How competitive is cross-border trade of electricity? Theory and evidence from European electricity markets

Georg Gebhardt[1] and Felix Höffler[2]

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Abstract

Integrating national markets is a major policy target in the European energy market. Yet, wholesale prices for electricity still differ significantly. Whether these price differences are caused only by limited interconnector capacities or also by lack of cross-border competition is an open question. To address this question, we develop a new approach to determine to which extent price differences stem from limited participation in cross-border trade. We derive a theoretical integration benchmark, using Grossman's (1976) notion of a rational expectations equilibrium. We compare the benchmark to data from European electricity markets. The data reject the integration hypothesis and indicate that well informed traders do not engage in cross-border trade.

Keywords: Market integration, electricity markets, interconnector, competition policy, rational expectations equilibrium

JEL-Classification: G14, D84, L94

[1] Department of Econmics, University of Munich, Ludwigstr. 28 (Rgb), D-80539 Munich, Tel.:++49 (0)89 2180 2876, georg.gebhardt@lrz.uni-muenchen.de

[2] Chair of Regulatory Economics, WHU - Otto Beisheim School of Management - Burgplatz 2, 56179 Vallendar , Germany. ++49(0)261 6509220. felix.hoeffler@whu.edu . Research Affiliate, Max Planck Institute for Collective Goods, Bonn.

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1 Introduction

The integration of regional markets into a single supraregional market features high on the agenda of policy makers; integrated markets allow more efficient production and increase competition. A case in point is the European market for electricity. In its 2007 “Sector Inquiry" the EU commission states:

> Well functioning energy markets that ensure secure energy supplies at competitive prices are key for achieving growth and consumer welfare in the EU. To achieve this objective the EU decided to open up Europe's gas and electricity markets to competition and to create a single European energy market. (EU, Sector Inquiry 2007, para.1)

However, “...the objectives of the market opening have not yet been achieved." (ibid., para.2). Spot market prices still differ significantly among the member countries. At least some of this price divergence is caused by limited interconnector capacities between the national electricity grids; exactly how much, remains an open question. Limited interconnector capacity could just mask a lack of participation in cross-border trade. This is possible since at many European borders congestion is managed not by a centralized nodal pricing system, but by using physical transmission rights: firms first have to acquire physical interconnector capacity to be then able to participate in cross-border trade.

In this paper, we investigate the question of market integration and competition by first proposing a theoretical benchmark and then empirically applying it to the case of the European electricity markets using physical transmission rights. The results should help to inform regulators and policy makers to assess whether price differences are solely a result of technical congestion (such that capacity increases would be an obvious policy implication) or possibly a result of strategic behavior (such that alternative institutional designs or stricter regulatory oversight might be called for).

For the test we consider interconnector prices and spot market prices. The (theoretical) integration benchmark is based on a standard idea in economics: Prices aggregate information. All traders value interconnector capacity at the spot market price differential between the two sides of the border. Every trader has some private information about this price differential, but there is no aggregate uncertainty since all traders together determine spot market prices. If interconnector prices aggregate the traders' information, interconnector prices should perfectly predict the price differential in the direction in which trading is profitable, and should be zero in the opposite direction.[3]

If not all traders are willing to engage cross-border trades — this is our definition of imperfect integration — interconnector prices contain less information; however, there could be a confounding source of noise: Since traders must buy interconnector capacity before they can trade in the spot markets, they may receive additional information

[3]We model this using Grossman's (1976) notion of a rational expectations equilibrium.

between the two trades; in this case, even if all traders try to engage in cross-border trade, interconnector prices cannot contain this additional information. Yet, the arrival of additional information has a second effect - traders assign an option value to interconnector capacity: Suppose, in the interconnector market, a trader expects that the spot price will be higher in country A, but is aware that additional information, arriving before the spot market, may invert her estimate of the price differential; this trader is willing to pay a positive price also for capacity into country B. Thus, if we observe that interconnector prices are only a noisy predictor of the price differential but that there is no corresponding option value, i.e., the lower interconnector price is zero, we can conclude that our integration benchmark is violated.

We compare this theoretical benchmark for integration to data from the Danish–German and the Dutch–German borders for the years 2002-2006. We have price data resulting from interconnector capacity auctions and the respective spot markets, in each case for hourly, day-ahead electricity contracts. In the first two countries, electricity prices are very similar on average; on the second border, spot market prices in the Netherlands are on average significantly higher than in Germany.[4]

The stylized facts of the data are not in line with the integration benchmark. The lower of the two interconnector prices is almost always zero or very close to zero, suggesting that cross-border traders expect little new information to arrive. At the same time, interconnector prices predict the spot market price differentials on average correctly but only with a lot of noise, suggesting that cross-border traders possess a limited amount of information. We conclude that the missing information is private information of market participants who do not conduct cross-border trades.

In order to make this reasoning more precise, we calibrate our theoretical model to find out exactly how much information arrives between the interconnector and the spot markets, and how much information the interconnector prices actually contain. We find that the information cross-border traders receive after they have bought capacity but before they trade across borders is essentially zero. The information cross-border traders possess when they buy capacity is only between 24% (Germany/Netherlands) and 36% (Germany/Denmark) of the total variance of the price differential. Thus, our main conclusion is that traders with a large amount of relevant information do not participate in the interconnector auction although they could generate profits based on their information. To explain the absence of these informed traders is beyond the scope of our paper; however, cross-border collusion could provide a plausible motive for such behavior; the suspicion of cross-border collusion is expressed by several competition authorities.[5]

Our results are complementary to the theoretical analysis of the competitive effects of limited transmission capacity developed by Borenstein, Bushnell, and Stoft (2000), who

[4] Another important example for electricity markets is the path 15 interconnector between Northern California and Southern California, which often is a bottleneck between the two regions.

[5] We provide references in the Discussion.

show that expanding transmission capacity between two otherwise separated markets may result in a large reduction of market power. The authors caution, however, that they have "considered only one-shot Nash equilibria (. . .). In reality, the firms that compete in electricity markets will do so repeatedly and, thus, may be able to reduce rivalry through the threat of retaliation. To the extent that firms can reach more cooperative outcomes through such supergame strategies, the competitive effects of transmission lines (. . .) are likely to be dampened." (p. 320). Our analysis suggests that multi-period considerations are likely to play a role in electricity markets.[6]

Due to the high policy relevance of market integration, empirical studies have looked at the price dispersion between EU countries. Zachmann (2008) shows that, by and large, there was no convergence of wholesale prices in Europe for the period we investigate (2002-2006). Our research question is complementary to this approach, since we do not look at the levels of (differences in) spot prices; our definition of integration could be in line with different spot prices in different countries – as long as all traders participate in cross-border trade, and as long as the price difference is just due to a lack of physical capacity.

An introduction to "interconnector economics" can be found in Turvey (2006), or, more generally, in Crampes and Laffont (2001). Hobbs, Rijkers, and Boots (2005) and Höffler and Wittmann (2007) discuss the effects of different institutional designs for the interconnector auctions on the market outcome. None of these approaches directly tackles the question of how to explain the relation between spot market prices and interconnector prices, which is the main contribution of our paper.

Our analysis is also related to the literature on the Law of One Price (LOOP), see, e.g., Engel and Rogers (2001) and Goldberg and Verboven (2005). The LOOP cannot be expected to hold with infrastructure bottlenecks, which are common in electricity or gas, but could also occur for other commodities like crude oil if transport capacities are scarce. We extend this literature in that we do not only consider the spot market prices but also transport capacity prices. This approach allows us to separate the effects of transport capacity constraints from limited participation in cross-border trading.

