



Auction and continuous market for power : organization and microstructure

Clara Balardy

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THÈSE DE DOCTORAT
DE L'UNIVERSITÉ PSL

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**Auction and continuous market for power:
organization and microstructure**

Soutenue par

Clara BALARDY

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Popolo marinaro, popolo libero

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Chapter 1

Introduction

The end of the 20th century marked a significant change in the electricity sector in many countries around the world, particularly in the European Union. State-own monopolies (France, Italy, UK, Scandinavia), private regulated firms (Belgium) or regional authorities (Germany, the Netherlands) over the whole power chain (production, transmission, distribution and supply) got unbundled and competition was introduced in the generation and the supply segments (Newberry, 2005). The transmission and the distribution remain today natural monopolies run by respectively the Transmission System Operators (TSOs) and the Distribution System Operators (DSOs). The liberalization introduced a market-based system to increase competition and reduce the allocation inefficiencies. The deregulation also had the objective to straighten the relation between the member states by creating a unique market and thus increasing the total welfare (Crampes and Léautier, 2016).

The first step of the deregulation was the European directive on internal energy market (1996) which set the basis for the liberalization. The Energy Act (1998) abolished the regional monopolies in Germany and, in 2000, the Leipzig Power Exchange (LPX) started to operate the German power market using uniform auctions to allocation hours of power. The exchange was created in order to run an organized market place to deliver a fair reference and transparent market price for electricity. At first, power markets in Europe were organized locally (within member states) until 2006 when was introduced the Trilateral Coupling (TLC) between France, Belgium and the Netherlands. In 2010, the initial coupling project evolved to the Central Western Europe (CWE) project including

Germany in the coupling with France and the Benelux region. Market Coupling optimizes the allocation process of cross-border capacities thanks to a coordinated calculation of prices and flows between countries. Just before the introduction of the CWE initiative, EPEX SPOT SE was created. The entity is the result of the merger between EEX AG, the former German power exchange who previously merged with LPX and PowerNext SA, the former French power market. EPEX SPOT SE is still running today the spot power market in France, Germany, Austria, Benelux, Switzerland and the UK. The continuous market known as the intraday market for hourly contracts was introduced in 2010 and in 2011 for quarter hour contracts. In 2014, the exchange introduced the 15 minute call auction for quarter hour contracts.

Power trading differs from traditional trading of financial products such as stocks due to its inherent properties: existence of a maturity, it is not storable at a large scale and should be transported through the grid. This last feature adds complexity in the trading as market participants should be balanced at delivery: the volume injected in the grid should be equal to the one ejected. If this equation is not respected, there is a threat for the security of supply and a risk of a blackout.

The German spot power market

The spot power market takes place between the long-term and the balancing markets. The long term market (futures) has the objective to cover the supply needs and optimizes the production needs. The balancing market balances unplanned fluctuations in the generation of power and aims to minimize the imbalance between the production and the consumption. It is run by the TSOs in most EU countries using procurement auctions. All this chain contributes to the security of supply.

The German spot power market period starts at noon the day before the delivery of the electricity and finishes 5 minutes before the delivery of the contract. It is composed of the day-ahead auction, the intraday auction and the continuous market. Market participants on the German spot power market can be utilities (usually the former monopolies), producers, retailers, aggregators (whom aggregate the demand or the supply of a group of small customers), energy intensive industries, municipal and regional suppliers, trading companies or banks. TSOs also participate in the market to buy grid losses or as aggregators for the solar production under Feed-In-Tariff.

