Bid data at price area level would therefore be highly valuable in increasing the precision of empirical analyses of market performance in the Nordic market. We strongly recommend Nord Pool to disclose bid and supply data at a more disaggregated level.

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## Appendix A: Proof of Proposition 1

A total differentiation of the $k$ equilibrium conditions in (2) yields $\mathbf{Adq} = \mathbf{b}d\sigma$, where $\mathbf{A}$ is a $k \times k$ symmetric matrix with diagonal element $i$ equal to

$$1 + a_i = 1 + \frac{\alpha_i P_Q - MC_q^i}{P_Q + \alpha_i(q_i - f_i)P_{QQ}},$$

and all off-diagonal elements of $\boldsymbol{A}$ are equal to 1, $\mathbf{dq} = (dq_1, \cdots, dq_i, \cdots, dq_k)'$, and $\mathbf{b}$ is a $k \times 1$ vector with element $i$ equal to

$$b_i = -\frac{P_\sigma + \alpha_i(q_i - f_i)P_{Q\sigma}}{P_Q + \alpha_i(q_i - f_i)P_{QQ}}.$$

To evaluate the determinant $|\mathbf{A}|$, subtract the last column in $\mathbf{A}$ from each of the other $k-1$ columns, multiply the resulting matrix by $(\frac{a_k}{a_1}, \cdots, \frac{a_k}{a_i}, \cdots, \frac{a_k}{a_{k-1}}, 1)'$ and add all the first $k-1$ rows to row $k$ to obtain a triangular matrix with diagonal element $k$ equal to $a_k(1 + \sum_{j=1}^k \frac{1}{a_j})$ and all other diagonal elements equal to $a_k$. We can then solve for

$$|\mathbf{A}| = \prod_{j=1}^k a_j (1 + \sum_{j=1}^k \frac{1}{a_j}).$$

To find the effect of $d\sigma$ on $dq_i$, we must find also the determinant $|\mathbf{A}_i|$ of the matrix $\mathbf{A}_i$ resulting from substituting $\mathbf{b}$ for column $i$ in $\mathbf{A}$. Subtract the last column in $\mathbf{A}_i$ from each of the other $k-1$ columns, multiply the resulting matrix by $(\frac{a_k}{a_1}, \cdots, 1, \cdots, \frac{a_k}{a_{k-1}}, 1)'$ and add all $k-1$ rows except $i$ to the last row to get

$$\begin{pmatrix}
a_k & 0 & \cdots & \frac{a_k}{a_1}(b_1 - 1) & \cdots & 0 & 0 & \frac{a_k}{a_1} \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\
0 & 0 & \cdots & b_i - 1 & \cdots & 0 & 0 & 1 \\
\vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\
0 & 0 & \cdots & \frac{a_k}{a_{k-1}}(b_{k-1} - 1) & \cdots & 0 & a_k & \frac{a_k}{a_{k-1}} \\
0 & 0 & \cdots & a_k(\sum_{j \neq i}^k \frac{b_j - 1}{a_j} - 1) & \cdots & 0 & 0 & a_k(1 + \sum_{j \neq i}^k \frac{1}{a_j})
\end{pmatrix}$$

Multiply this matrix by $(1, \cdots, 1, \frac{a_{i+1}}{a_k}\frac{1-b_i}{b_{i+1}-1}, \cdots, \frac{a_{k-1}}{a_k}\frac{1-b_i}{b_{k-1}-1}, \frac{1-b_i}{a_k(\sum_{j\neq i}^k \frac{b_j-1}{a_j}-1)})'$ and add row $i$ to each of the last $k-i$ rows to get the triangular matrix

$$\begin{pmatrix} a_k & 0 & \cdots & \frac{a_k}{a_1}(b_1-1) & \cdots & 0 & 0 & \frac{a_k}{a_1} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & b_i - 1 & \cdots & 0 & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & 0 & \cdots & 0 & a_{k-1}\frac{1-b_i}{b_{k-1}-1} & \frac{1-b_i}{b_{k-1}-1}+1 \\ 0 & 0 & \cdots & 0 & \cdots & 0 & 0 & (1-b_i)\frac{1+\sum_{j\neq i}^k \frac{1}{a_j}}{\sum_{j\neq i}^k \frac{b_j-1}{a_j}-1}+1 \end{pmatrix}$$