The remainder of the paper is organized as follows: In section 2 we introduce the institutional set up of the cross-border electricity trade in Europe. Section 3 describes the data and the main stylized facts. Section 4 describes the theory and its predictions. Section 5 presents the calibration of the model and the main empirical results. The findings are discussed in section 6; section 7 concludes. The full theoretical model is relegated to Appendix A, details of the calibration method are in Appendix B.

[6] Another related article is (Neuhoff 2002), who investigates the effect of the market design of cross-border electricity trade on the level of competition.

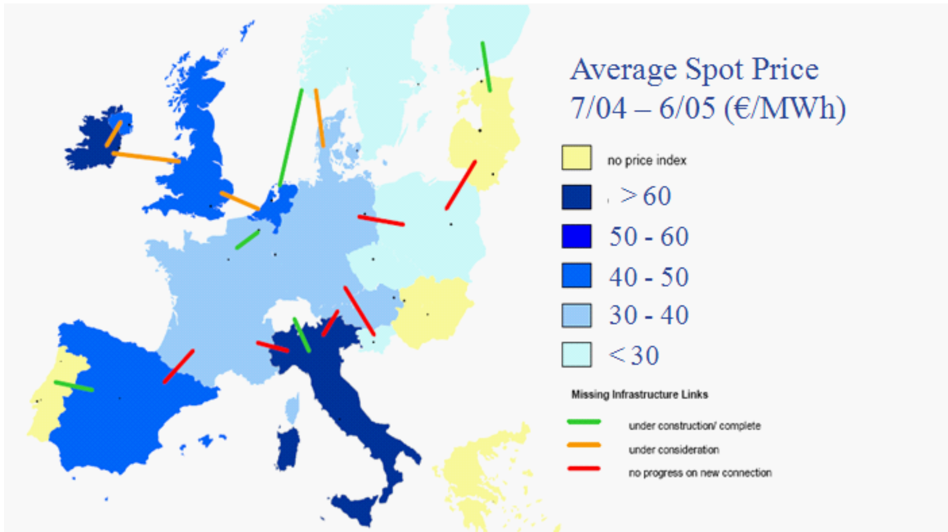

Figure 1: Spot price differences

2 European Electricity Markets

The European Union has clearly spelled out that a unified electricity market should be implemented in Europe. Since electricity can be transported at the high voltage level at very low cost, there could be supraregional or supranational electricity markets. A geographically large market, based on imports and exports of electricity, could increase the level of competition and increase efficiency by supplying electricity by the least-cost producer.

> Electricity should, as far as possible, flow between Member States as easily as it currently flows within Member States. Improved cross border flows will increase the scope for real competition which will drive economic efficiency in the sector... (European Commission 2004, 3)

However, it is obvious that this goal has not been achieved yet. In Europe, wholesale electricity markets are still largely national markets. There exist different electricity exchanges in almost all countries, and the spot market prices differ considerably, up to more than 100 percent. Figure 1 shows the results of an investigation of this issue by the European Commission.[7]

An important reason for the fragmentation of the European electricity market are limited interconnector capacities. In its "Sector Inquiry", the EU Commission finds that

[7] Communication from the EU Commission to the Council and the EU Parliament. Report on progress in creating the internal gas and electricity market, COM (2005) 568 final (15/11/2005), p.5. Similar findings are in the “Sector Inquiry" of 2007, Part 2, p. 180 (European Commission 2007).

"In electricity, integration is hampered by insufficient interconnector capacity"(European Commission 2007, para. 23). There exist only limited capacities for the exchange of electricity between national grids.[8] There are historical reasons for this: "Transmission networks were not developed in order to support efficient trade", but rather to optimize intra-country operations (CEER 2003, par. 8). With the liberalization of national electricity markets, increasing interest in the international trade of electricity has turned cross-border transmission capacities into a bottleneck. At most interconnectors, the scarce capacities are now allocated in auctions.[9]

Although limited interconnector capacities set an upper bound for trading volumes between countries, an important question is whether differences in prices between national electricity markets, and therefore limited cross-country competition, is only due to congestion. The availability of interconnector pricing data and of spot market prices allows us to investigate this question. We focus on two interconnectors and the interaction between the spot markets: (i) Denmark (West) and Germany, with the spot markets 'Nord Pool West' and 'EEX', and (ii) the Netherlands and Germany, with the spot markets 'APX' and 'EEX'. Figure 1 illustrates that these two examples captures the main interesting cases, i.e. the comparison of markets with – on average – similar spot prices (Denmark and Germany) and markets with – on average – different price levels (Netherlands and Germany).[10]

For the time period we investigate (2002-2006), at the Danish-German interconnector and at the Dutch-German interconnector there were day-ahead auctions for hourly contracts, i.e. for the right to transport 1 Mega Watt for a specific hour the next day.[11] Holding such a transmission right was compulsory if one wanted to engage in cross-border sales on the electricity exchange; if, for instance, a Danish power producer wanted to offer electricity on the German EEX, it had to hold sufficient transmission rights to be able to fulfill a successful bid.

[8] We abstract from insufficient transmission capacities within each national grid. Congestion on the national level is rather rare for the countries we are considering. We also abstract from implications of loop flows for the network operations.

[9] For the time period of this paper, physical transmission rights were the most common method of congestion management. Recently, also at the interconnectors investigated in this paper, "market coupling" has been introduced, i.e., an attempt to get closer to "nodal pricing" with purely financial transmission rights.

[10] These are physical hourly contracts in which a bidder has to specify day ahead a demand / supply function for electricity of a particular hour. Thus, there are essentially 24 markets per day. Bids have to be continuous. Delivery of successful bids is on the high voltage level to a virtual trading point. This implies that for trades on the electricity exchange, no transportation cost within a country has to be incurred (any transportation cost towards the customer on lower voltage levels has to be borne by downstream companies). Therefore, it makes sense to compare the spot market prices.

[11] The daily auction was just one part of the allocation scheme. One part of total capacity was sold in an annual auction, a second part in a monthly auction, and the remainder (including capacities not nominated from the long term auctions) where offered in the daily auctions. Since there were also long term auctions, buying capacity in the daily auction to support long-term electricity supply contracts was probably not important. For details see (Höffler and Wittmann 2007).

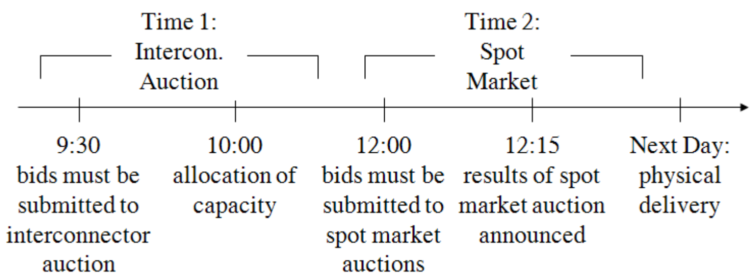

Figure 2: Timing of capacity auction and spot market

Therefore, the interconnector auction took place first; afterwards firms got informed about the auction outcome, and on that basis might submit bids in the adjacent market's spot market. Figure 2 shows the typical timing of the actions.[12] Note that there is only a time frame of 2.5 hours between the submission of the bids for the two auctions. Thus, differences in information between the two auctions must be due to interim information arriving precisely between 9:30 a.m. and 12.00 a.m.

There is certainly no aggregate uncertainty regarding the spot market prices, since all traders jointly determine the spot market prices. Any random events (e.g. like weather conditions, unexpected power plant outages, etc.) either enter the prices via the behavior of the traders, or (if they happen after the closing of the spot market) have to be handled by the transmission system operator on the day of delivery, and can have no effect on the spot prices.