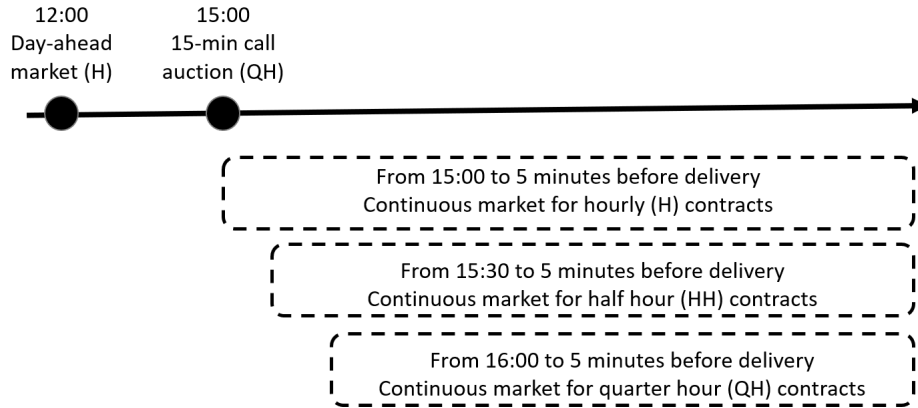


Figure 1.1: Sequence of the German spot power market

The spot period starts with an hourly uniform price sealed bid auction called "day-ahead" market for the 24 hours of the next day. The 24 auctions occur every day, 7 days a week, all year long. Every day at noon the algorithm fixes the market prices and volumes for the 24 hours of the next day. Prior to the auction, market participants have to send a curve between -500€ per Megawatt Hour (MWh) and 3000€ per MWh for each desired contract. They have to make at least a couple price-quantity for those two values in order to get an individual curve that then the algorithm aggregates at the market level. Participants can add additional price levels and indicate for each level how much they want to buy or sell. The minimum price increment of the auction is 0.1€ per MWh and the minimum volume increment is 0.1 MWh. Each couple price-quantity is linked to the next one by linear interpolation. Market participants have also the possibility to send "block orders" to the market. A block is composed of a combination of hours with a "all-or-none" restriction (either the volume is fulfilled for all the hours or the order is not executed). There exists pre-defined blocks such as the base block (24 hours) or the peak block (from 8:00 to 20:00), or user-defined blocks. The last type of blocks is smart blocks which includes linked blocks (set of blocks with a linked execution constraint) and exclusive blocks (set of block orders within which a maximum of one block order can be executed). The block orders do not have their own auction, they are dispatched in the related auctions. The algorithm also has to take into account the interconnection of the day-ahead auction with the day-ahead auctions of 13 other European countries. Market coupling was created to harmonize the market price of power in Europe subject to the

interconnection capacity - implicitly allocated. It is also very important for the security of supply. TSOs transmit to the exchange the capacity available at each border via the flow base matrix which is added in the algorithm's computation. The flow-based methodology describes the cross-border capacity at each border taking into account the impact of the cross border exchanges on the grid security constraints. The interconnection permits to harmonize the market prices between countries. During hours where the interconnection capacity is not fully used, the market prices of the two interconnected countries are the same. The algorithm compiles all those information and gives the result of the 24 auctions at 12:40 the day before delivery. This auction is usually used as a base to complete the long term commitment of the market participants: they usually buy a base volume for the year, then monthly futures to take into account the seasonalities and the spot is used for the daily adjustments to the consumption and the actual production forecasts.

At 15:00 the day before delivery, the call auction occurs. It is a uniform price sealed bid auction for the 96 quarter hours of the next day. The 96 auctions occur every day, 7 days a week, all year long. Market participants have to send their orders before 15:00 the day before delivery. They have to give couples price-quantity for at least the minimum (-3000€ per MWh) and the maximum (3000€ per MWh) price levels of the auction. They can also add some more price steps to fit their needs. The minimum price increment is 0.1€ per MWh and the minimum volume increment is 0.1 MWh. The bids are linearly interpolated between couples. No blocks are available in this auction and the auction is local - not interconnected. The auction clears the market and gives the results right after. This auction was introduced in 2014 and it is very useful as it permits market participants to trade at the balancing granularity: German market participants have the responsibility to be balanced every 15 minutes. It is particularly useful for intermittent (solar and wind) producers who face sporadic generation and generation ramps. The figure 1.2 clearly shows how quarter contracts can help solar producers to handle the generation ramps more precisely.