We are now in a position to solve:

$$|\mathbf{A}_i| = [\frac{b_i}{a_i} + \sum_{j=1}^k \frac{b_i - b_j}{a_i a_j}]\prod_{j=1}^k a_j.$$

By Cramer's rule, $\frac{\partial q_i}{\partial \sigma} = \frac{|\mathbf{A}_i|}{|\mathbf{A}|}$. Hence,

$$Q_\sigma = \sum_{i=1}^k \frac{\partial q_i}{\partial \sigma} = \sum_{i=1}^k \frac{|\mathbf{A}_i|}{|\mathbf{A}|} = \frac{\sum_{i=1}^k \frac{b_i}{a_i} + \sum_{i=1}^k \sum_{j=1}^k \frac{b_i - b_j}{a_i a_j}}{1 + \sum_{j=1}^k \frac{1}{a_j}} = \frac{\sum_{i=1}^k \frac{b_i}{a_i}}{1 + \sum_{i=1}^k \frac{1}{a_i}}.$$

Substituting the expressions for $a_i$ and $b_i$ into $Q_\sigma$ above produces (3)-(5).

A particular Cournot equilibrium is stable only if (Dixit, 1986):

$$(-1)^k \prod_{i=1}^k [\alpha_i P_Q - MC_q^i][1 - \sum_{i=1}^k \frac{P_Q + \alpha_i(q_i - f_i)P_{QQ}}{MC_q^i - \alpha_i P_Q}] > 0.$$

By $\alpha_i P_Q < MC_q^i$, this condition is equivalent to the denominator of $H$ defined in (5) being strictly positive. The numerator of $H$ is strictly positive. Hence, $H > 0$ in stable equilibrium.■

**Price-dependent bids** Proposition 1 is based on the assumption that firms with market power bid all their production inelastically into the market. To check the robustness of the proposition to this assumption, we now consider a more general model in which firms also submit price-dependent bids in a way that is consistent with horizontal shifts of the equilibrium supply curve. Assume that all firms $i \in K$ supply $q_i$ inelastically into the market, but also submit a bid-curve $\lambda MC^r(\hat{q}_i - q_i)$, where $\lambda \geq 0$. The baseline case is for $\lambda \to \infty$. If the wholesale price equals $p$, then quantity $\hat{q}_i$ produced by firm $i$ is given by $\hat{q}_i = q_i + (MC^r)^{-1}(\frac{p}{\lambda})$. Assume for simplicity that total demand is price-inelastic and given by $\sigma$. If we now define $D(p, \sigma) = \sigma - k(MC^r)^{-1}(\frac{p}{\lambda})$, then the inverse demand curve for the Cournot quantity $Q = \sum_{i=1}^k q_i$ is still given by $P(Q, \sigma)$. The inverse demand slope becomes $P_Q = -\frac{\lambda}{\lambda+k}MC_q^r$.

Firm $i$ maximizes

$$\alpha_i P(q' + Q_{-i}, \sigma)((M^r)^{-1}(\frac{1}{\lambda}P(q' + Q_{-i}, \sigma)) + q') - \int_0^{((M^r)^{-1}(\frac{1}{\lambda}P(q'+Q_{-i},\sigma))+q')} MC^i(z)dz$$
$$+\alpha_i(g_i - P(q' + Q_{-i}, \sigma))f_i + (1 - \alpha_i)\int_0^{((M^r)^{-1}(\frac{1}{\lambda}P(q'+Q_{-i},\sigma))+q')'+Q_{-i}} P(Z, \sigma)dZ$$