3 Theory

In this section we describe a theoretical benchmark to which we will compare the data. A full fledged theoretical model which yields this benchmark is lengthy and therefore relegated to Appendix A.

Our benchmark is a benchmark of perfect competition that takes into account the specific information structure of the interaction, namely that different bidders may have different information. Furthermore, we have to account for the sequential structure of the two auctions and the possibility that new information arrives in-between. To capture this, we use the standard notion of a rational expectations equilibrium; more precisely, we use the concept of the fully revealing rational-expectations equilibrium, introduced by Grossman (1976). Rational expectations means that each trader uses all information available to her, in particular, the information contained in the realized market prices; furthermore a *fully revealing* rational-expectations equilibrium requires that the price

[12] Note that the two spot market clear simultaneously but independently. Thus, bids in one market can not be conditional on outcomes of the other spot market.

is a sufficient statistic for the information of each trader. In such an equilibrium, no trader has a desire to revise her demand once the realized prices become known, and even if the trader could observe the signals of all other traders, she would still not want to revise her demand. This formalizes the fundamental economic idea that prices aggregate information.

The benchmark suggested is therefore an *equilibrium definition* that satisfies price taking behavior, market clearing, and full information revelation. What we do not provide is a game theoretic foundation of such an equilibrium outcome, i.e., we do not describe the strategies of bidders.[13] This is identical to the typical competition policy exercise where the market outcome is compared to the standard competitive equilibrium outcome by, e.g., using the Lerner index to see by how much the market price differs from the marginal cost. Also in this case, competition policy does not describe how the competitive benchmark (price = marginal cost) comes about. We do exactly the same, the only difference is that we incorporate the information structure by demanding full information revelation in equilibrium.

In the model, there are N traders who can trade electricity between two countries if they acquire interconnector capacity. By acting on the spot markets in the two countries, these traders will jointly determine the spot prices. In the morning, each trader wakes up and receives a piece of relevant information (a signal) about the spot price difference between the two countries for each hour of the following day. The price difference is the value of the interconnector capacity. Based on the private information, traders decide on buying capacity. Afterwards, additional public information may be revealed to all traders (e.g., a weather forecast update). Taking also this "interim information" into account, traders trade on the spot markets, using their interconnector capacity. There exists no "aggregate uncertainty", i.e., a trader who would know all the individual signals and the interim information knows exactly the spot price difference. This is realistic, since the spot price is determined collectively by all traders, without any exogenous force intervening in the price building.

Given this setup, Grossman's equilibrium notion makes the following predictions:

Prediction 1 *If all traders participate in the interconnector auction, and no interim information exists, the interconnector price into the direction of the higher spot price region is exactly equal to the spot price difference. It is zero in the opposite direction. [See Proposition 1 in Appendix A].*

[13] The fully revealing rational-expectations equilibrium makes a prediction of the resulting market price but it remains silent on how these prices come about; in particular, demand curves are not well specified. This problem has already been extensively studied in the literature, and Hellwig (1980) has shown that the fully revealing rational expectations equilibrium can be interpreted as the limit of a slightly perturbed market as the perturbation goes to zero. In the perturbed market, traders have well defined demand functions which are used by the Walrasian auctioneer to derive equilibrium prices and quantities. We consider the direct use of the unperturbed model as a useful shortcut whose simplicity compensates for its reduced intuitive appeal.

This just reflects that the interconnector price is fully revealing, i.e., aggregates all available information. If there is no interim information, and all traders who hold information trade already in the interconnector auction, the interconnector price must contain all information about the value of the interconnector capacity, which is exactly the price difference into the direction of profitable trade. The value of interconnection capacity in the opposite direction given full information revelation is zero, hence the price of interconnector capacity is zero in the direction of the lower spot price.

Prediction 2 *If all traders participate in the interconnector auction, and there is interim information, then the interconnector price equals the spot price difference into the direction of higher prices only on average. The price in the opposite direction is strictly positive. [See Proposition 2 in Appendix A].*

In the model, we treat the interim information as a random shock with mean zero. Thus, even if one would hold all information of all trader in the first stage (interconnector auction), one would not be able to predict the spot price difference perfectly, since the interim information is missing. Thus, also a fully revealing interconnector price can not perfectly predict the spot price difference. However, since the interim information has mean zero, the prediction is right on average.

Since there is some noise left at the first stage, the interconnector price into the direction where – based on the aggregate first stage traders' information – the spot price is expected to be lower must also be positive. The reason is that this interconnector capacity now has an option value. Traders know that, with some probability, the interim information will revert the sign of the expected spot price difference. Therefore, it is valuable to hold such capacity into the opposite direction.

As a last case, we look at a situation where not all traders engage in cross-border trade.

Prediction 3 *If not all traders participate in the interconnector auction, and there is no interim information, the interconnector price equals the spot price difference into the direction of the higher price only on average. The price in the opposite direction is zero. [See Proposition 3 in Appendix A].*

If not all traders take part in the interconnector auction, then clearly the interconnector price cannot reveal all information, even if there is no interim information. In the model, we assume that the individual signals all have mean zero, hence if one would know a strict subset of all trader's information, one would be able to predict the price differential correctly on average. Since the information of some of the traders is missing, the prediction will not be perfect and we will find some noise when comparing the interconnector price to the spot price differential. However, this noise will not give rise to an option value for those traders who participate in the interconnector auction in the absence of interim information. The option value is created for a trader who knows that later on (before the spot market) she will learn more about the spot price differential. This is not the case here, since not the interim information is lacking (by assumption, this is zero in this case), but the information of the non-participation traders. And their information will only be revealed in the spot market prices (and then it is too late to create value for the traders who participated in the interconnector auction). Therefore, the interconnector price into the direction of the lower spot price will be zero.

4 The Data

Our data for the spot prices stem from the respective electricity exchanges, APX (Netherlands), EEX (Germany), and NordPool (Denmark). They are in current Euro / MWh for each respective hour in the day ahead trading for the time from the first hour (0-1) on 1/1/2002, to the last hour (23-24) on 30/9/2006, implying 41,616 observations. Interconnector prices were provided by the operators of the interconnector auctions,[14] and also contain 41,616 observations, one for every hour of the same time period. Table 1 contains the summary statistics for the prices.

Table 1: Summary Statistics

	Region	Mean	Std. Dev.	Min.	Max.
Spot Price	Denmark	33.6	17.1	0	597
	Germany	35.0	29.3	0	2000
	Netherlands	43.2	59.4	0	2000
Interconnector Prices	Den → Ger	4.3	13.3	0	500
	Ger → Den	2.1	5.2	0	64
	NL → Ger	0.04	0.09	0	5
	Ger → NL	6.7	25.7	0	639

Values in €/MWh

As noted before, the price is on average almost the same in Germany and Denmark, while on average the price is 23% higher in the Netherlands than in Germany. Average interconnector prices can be ordered according to the average spot market price difference: they are on average highest for trade from Germany to the Netherlands, followed by trade from Denmark to Germany. They are on average close to zero for trade from the Netherlands to Germany.