At 15:00 the day before delivery also starts the intraday continuous market. It is a continuous based market (pay-as-bid principle) for the 24 hours of the next day that closes 5 minutes before delivery. The trading session length is then different for each contract. With the overlap between the trading sessions of the current and the next day, the market is always open, 24 hours a day. Market participants send limit orders that are directly

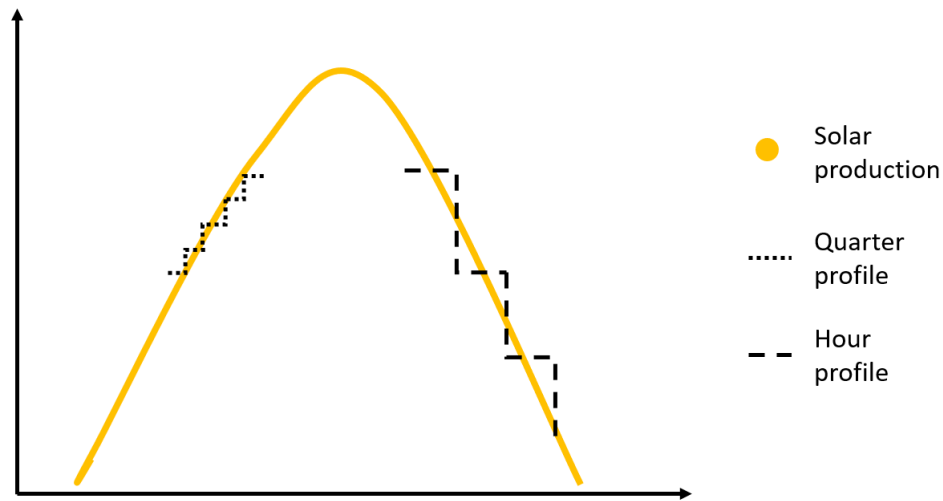


Figure 1.2: Quarter versus hour contracts

executed if they match an order already in the order book or will appear in the order book if it doesn't find a counterpart. Orders submitted should be in a price range comprises between -9999€ per MWh and 9999€ per MWh. The minimum price increment is 0.1€ per MWh and the minimum volume increment is 0.1 MWh. There is an order book for each individual hour and for each block type (pre-defined or user-defined). Orders can have restrictions such as: "all-or-none" (the order is fully executed or not at all), "immediate-or-cancel" (either the order is immediately executed or get cancelled), "fill-or-kill" (either the order is immediately fully executed or get cancelled) or iceberg (order can be split in a minimum of 25 MWh batches). The continuous mechanism is interconnected between countries under the constraint of the available interconnection capacity. While the TSOs get remunerated in the day-ahead auction for the scarcity of the interconnection capacity, the capacity is free on the continuous market and implicitly allocated. When there is an available capacity of interconnection between a source and a sink country for a specific contract, the sell orders up to the available capacity level will be visible in the order book of the sink country. Concomitantly, buy orders up to the available capacity level will be displayed in the order book of the source country. The exchange does not display the name or the origin of the market participants - a trader does not know if the order she is interested in is local or from an interconnected country. Interconnection is available from 18:00 the day before delivery up to an hour before delivery. From an hour to 30 minutes before delivery, market participants can only trade within Germany, across the

4 TSO zones¹ and from 30 to 5 minutes before delivery, they can only trade within their TSO zone. The price of a transaction is the price of the aggressor order. An order is originator (or liquidity provider) if it is in the order book while an order is aggressor (liquidity demander) if it hits an order already in the order book. The continuous market permits market participants to trade close to delivery and adjust their position directly after the arrival of new information such as weather forecasts, unplanned outage, ... The figure 1.3 shows an example of a trading session for an hourly contract: an hour of power between 20:00 and 21:00 on June, 2 2015. We can observe the increasing volume on both side of the market when the trading session progresses as well as the more frequent best bid (grey curve) and best ask (orange curve) changes closer to delivery.