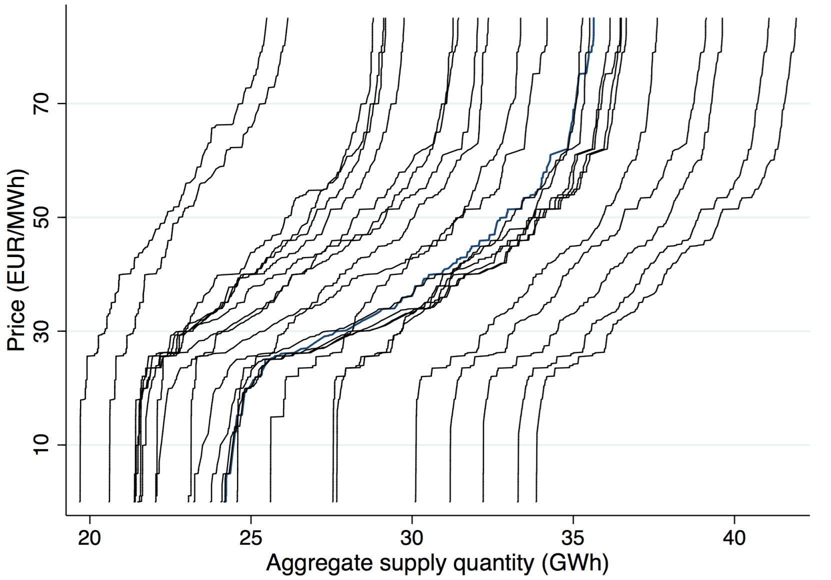
over its Cournot quantity $q'$. The $k$ first-order conditions

$$P(Q, \sigma) - MC^i(\hat{q}_i) = \alpha_i(\hat{q}_i - f_i)\frac{\lambda + k}{\lambda + k - 1}|P_Q(Q, \sigma)| \ \forall i \in K$$

are essentially the same as in equation (2). In particular, the incentive to exercise market power depends on the aggregate slope $|P_Q|$ multiplied by a constant $\frac{\lambda+k}{\lambda+k-1}$.