Table 2 provides the summary statistics for the difference of the spot market prices (*Spotdiff*) and of the interconnector prices (*Interdiff*) for both borders. For the calibration exercise of the next section, it will turn out to be important to distinguish between the higher and the lower interconnector price at each point in time. The summary

[14] We use the data for the interconnector between the German E.ON network and the Dutch network. There is also an interconnector connecting the German RWE network and the Dutch network.

statistics for these data are also provided in Table 2. *Intermax* *(Intermin)* describes — for each hour — the price for capacity in the direction with the higher (lower) price. To allow comparisons with *Interdiff*, the interconnector price from Germany to another country is reported as a negative value, the interconnector price in the opposite direction as a positive value; e.g. suppose the price from Germany to Denmark was 1.5 € while in the opposite direction it was 1.0 €, then *Intermax* is -1.5 € and *Intermin* is 1 €.

Table 2: Price Differences

	Ger-Den		Ger-NL	
	Mean	Variance	Mean	Variance
Spotdiff	1.4	606.5	-8.28	2,777.9
Interdiff	2.14	191.3	-6.61	658.0
Intermin	-0.01	0.13	0.02	0.05
Intermax	2.18	219.5	-6.63	658.2

Values in €/MWh

It is remarkable that the variance of the smaller of the two prices is by far lower than the variance of the larger of the two prices. This reflects that the lower of the two prices at each interconnector is essentially zero, or very close to zero almost always. Table 3 shows the frequency of zero prices (or prices close to zero) for the lower of the two interconnector prices. Almost half of the time, the price for interconnector capacity is exactly zero in one direction. While in the German-Danish case this can be either direction, in the German-Dutch case it is (almost always) the price from the Netherlands to Germany which is zero, while the price in the opposite direction is strictly positive. Because the lower of the prices is mostly close to zero, the variance of the difference of the two prices is (*Interdiff*) essentially equal to the variance of the larger of the two prices (*Intermax*).

Table 3: Frequency of zero interconnector prices

	Den - Ger		NL - Ger	
Interconnector Price	#	%	#	%
Min = 0.00 €/MWh	17,706	42.5%	19,242	46.2%
Min < 0.03 €/MWh	32,505	78.1%	30,967	74.4%
Min < 0.05 €/MWh	34,877	83.8%	33,068	79.5%
Total	41,616	100%	41,616	100%

Figures 3 and 4 show the data for both interconnectors. The horizontal axis shows the interconnector price difference, which is essentially the higher of the two interconnector prices since the lower interconnector price is (very close to) zero. The vertical

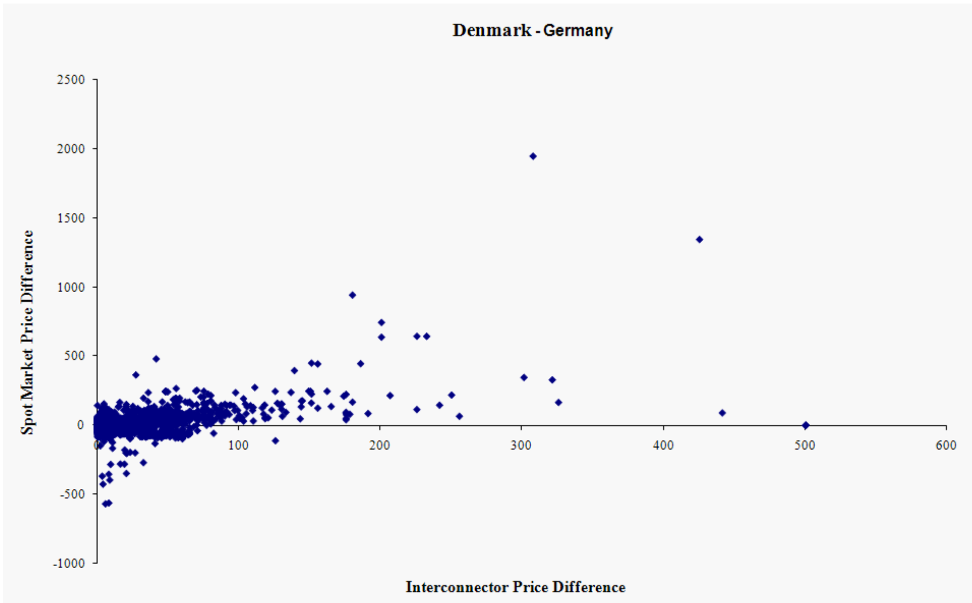

Figure 3: Spot market price and interconnector prices Denmark – Germany

axis shows the realized profit from using the capacity, i.e., the difference in the spot market prices.[15]

Using a simple (linear) regression would not be appropriate due the possibility of interim information arriving. However, a naive linear regression highlights some interesting aspect of the data. On average, the interconnector prices predict the price differential in the spot market correctly (the coefficients is close to unity).[16] Most striking is the large amount of noise, i.e., how little information capacity prices contain about the value of capacity, i.e. the price differential.

[15] All points above the horizontal axis reflect 'correct' price constellations: the price for usage of the interconnector was non-zero in the direction of the market where the spot price turned out to be higher. Note that only points above a line from the origin with slope one reflect ex-post profitable usage of the interconnector (the interconnector price was below the gain from exploiting the spot market price difference). For points below the horizontal axis, the price for usage of the interconnector was positive for the direction in which the spot market turned out to be smaller, reflecting 'mistakes'.

[16] Estimation results:

	Intercept	Coefficient	R^2
Denmark-Germany	−1.22	1.22	0.42
Netherlands-Germany	1.82	0.96	0.22

In the Dutch case, the intercept is positive, which would be in line with the assumption of some fixed trading costs (only if the spot market price difference exceeds some threshold will traders start to trade). The negative intercept in the case of Denmark is more difficult to explain in such a simple model.

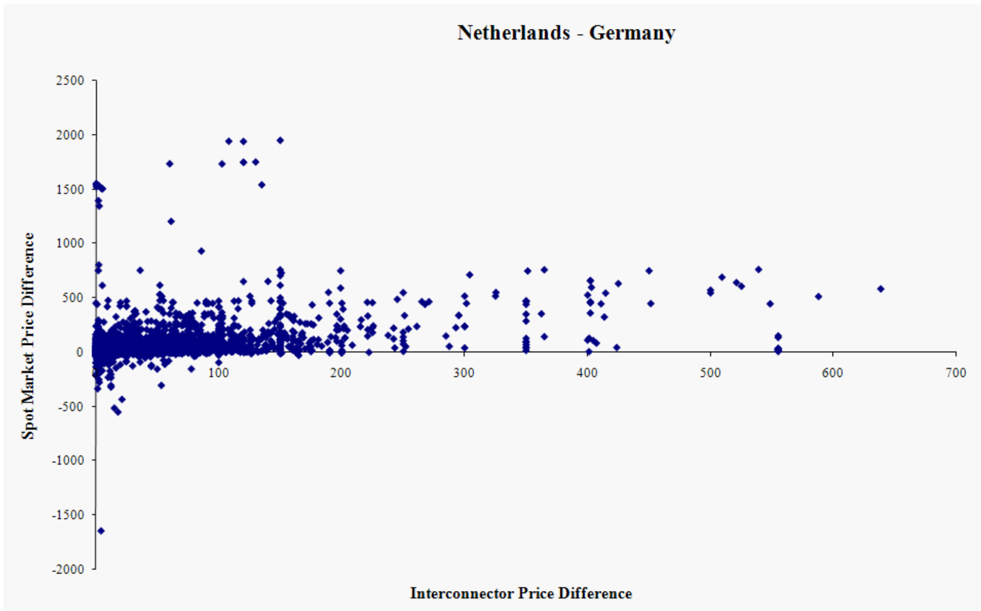

Figure 4: Spot market price and interconnector prices Netherlands – Germany

The large amount of noise is closely related to an additional important feature of the data: The variance of the larger of the two prices is considerably smaller than the variance of the spot price differential. Since we can interpret interconnector capacity as a risky asset that has the realized price differential as a payoff, this implies that interconnector capacity is an asset whose price has a lower volatility than its payoff. If, on average, the ex-ante capacity price moves much less than the ex-post realized value of capacity, it cannot contain a lot of information about the value of capacity. This lack of volatility is highly unusual because financial assets almost always display excess volatility; e.g. stock price volatility is larger than dividend volatility. Similar results have been obtained for assets ranging from bonds to foreign exchange rates (see Shiller 1981 for an overview); moreover, Cochrane (1991) argues that excess volatility is just the flip-side of the most common deviations from the efficient market hypothesis, such as bubbles and return predictability. This finding makes it very unlikely that any of these well known anomalies can account for the data observed on the interconnector capacity markets; rather these data require an explanation that is specific to cross-border trades in electricity.