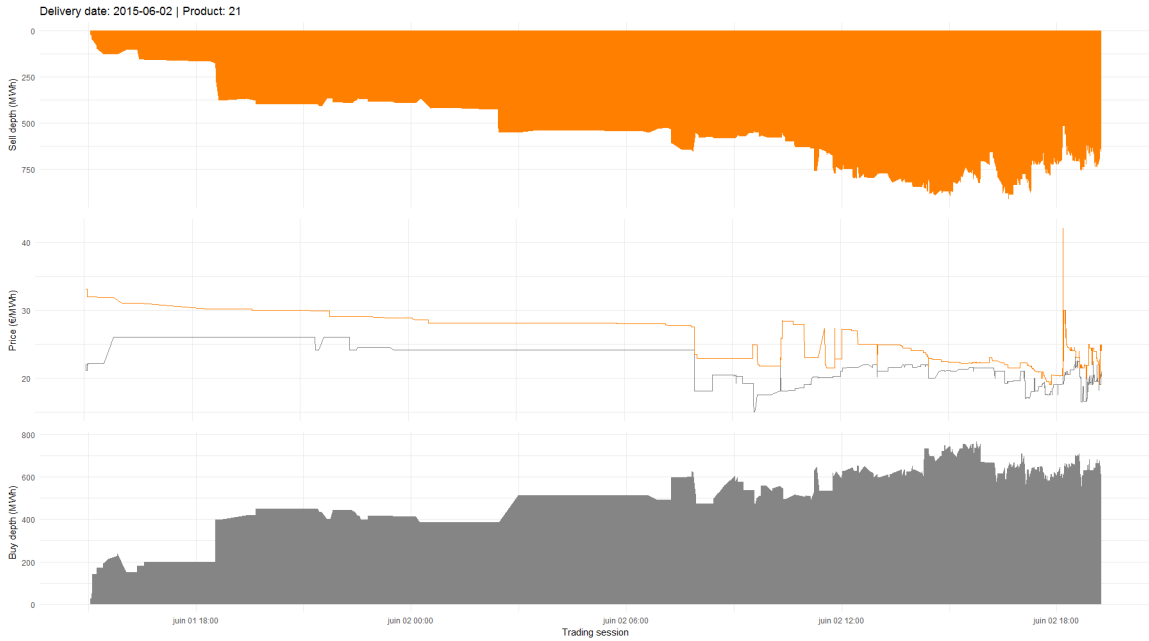


Figure 1.3: Example of a trading session

Additional to the hourly contracts, the intraday continuous market also proposes half hour and quarter hour contracts. Their trading sessions start respectively at 15:30 and 16:00 the day before delivery and close 5 minutes before delivery. They work similarly to the continuous market for hourly contracts. The continuous market for 30 minutes contracts is interconnected between France, Germany and Switzerland while the market

¹Germany has 4 TSOs (Amprion, Tennet, TransnetBW and 50Hertz) whom each one controls a defined area. They are in charge of the high voltage grid.

for 15 minutes contracts is not interconnected. Both markets do not propose block orders. They permit market participants to sharpen their commitment at the lowest granularity close to delivery. Quarter hour products are particularly useful for German market participants whom should be balanced every 15 minutes.

The increasing renewable capacity

Over the past decades, the main challenge of the electricity industry is the transition to a low carbon and clean power production. This transition is driven by the growing environmental concerns and the distrust of people in nuclear energy following the Fukushima nuclear disaster in 2011. To manage this transition, countries have massively increased their renewable production capacity, particularly Germany with a massive investment in the sector. Figure 1.4 shows the capacity of the hydro, biomass, wind (offshore and on-shore) and solar generation from 2002 to 2019. We can clearly observe a larger increase of the wind and the solar generation over the years: in the past 10 years, the installed capacity of solar (respectively wind) production has increased by more than 353% (resp. 135%).