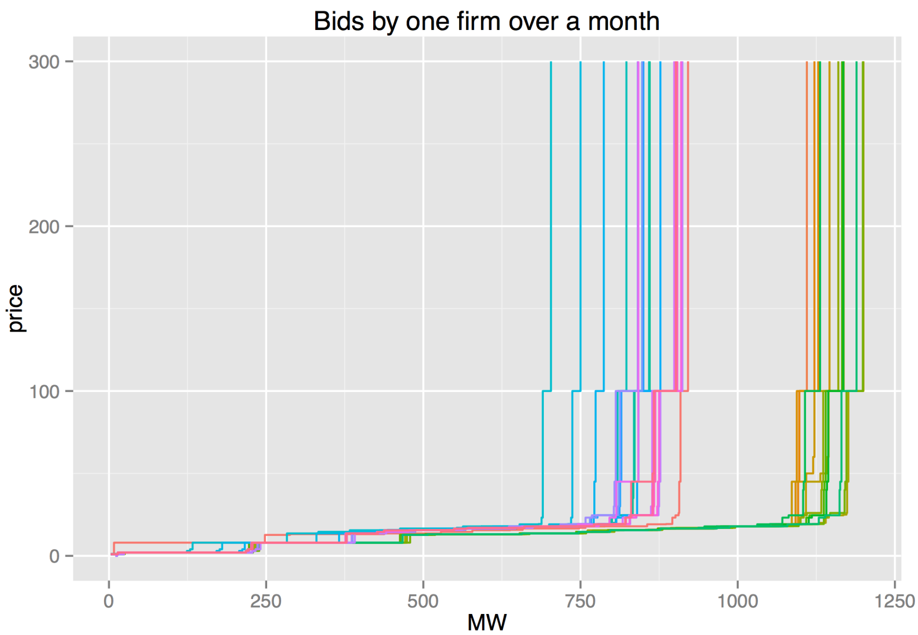
# Appendix B

Figure B1: Horizontal supply shifts in Germany



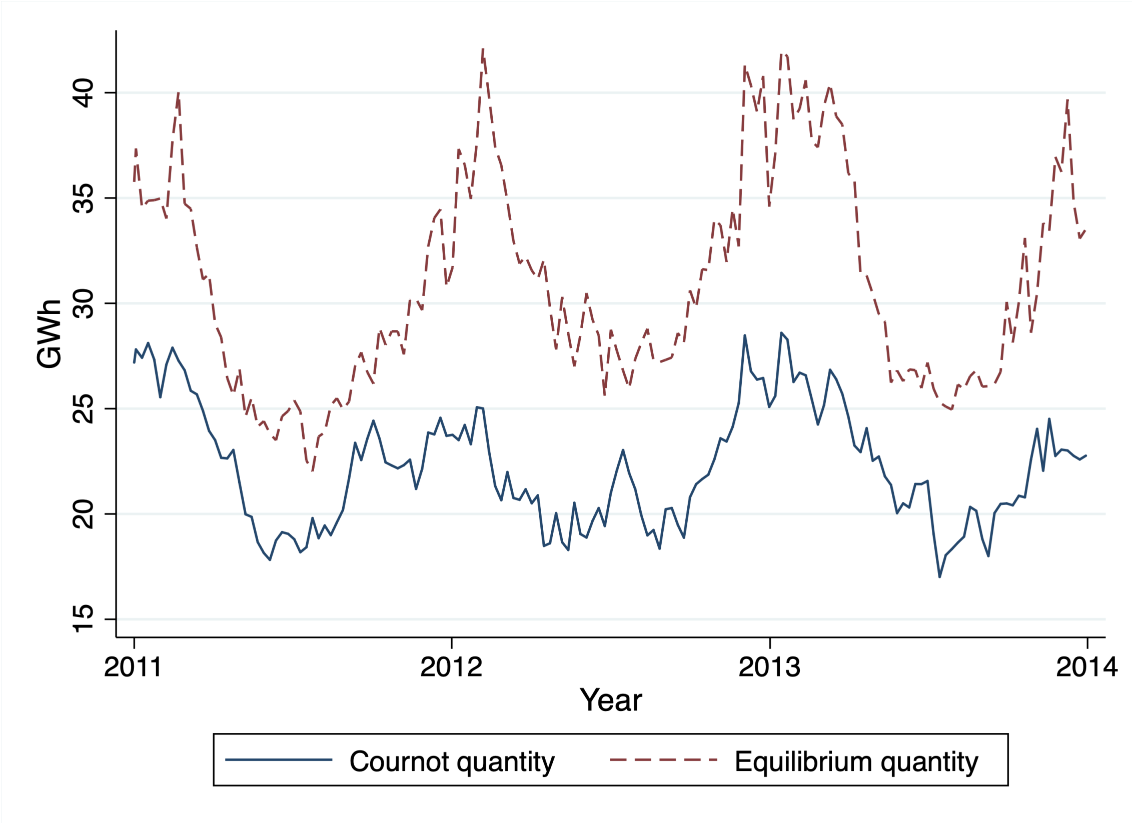

Note: This figure depicts aggregate supply bids in the German bidding area day-ahead market (EPEX) during one day.

Figure B2: Horizontal supply shifts in MISO




Note: Supply bids for one firm over one month in MISO. Source: Mercadal (2016).