We can summarize the data discussion with three stylized facts:

1. The difference in the interconnector prices predicts the price differential very well in the sense that a naive regression of the price differential on the interconnector price yields a highly significant coefficient of about one.

2. The correlation is, however, quite weak, i.e. there is a lot of noise.

3. The lower interconnector price is close to zero almost always.

5 Calibration

The data discussion already suggests that the only theoretical prediction broadly in line with the data is Prediction 3. Prediction 1 clearly does not hold, due to the large amount of noise. The interconnector price clearly does not predict the spot price differential with a high precision. Large noise can be caused either by a large amount of interim information, or by non-participation. That interim information plays a small role is suggested by the fact that the lower of the two interconnector prices is very low. Thus, the option value of trades "in the opposite direction" is very low (and exactly zero more than 40% of the time). Thus, Prediction 2 seems not to fit well, too. This suggests that it is mainly non-participation of informed traders which can explain the noise (Prediction 3).

To make this observation more precise, and to offer a methodology for less clear-cut cases, where, e.g., the lower of the two interconnector prices is not that close to zero, we calibrate a version of our theoretical model. The aim is to disentangle how much of the noise can be attributed to interim information and how much to non-participation.

In the calibration, we want to choose the simplest and most conservative benchmark which answers the question: what is the maximum amount of interim information that we can allow for, while still explaining the (low) variance in the interconnector prices "in the opposite direction". To do so, we treat each pair of capacity prices and interconnector prices as an independent observation. We can and should do so, because each hour of capacity is a separate asset for which once a price is quoted. This is in stark contrast to almost all other asset markets, in which long term assets are traded. Two stock prices, on two subsequent days, price essentially the same dividend stream; two capacity prices, on two subsequent days, relate to two entirely different payoff streams resulting from capacity utilization on the two different days.

Why do we not make use of the time series structure of our data, given the fact that energy prices are often autocorrelated; and why do we not account for seasonal effects or weekday effects? Might this not explain part of the variance? Clearly, we could try to increase the R^2 of the naive regression by including additional explanatory variables, such as the day of the week or a weather forecasts. However, we will fail to increase the R^2 if the market for interconnector capacity is informationally efficient. In an informationally efficient market, prices contain all the information available at the time of market clearing and additional variables, available at the time of market clearing, have no additional explanatory power. As a matter of fact, the market for capacity prices is not completely informationally efficient, just as no other asset market is, and we can find additional variables with explanatory power. If we include these variables, the R^2 of the naive regression will go up; but this means that the contribution of the explanatory power of the interconnector prices will even go down! The puzzle of the low informational content of capacity prices will become even larger. Therefore, by not including additional explanatory variables, we indeed take a conservative benchmark.

The calibration proceeds as follows. We write the price differential as a random variable $\widetilde{\Delta p}$, which is a sum of variables, namely:

$$\Delta p \equiv \delta + d_0 + d_1 + d_2,$$

where δ is the deterministic unconditional expectation of the price differential and d_0, d_1, and d_2 are i.i.d., normally distributed variables with mean zero, where

- d_0 with variance σ_0^2 represents the information the $\hat{N}$ firms have that trade in stage one,
- d_1 with variance σ_1^2 represents public interim information,
- and d_2 with variance σ_2^2 represents the information of the $N - \hat{N}$ firms that were not in the market for interconnector capacity.

What we are interested in are the (unobserved) variances σ_0^2, σ_1^2, and σ_2^2. Since we assumed normal distributions, the sum of these variances is just the (observed) variance σ^2 of Δp, i.e., the variance in the spot price differential. If, for instance, we would know σ_1^2, we could exactly say how much of the total variance σ^2 is explained by interim information.

As it turns out (details are given in Appendix B), we can indeed identify the variances using the observed values of δ, the average of the spot price differential, its variance σ^2, and the variances of the larger and the lower of the interconnector prices ($\bar{\sigma}^2$ and $\underline{\sigma}^2$). These observed values are given in Table 4.

Table 4: Observed Values

	Germany/Denmark	Germany/Netherlands
δ	1.4	-8.28
σ^2	606.5	$2,777.9$
$\underline{\sigma}^2$	0.13	0.05
$\bar{\sigma}^2$	219.5	658.2

Using these in the calibration procedure described in detail in Appendix B, we get as our main result values for the components of the total variance in the spot price difference (Table 5).

Table 5: Calibration Results

	Germany/Denmark	Germany/Netherlands
σ_0^2	220.2	654.9
σ_1^2	11.3	5.4
σ_2^2	375.0	2,117.6

We can conclude that a highly similar picture emerges in the two cases: There is very little interim information (σ_1^2 is very small), which accords well with the observation that lower prices are almost always zero. At the Germany/Denmark interconnector, only 2% (11.3/606.5) of the variance is due to interim information, for Germany/Netherlands it is even less than 1%.[17] Just between a quarter and a third of the total information is included in the interconnector prices: $\sigma_0^2/\sigma^2 \approx 0.36$ for the German- Danish border and $\sigma_0^2/\sigma^2 \approx 0.24$ for the German-Dutch border. This indicates that firms with a significant amount of private information do not participate in the interconnector market.

6 Discussion

Given the prices we observe, there seem to be firms which have private information but do not use it. These firms could (on average) make profits by trading in the market, but they do not do so. We can conclude that these firms do not maximize expected per period payoff. One hypothesis that would be consistent with the observed prices is that national electricity providers do not compete with each other cross-border to avoid the price reductions arising from this, which can be significant as shown by Borenstein, Bushnell, and Stoft (2000). Such a collusive arrangement could be an equilibrium in a repeated game.

The industry structure of the markets makes such an explanation not unlikely. Electricity markets are highly concentrated: For the time investigated, in Germany, the share of total production capacity (installed capacity) of the three largest firms is 69%, in Denmark it is 72%, in the Netherlands it is 69%. At the same time, a large part of the electricity market is still an OTC (over the counter, i.e. bilateral trades) market (for Germany, 88% of the market is OTC, in Denmark it is 62%, for the Netherlands it is 85%).[18] Thus, it could be a motivation to exploit market power in the home market, in particular, on the OTC markets, and mutually abstain from competing in the neighboring market, where entry is easiest on the wholesale level (i.e. at the electricity exchanges). This is in line with the view of the Danish competition authority:

[17] That interim information is relatively more important in the Denmark/Germany case is plausible due to the high amount of wind power in Denmark. This makes short term changes in the weather forecast more important.

[18] Data are from the contributions of the Danish, Dutch and German energy regulators' annual reports to the European Commission 2005. The figure for Germany includes the 7% capacity of STEAG, which is contracted long term to RWE. Downloadable from ERGEG's (European Regulators Group for Electricity and Gas) website, http://www.ergeg.org/ portal/page/portal/ERGEG_HOME/ ERGEG_DOCS/ NATIONAL_REPORTS/2005.