Figure B3: Cournot quantity and cleared volume

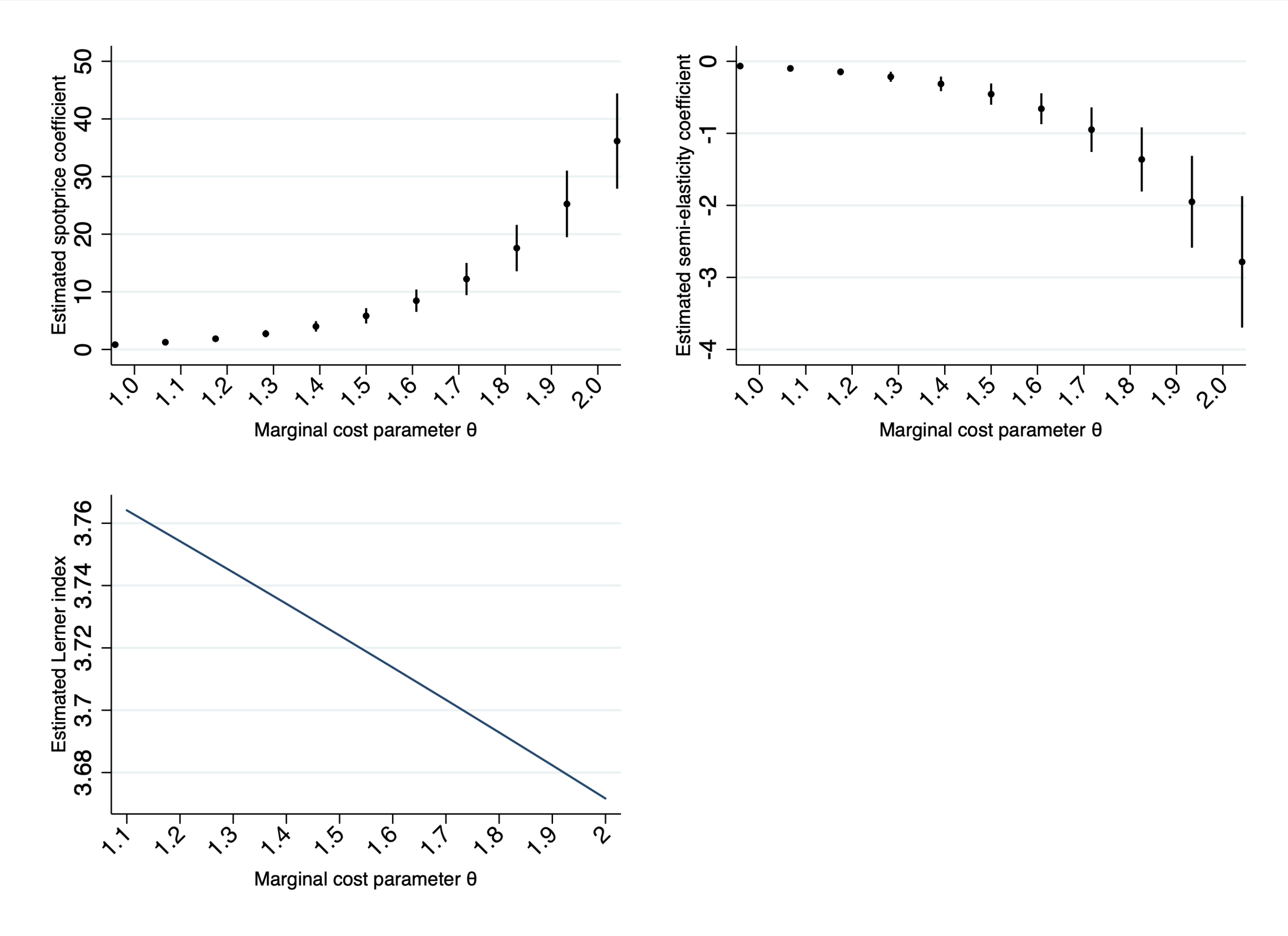



Note: This figure depicts the Cournot quantity and total cleared volume as a function of time.

Figure B4: Price areas after Nov 1 2011


Note: Geographical borders of the price areas in the Nordic region after November 1 2011.