> Cross border trade in the Danish-German interconnector functions poorly. These elements mean that the dominant players in West and East Denmark are not exposed to effective competition.[19]

The dominant power producer thus might have a lot to lose from increased cross-border competition. At the same time, it is reasonable to assume that large producers have a lot of price relevant information that is not available to pure electricity traders. While a lot of information is public (like weather conditions, fuel prices), important supply side information is proprietary, in particular the actual availability of production capacity (e.g. power plant outages due to revisions, repair or maintenance). Furthermore, large incumbents might have better abilities to process the publicly available information.

Thus, large, well-informed producers might forgo relatively small profits from cross-border trading, in order to protect the dominant position in the home market. This is also reflected in the view of the European Commission on the behavior of European Electricity incumbents:

> Cross-border sales do not currently impose any significant competitive constraint. Incumbents rarely enter other national markets as competitors. (European Commission 2007, para. 21)

Thus, it is likely that mainly pure traders, who want to exploit trading opportunities between the regions, are active and determine the interconnector price. Since a significant part of the information is missing, transportation prices are only a bad predictor of the spot market prices (although correct on average). Prices in the opposite direction are zero because there seems to be little interim information.

To summarize: If only poorly informed traders trade in the interconnector market, but all traders (including the traders of the large incumbents) take part in the spot market, it will not be surprising to see a large variation between interconnector prices and the spot market prices. We believe that this is a convincing explanation of the data. However, as far as collusion is concerned, it is speculative.

7 Conclusion

We have analyzed a situation in which a commodity is traded in two connected spot markets. The commodity can be shipped between the two markets, but this incurs transportation costs. Firms first have to buy transportation capacity and afterwards submit demand functions or supply functions in the spot market. If spot markets are integrated and competitive, only specific combinations of transport prices and spot market prices are possible. If all firms participate in both steps (transport market and

[19] Regulator's Annual Report to the European Commission - 2005. Contribution for Denmark compiled by Danish Energy Regulatory Authority, p. 13.

spot market), either (i) transport prices already include all the information and they perfectly predict the spot market prices. This obtains if no new information becomes available between the two steps. Or (ii), with interim information, transport prices do not perfectly predict the spot market prices; but then, transport prices must never be zero in one direction, since transport capacities contain an option value. Alternatively, if not all informed firms participate in the transport market, we expect the transport prices to correctly predict the spot prices only on average, even in the absence of interim information.

The data from the electricity markets suggest that the last hypothesis is the only one consistent with the data. Given the underlying market structure, it could be a plausible explanation that well informed producing companies do not participate intensively in cross-border activities in order to exploit market power in the own region. This assumes some sort of collusive behavior of large producers between the two regions.

We have compared the data to a highly stylized and theoretical benchmark. There are probably many aspects in which the real electricity markets deviate from this benchmark. Capacity prices might be subject to strategic withholding, i.e., the "use-it-or-lose-it" requirement might not perfectly prevent market participants from buying capacity which is then left idle. A German incumbent, for instance, might buy capacity towards Germany just to block international competitors.[20]

Furthermore, we assumed that spot markets are competitive and that cross-border trades do not influence the spot prices. Clearly, all of this is debatable. However, it is important to stress that any competition policy analysis pursues the same line of comparing the market outcome to an "unrealistic" competitive benchmark, since the aim of the exercise is exactly to answer the question: how far are we away from a competitive, say, electricity wholesale market.

Our contribution is to show that – even if the market would not suffer from any imperfections like blocking entry through idle capacity – other forms of imperfection can happen and how they can be detected in the data. Incompatibility of empirical findings with the theoretical prediction then suggests that some market participants behave strategically, like a deviation from marginal cost pricing suggests that firms strategically overprice.

In terms of policy advice, our results suggest that it is not sufficient to compare only spot prices and their convergence. In the extreme, national monopolists might set (almost) identical prices in two countries, while the small price difference triggers a lot of cross-border trade by uninformed traders. Our approach would then detect the absence of trade from informed traders and would indicate the need for action by the competition authority. Finally, in terms of how to organize congestion management, our results highlight an additional advantage of "market coupling", i.e., integrating the national

[20] Indeed, there is some evidence that a considerable amount of the physical capacity at the two interconnectors investigated in this paper is left idle. See (Höffler and Wittmann 2007), p. 122-123.

However, such blocking would tend to lead to systematically higher interconnector prices, i.e., prices higher than the spot price differential, which we do not find in the data.

wholesale markets. In such a system, acting only local, is no longer possible, since the transmission market and the spot market collapse into one price setting procedure for nodal prices.

8 Appendix A: Model

We model the cross-border trade of electricity between two countries, home and abroad ($C \in \{H, A\}$), as two sets of markets that open sequentially. In the second stage, every market participant, indexed by $n \in \{1, \ldots, N\}$, trades in at least one spot market. However, only those market participants that have acquired interconnector capacity in the first stage can engage in cross-border trade. In the spot markets, demand and cost functions depend on a random shock $\tilde{s}$. We are interested in the outcomes, prices p^{H*} and p^{A*}, of the second stage spot markets only in so far as they influence the interconnector fees in the first stage; i.e., we care only about the price differential between the two spot markets that obtains if the shock s is realized:

$$\Delta p(s) \equiv p^{H*}(s) - p^{A*}(s).$$

Let s consist of $N + 1$ components:

$$s = (s_1, \ldots, s_N, s_I).$$

Before time one, s_n is revealed to firm n, but not to the other firms. This could be the level of firm n's demand or factors influencing firm n's supply, like power plant outages. All firms learn interim information s_I between time one and two; i.e., after they have bought interconnector capacity, but before they have to decide wether to use it by submitting cross-border trades. The variable s_I could be interpreted as information such as more up-to-date weather forecasts.[21]

The functional form and distribution of s and $\Delta p(s)$ are characterized by three assumptions: (1) The price differential is the sum of a deterministic component δ and the shocks $s_1, \ldots, s_N$ and s_I:

$$\Delta p(s) \equiv \delta + \sum_n s_n + s_I;$$

(2) the firm-specific information $s_1, \ldots, s_N$ takes the form of random variables i.i.d. from a Normal distribution with mean zero and variance $\frac{\sigma^2}{N}$; (3) public interim information s_I is independently drawn from a Normal distribution with mean zero and variance σ_I^2. Note that the spot market price differential is assumed to be independent of cross-border trades.[22]

During the first stage, all market participants can buy interconnector capacity in both directions on two competitive markets, capacities that may allow them to profit

[21] We use public interim information for simplicity only. We get qualitatively the same results with private interim information.

[22] This assumption can be justified by the fact that interconnector capacity is small relative to the total spot market. If we relax this assumption, the traders do not necessarily exhaust the capacity of the interconnector for a range of values of s, because they expect a price differential of zero. This introduces a discontinuity that complicates the exposition considerably, while all the results continue to hold qualitatively.

from spot price differentials by engaging in cross-border trades. The maximum interconnector capacity is $\bar{K}$ in either direction. Let k_n be the actual use of the interconnector by firm n; a positive k_n indicates that electricity flows from abroad to home. Let $K = \sum_n k_n$ be the total net use of the interconnector. Each trader n can hold no-interest-paying cash or buy capacity in either or both directions. We denote the (non-negative) capacity that trader n buys to send electricity from home to abroad by k_n^{HA} and the (non-negative) per unit fee she pays by f^{HA}. Capacities and fees in the reverse direction are called k_n^{AH} and f^{AH}, respectively. Before time one, each trader n observes the component s_n of the shock, an information that she can use to decide on her capacity demands at time one. Between times one and two, interim information s_I is revealed to all traders and, at time two, they have to decide on $k_n \in [-k_n^{HA}, k_n^{AH}]$, the net capacity they want to use for cross-border trades. Trader n's capacity purchase and utilization decisions result in time three profits of

$$\Pi = \Delta p \cdot k_n - f_n^{HA} \cdot k_n^{HA} - f_n^{AH} \cdot k_n^{AH}.$$

Assuming that all market participants are risk neutral, each buys interconnector capacity to maximize $E(\Pi)$.