Figure B5: Marginal cost sensitivity



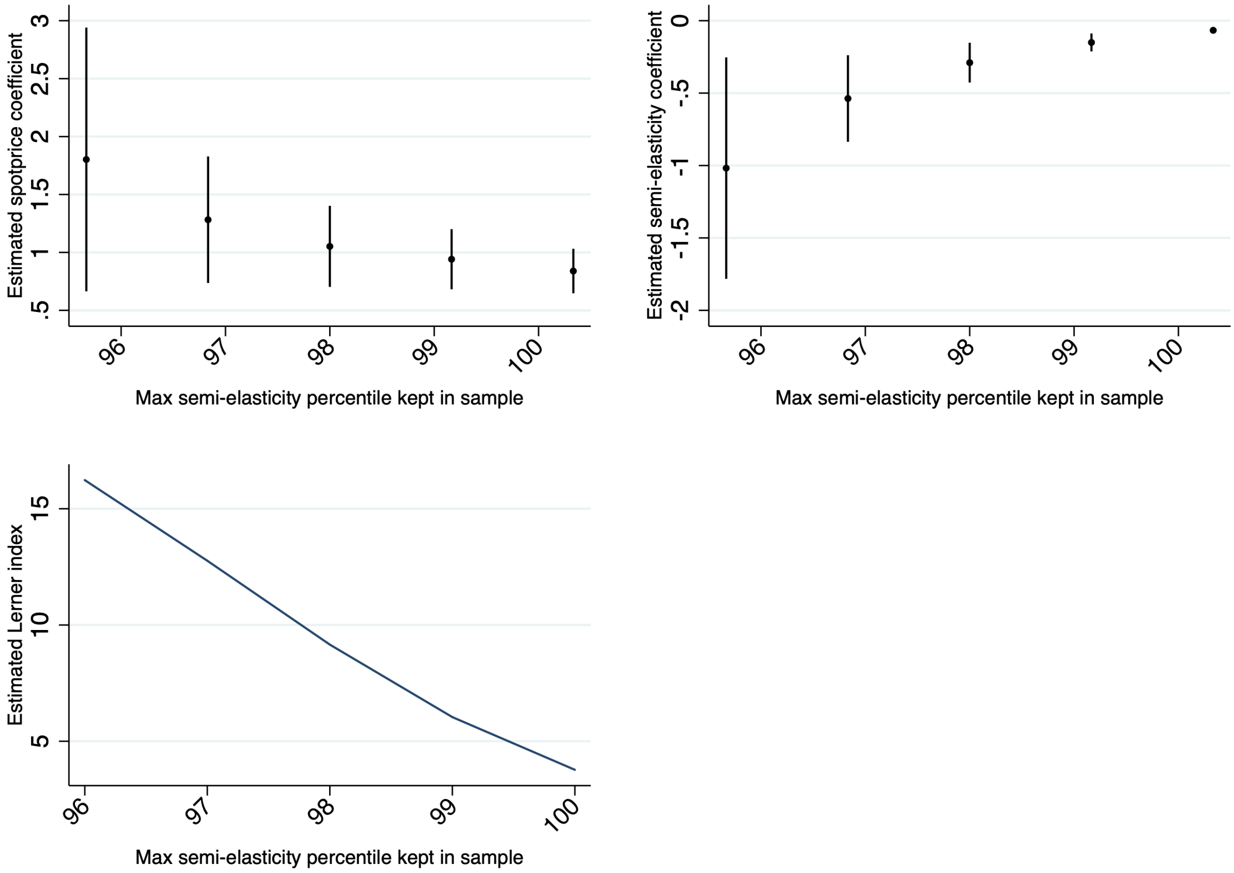

Note: The top left figure depicts estimated price coefficients under baseline specification (2) for different marginal cost assumptions. Marginal cost is assumed to be of the form $MC^i(q_i) = \gamma + cq_i^{\theta}$, where $\theta \in [1, 2]$. The corresponding semi-elasticity coefficients are depicted in the top right figure, and the corresponding Lerner indices are depicted in the bottom left figure. Vertical lines are 95 percent confidence intervals.

Table B1: Sensitivity to choice of instruments. Dependent variable: Cournot quantity

| | (1) | (2) |
|---|---|---|
| Price (p) | 0.71*** | 0.77*** |
| | (0.0833) | (0.0918) |
| Semi-elasticity ($\|P_Q\|(Q-F)$) | −0.055*** | −0.061*** |
| | (0.00923) | (0.0101) |
| Temperature | −0.014 | −0.013 |
| | (0.0270) | (0.0298) |
| Lerner index | 3.73 | 3.75 |
| Fixed effects | Week | Week |
| Cragg-Donald F-stat | 142.7 | 136.8 |
| N | 26304 | 26304 |

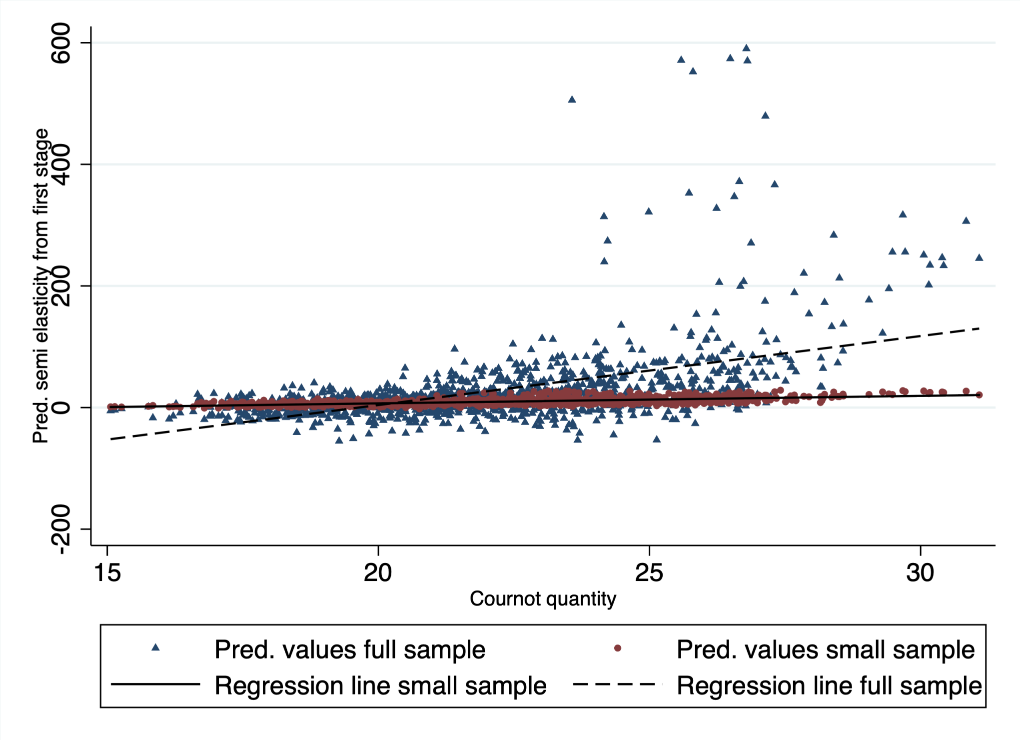
* p < .10, ** p < 0.05, *** p < 0.01
Note: This table depicts results from baseline specification (2) using different sets of instruments. In specification (1), the price and semi-elasticity are instrumented using the square of forecasted demand and wind power production, but Norwegian wind output is constant during each month-of-sample. In (2), Danish wind output has been replaced by the corresponding day-ahead forecast at the time of bidding. In both specifications, Cournot bids have been computed based on each respective wind definition.