To characterize the equilibrium prices on the market for interconnector capacity, we use the concept of the fully revealing rational-expectations equilibrium, introduced by Grossman (1976). It requires that traders act as price takers and stipulates market clearing; i.e., given equilibrium fees f^{HA*} and f^{AH*},

$$\sum_n k_n^{HA} = \sum_n k_n^{AH} = \bar{K}.$$

In addition, in a fully revealing rational-expectations equilibrium the price is a sufficient statistic for the information of all traders.

8.1 No Interim Information

First, we assume that the information consists only of private information $s_1, \ldots, s_N$. Let $S_N = \sum_n s_n$ denote the sum of all private signals. If no interim information arrives at the market between times one and two, the following proposition characterizes stage one prices:

Proposition 4 *If $\sigma_I^2 = 0$, the interconnector fees equals Δp in one direction and zero in the other; i.e.*

$$\begin{aligned} f^{AH^*} &= \max\{\delta + S_N, 0\} \text{ and} \\ f^{HA^*} &= \max\{-\delta - S_N, 0\}, \end{aligned}$$

and the variance of $\widetilde{\Delta p}$ conditional on the equilibrium fees f^{HA^*} and f^{AH^*} equals zero,

$$Var\left(\widetilde{\Delta p}\,\middle|\, f^{HA^*}, f^{AH^*}\right) = 0.$$

Proof. Note that for any value of S_N the larger of the two equilibrium fee is strictly monotonic in S_N. To prove that f^{HA*} and f^{AH*} are an equilibrium, note first that due to the strict monotonicity of the fees in S_N the traders can infer S_N from the fees in equilibrium. Second, the distribution of $\widetilde{\Delta p}$ given S_N is the same as the distribution given S_N and any s_n (S_N is a sufficient statistic for (S_N, s_n)). In equilibrium, all traders expect the same profits $\pi^{HA}(S_N) = \max\{-\delta - S_N, 0\}$ and $\pi^{AH}(S_N) = \max\{\delta + S_N, 0\}$ from owning capacity. If $f^{HA*} = \pi^{HA}(S_N)$ and $f^{AH*} = \pi^{AH}(S_N)$, they are just indifferent between buying or not, and they can be allocated $\bar{K}$ units of capacity in both directions so that both markets clear.
For uniqueness, suppose that there is a different set of fees, $f^{*\prime} = (f^{HA*\prime}, f^{AH*\prime})$, that also are fully revealing; i.e., all traders know the realization of S_N. At least one element of $f^{*\prime}$ cannot be equal to the expected profits from owning capacity in this direction, and demand must be either zero or infinity for this direction so that $f^{*\prime}$ cannot be an equilibrium; hence the equilibrium must be the only fully revealing rational-expectations equilibrium. ■

This is the basis for Prediction 1 in the main part of the text.

8.2 Interim Information

If interim information arrives at the market between times one and two, the interconnector prices can no longer contain all the information. Interconnector prices are characterized by the following proposition, which is the basis for Prediction 2 in the main part of the text.

Proposition 5 *If $\sigma_I^2 > 0$, the interconnector fees equal*

$$f^{AH^*} = \int_{\delta+S_N}^{\infty} [\delta + S_N + s_I]\, \phi\left(\frac{s_I}{\sigma_I}\right) ds_I \text{ and}$$

$$f^{HA^*} = -\int_{-\infty}^{-\delta-S_N} [\delta + S_N + s_I]\, \phi\left(\frac{s_I}{\sigma_I}\right) ds_I,$$

where $\phi(\cdot)$ is the p.d.f. of the standard Normal distribution.

Proof. Note that both equilibrium fees are strictly monotonic in S_N:

$$\frac{\partial f^{HA*}(S_N)}{\partial S_N} = \Phi\left(\frac{S_N}{\sigma_I}\right) > 0, \text{and}$$

$$\frac{\partial f^{AH*}(S_N)}{\partial S_N} = -\left[1 - \Phi\left(\frac{S_N}{\sigma_I}\right)\right] < 0,$$

To prove that f^{HA*} and f^{AH*} are an equilibrium, note first that due to the strict monotonicity of the fees in S_N the traders can infer S_N from of either of the fees in equilibrium. Second, the distribution of $\widetilde{\Delta p}$ given S_N is the same as the distribution given S_N and any s_n (S_N is a sufficient statistic for (S_N, s_N)). In equilibrium, all traders expect the same profits

$$\pi^{AH}(S_N) = \int_{\delta+S_N}^{\infty} [\delta + S_N + s_I]\,\phi\left(\frac{s_I}{\sigma_I}\right) ds_I,$$

and

$$\pi^{HA}(S_N) = -\int_{-\infty}^{-\delta-S_N} [\delta + S_N + s_I]\,\phi\left(\frac{s_I}{\sigma_I}\right) ds_I.$$

from owning capacity. If $f^{HA*} = \pi^{HA}(S_N)$ and $f^{AH*} = \pi^{AH}(S_N)$, they are just indifferent between buying or not, and they can be allocated $\bar{K}$ units of capacity in both directions so that both markets clear.
For uniqueness, suppose that there is a different set of fees, $f^{*\prime} = (f^{HA*\prime}, f^{AH*\prime})$, that also are fully revealing; i.e., all traders know the realization of S_N. At least one element of $f^{*\prime}$ cannot be equal to the expected profits from owning capacity in this direction, and demand must be either zero or infinity for this direction so that $f^{*\prime}$ cannot be an equilibrium; hence the equilibrium must be the only fully revealing rational-expectations equilibrium. ■

Since the support of s_I is (theoretically) unbounded,[23] for any realization of S_N there is a strictly positive probability that this will happen, i.e. there is a strictly positive probability that capacity in either direction will become profitable, and traders are willing to pay a strictly positive price for capacity in both directions at time one. The larger the variance of s_I, the less important is ex ante information $(s_1, \ldots, s_N)$, and the closer both fees are to each other in equilibrium.

8.3 Limited Participation - No Interim Information

If some second stage market participants abstain from the interconnector auction, their information cannot be contained in the interconnector prices. There are two sets of second stage market participants: Those $\hat{N}$ who take part in the first stage and those $N-\hat{N}$ who do not. Let us denote the sum of all private signals of the $\hat{N}$ firms participating in the market by

$$S_{\hat{N}} = \sum_{n=1}^{\hat{N}} s_n.$$

We can then characterize the equilibrium fee structure in the following proposition, being the basis for Prediction 3 in the main part of the text:

[23] As Figures 3 and 4 indicate, there are rare occasions where possible gains from cross-border trader become very large; the highest gain for trading from Denmark to Germany was € 568, for the opposite direction € 1,946; for Netherlands to Germany, the maximum gain was € 1,954, and in the opposite direction € 2,778 (all values per MWh).

Proposition 6 *If $\sigma_I^2 = 0$ and only $\widehat{N} < N$ traders participate in the interconnector auction, the interconnector fee equals*

$$\begin{aligned} f^{AH^*} &= \max\left\{\delta + S_{\hat{N}}, 0\right\}, \text{ and} \\ f^{HA^*} &= \max\left\{-\delta - S_{\hat{N}}, 0\right\}, \end{aligned}$$

and the variance of $\widetilde{\Delta p}$ conditional on the equilibrium fees f^{AH^*} and f^{HA^*} equals the variance of the information of the missing traders, i.e.

$$Var\left(\widetilde{\Delta p}\middle| f^{HA^*}, f^{AH^*}\right) = \frac{N - \widehat{N}}{N}\sigma^2.$$

Proof. Identical to the proof of Proposition 2, except that $\widehat{N}$ takes the place of N. ■

9 Appendix 2: Calibration of the model

We write the price differential as a random variable $\widetilde{\Delta p}$, which is a sum of the variables $\Delta p \equiv \delta + d_0 + d_1 + d_2$. As explained in the main part of the text, δ is the deterministic unconditional expectation of the price differential and d_0, d_1, and d_2 are i.i.d., normally distributed variables with mean zero. d_0 with variance σ_0^2 represents the information the $\hat{N}$ firms have that trade in stage one; d_1 with variance σ_1^2 represents public interim information; and d_2 with variance σ_2^2 represents the information of the $N - \hat{N}$ firms that were not in the market for interconnector capacity.

The random variable $\tilde{d}_0$ is time zero information, i.e. the information of the $\hat{N}$ firms that take part in the market for interconnector capacity. From our model, it follows that this information is contained in the interconnector prices. The expectation of the price differential conditional on this information – i.e. conditional on the prices for interconnector capacity – is:

$$\widetilde{\Delta p}|(s_1, \ldots, s_{\hat{N}}) \sim N(\delta_0, \sigma_1^2 + \sigma_2^2), \text{where } \delta_0 = \delta + d_0. \tag{1}$$

The realization of $\tilde{d}_1$ takes place between time one and two and reflects the arrival of interim information. The price differential conditional on $(s_1, \ldots, s_{\hat{N}}, s_I)$, i.e. on all information that traders have when they decide on the utilization of their acquired capacities, is

$$\widetilde{\Delta p}|(s_1, \ldots, s_{\hat{N}}, s_I) \sim N(\delta_1, \sigma_2^2), \text{where } \delta_1 = \delta + d_0 + d_1. \tag{2}$$

Finally, $\tilde{d}_2$ is time two information, i.e. information obtained exclusively by firms not taking part in the interconnector market but only in the spot markets. Because all traders together determine the spot market prices, the price differential conditional on all trader's information and the public interim information is exactly the realization of the price differential:

$$\widetilde{\Delta p}|(s_1, \ldots, s_N, s_I) = \delta + d_0 + d_1 + d_2. \tag{3}$$

At time two, each trader will decide on the utilization of acquired capacity depending on the sign of the mean of the expected price differential after interim information; i.e. the sign of $\tilde{\delta}_1$. From the perspective of time zero, $\tilde{\delta}_1$ is a random variable that is normally distributed with mean δ_0 and variance σ_1^2. Given that we know from our theoretical model that equilibrium interconnector fees aggregate all information, we can calculate them as the integral over the profits for those realizations of interim information for which it is profitable to utilize the capacity in the respective direction:

$$f^{HA*} = E(\max\{\tilde{\delta}_1, 0\}|\delta_0) = \int_0^\infty \delta_1 \phi\left(\frac{\delta_1 - \delta_0}{\sigma_1}\right) d\delta_1 \tag{4}$$

and

$$f^{AH*} = E(\max\{-\tilde{\delta}_1, 0\}|\delta_0) = -\int_{-\infty}^0 \delta_1 \phi\left(\frac{\delta_1 - \delta_0}{\sigma_1}\right) d\delta_1 \tag{5}$$

where $\phi(\cdot)$ is the p.d.f. and $\Phi(\cdot)$ is the c.d.f. of the standard Normal distribution.

Note that if interim information becomes negligible the probability mass of the distribution of δ_1 becomes concentrated around δ_0. This implies that

$$\lim_{\sigma_1^2 \to 0} E(f^{HA*}|d_0) = \begin{cases} \delta_0, & \text{if } \delta_0 > 0; \\ 0, & \text{if } \delta_0 \leq 0. \end{cases} \tag{6}$$

and

$$\lim_{\sigma_1^2 \to 0} E(f^{AH*}|d_0) = \begin{cases} 0, & \text{if } \delta_0 \geq 0; \\ -\delta_0, & \text{if } \delta_0 < 0. \end{cases} \tag{7}$$

Hence, the fees converge to the fees in the model without interim information. In this sense, our quantitative model also captures the case without interim information.

To take the model to the data, it is useful to construct two more variables. Let

$$\bar{f} = \begin{cases} f^{HA*}, & \text{if } f^{HA*} \geq f^{AH*}, \\ -f^{AH*}, & \text{if } f^{HA*} < f^{AH*}, \end{cases} \tag{8}$$

be the higher one of the two equilibrium fees and

$$\underline{f} = \begin{cases} f^{HA*}, & \text{if } f^{HA*} \leq f^{AH*}, \\ -f^{AH*}, & \text{if } f^{HA*} > f^{AH*}, \end{cases} \tag{9}$$

the lower one. For $\sigma_1^2 \to 0$, we are back in the situation without interim information, and the lower of the two prices will be almost always zero because there is no option value. Formally, this means that the unconditional variance of $\underline{f}$, $\underline{\sigma}^2$, goes to zero:

$$\lim_{\sigma_1^2 \to 0} \underline{\sigma}^2 = 0. \tag{10}$$

Likewise, vanishing interim information implies that $\bar{f}$ will be very close to δ_0. Formally, this means that the unconditional variance of $\bar{f}$, $\bar{\sigma}^2$ goes to σ_0^2:

$$\lim_{\sigma_1^2 \to 0} \bar{\sigma}^2 = \sigma_0^2. \tag{11}$$

Note that $\underline{\sigma}^2$ increases in σ_1^2, while $\bar{\sigma}^2$ decreases in σ_1^2.

The aim of the following calibration exercise is to make our basic intuition precise by using the observed variances, σ^2, $\underline{\sigma}^2$, and $\bar{\sigma}^2$ to calculate the underlying variances of the different kinds of information: σ_0, σ_1 and σ_2. We use the following procedure:

From the data, we know the unconditional expectation of the price differential δ and the unconditional variance σ^2. Moreover we know $\bar{\sigma}^2$ and $\underline{\sigma}^2$. From the latter two, the two parameters σ_0^2 and σ_1^2 are identified. σ_2^2 can be calculated as the residual variance according to

$$\sigma_2^2 = \sigma^2 - \sigma_0^2 - \sigma_1^2. \tag{12}$$

We find numerically values for σ_0^2 and σ_1^2 that match $\bar{\sigma}^2$ and $\underline{\sigma}^2$ by the following simulation procedure.

1. We start with some values σ_0^2 and σ_1^2.
2. We draw many (1 million) signals s_0 from a Normal distribution with mean zero and variance σ_0^2.
3. Using σ_1^2 we calculate $\underline{f}$ and $\bar{f}$ for each s_0.
4. From the resulting sample we calculate $\underline{\sigma}^2$ and $\bar{\sigma}^2$.
5. Iteratively we adjust σ_0^2 and σ_1^2 until $\underline{\sigma}^2$ and $\bar{\sigma}^2$ match the empirically observed values.

Using this procedure, we produce the values in Table 5 from the observed values reported in Table 4.

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