Figure B6: Sensitivity to outliers



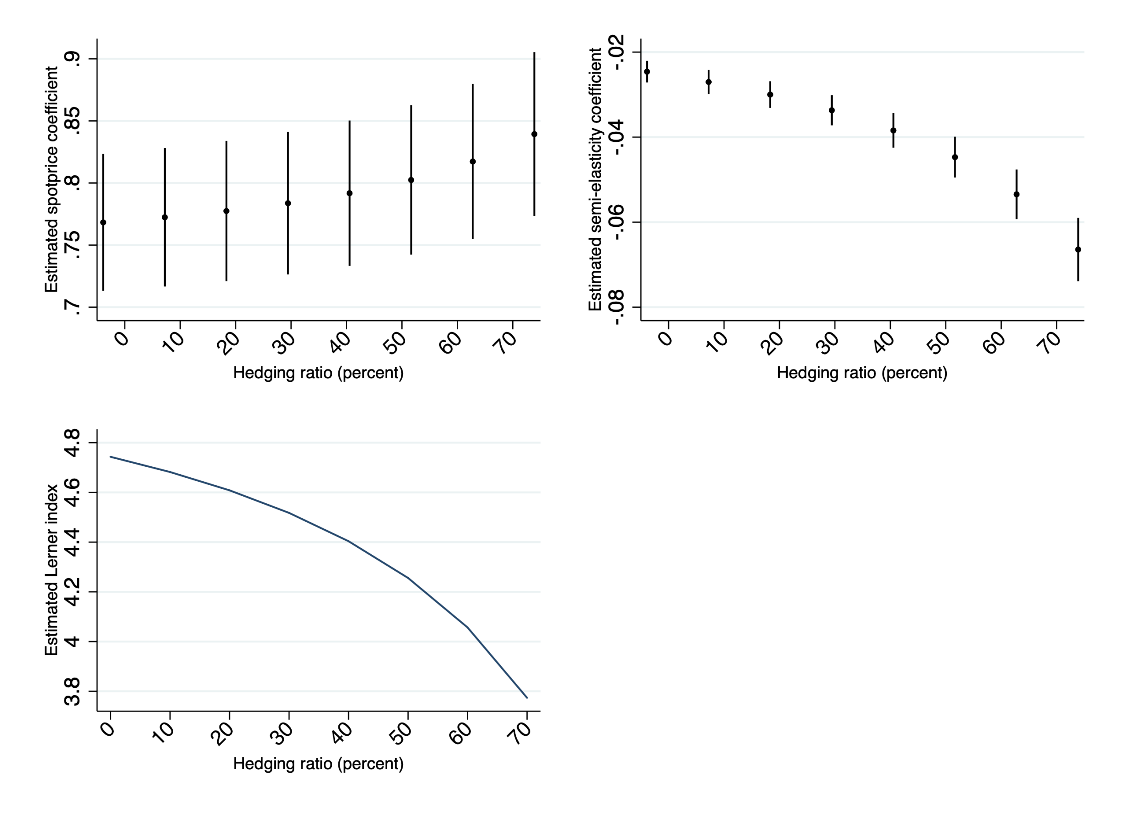

Note: The top left figure depicts estimated price coefficients under baseline specification (2) when removing all observations above the $96^{th} - 99^{th}$ percentile of the semi-elasticity variable. The corresponding semi-elasticity coefficients are depicted in the top right figure, and the corresponding Lerner indices are depicted in the bottom left figure. Vertical lines are 95 percent confidence intervals.

Figure B7: Predicted semi-elasticity and Cournot quantity



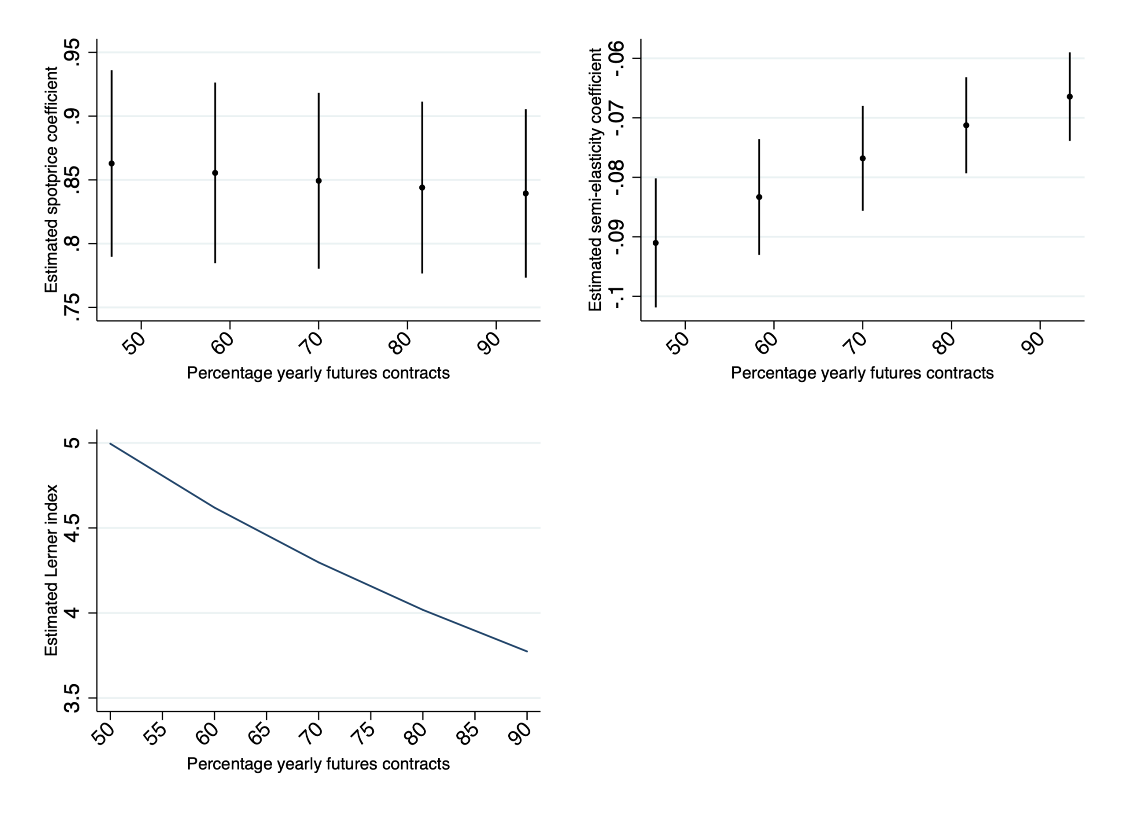

Note: This figure depicts the predicted semi-elasticity from the first stage regression when including the full sample (triangles), the corresponding Cournot quantity, and the corresponding regression line (dashed). Also shown are the predicted values excluding all semi-elasticity observations above the $98^{th}$ percentile (circles) and the corresponding regression line (solid).

Figure B8: Hedging ratio sensitivity




Note: This figure depicts estimated coefficients and markups under different assumptions about the mean hedging ratio.

Figure B9: Sensitivity to relative share of yearly vs. load following forward obligations




Note: This figure depicts estimated coefficients and markups under different portfolios of yearly vs. load following forward obligations. The mean hedging ratio is 70 percent for all cases.