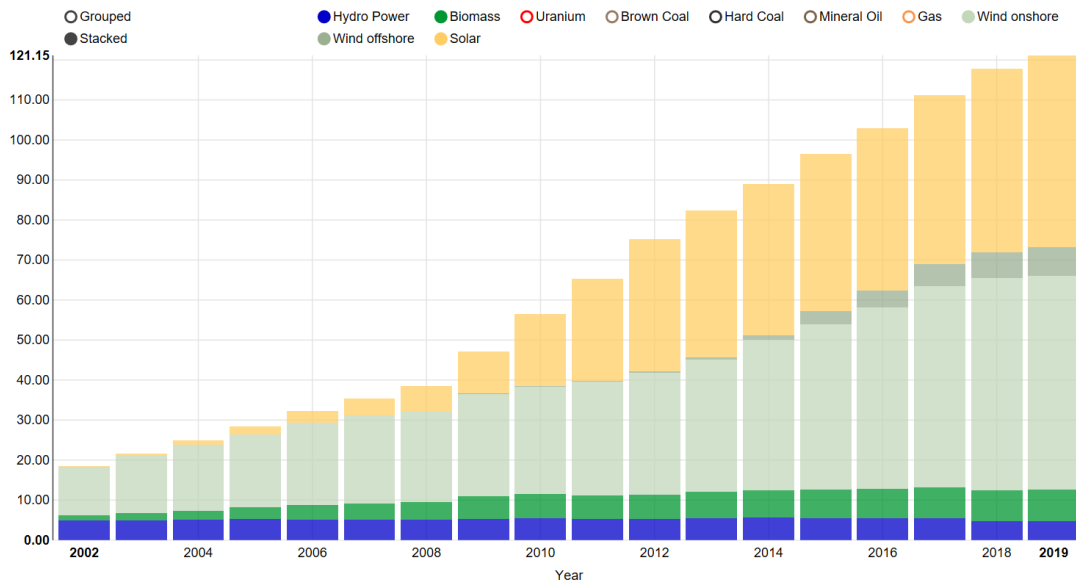


Figure 1.4: Evolution of the renewable capacity in Germany (source: Fraunhofer ISE)

The market is merit order based: cheaper units are allocated first. Due to the negligible marginal cost of wind and solar production, renewable production is always executed first

as it is bidden at a price close to zero. The associated uncertainty associated with the increasing renewable capacity leads to some periods with a lot of renewable and some others with almost no renewable production. On the one hand, in Germany, when there is a lot of wind and/or solar generation, we can observe very low prices as producers cannot reduce the power they will inject in the grid; thus, it will shift the merit order curve and less conventional power plants will be committed. Feed-In-Tariff (FIT) and direct marketing tariff schemes intensify the lowering effect because they incentivize wind and solar producers to bid negative prices equal to the value of the subsidy they received. At a higher level, it weakens the system as it distorts the long-term investment incentives. On the other hand, when the wind and solar production is very low, there is a need to turn on more conventional power plants or peak units, higher in the merit order and so more expensive. As the renewable decreases the overall market price, there is less incentive for peak unit producers to build new unit as they would be less mobilized. This can be a problem for the security of supply in cases of a low renewable production period. Also, conventional producers can amortize their investment on less days so they will have an incentive to bid a very high price on those days, above their marginal cost. In this sense, prices can be very high during renewable scarcity hours. The best example was during the solar eclipse of March 20, 2014 (EPEX SPOT, 2014) where volatility of the price between different quarter hours was over 400€. Various authors has been working on the integration of wind and solar production on the market such as various papers of P. Pinson, Paraschiv et al. (2014), Cludius et al. (2014), Ketterer (2014), Karanfil and Li (2017) or Martin de Lagarde et Lantz (2018) just to name a few.

This increase of intermittent production brought uncertainty to the market with a need to trade nearby delivery in order to adjust the trading position closer to real time and take into account the most accurate information. With conventional power plants, the production can be fixed long time before delivery as there is no uncertainty on the production; however, with wind and solar technologies, generators cannot precisely forecast the production in the long term. As the lead time to the delivery of the contract decreases, generators get better forecasts and thus want to adjust their position to avoid an unbalanced position at the end of the trading session - and the related penalty. Thus, there is an increasing interest in trading in the spot market particularly close to delivery which can be highlighted by the growing importance of the continuous market.

The demand-response

The uncertainty related to the renewable production has to be balanced with flexible (but usually expensive) assets that can quickly start or stop producing electricity such as power to gas units or thermal power plants. Since the 80s, utilities designed demand-side-management (Ruff, 2002) to align the market price to the consumption of the energy intensive industries: in the case of low price, they are incentivized to increase their production while on high price hours, they are incentivized to reduce their production - and may even get paid for that. With the emergence of smart meters at the residential level, the power industry has the objective to send the right price signal to households and gives them incentives to shift their consumption from peak to less expensive hours. The adequacy of the market and the retail prices is of major important in the reliability of the system which may lead to some serious crisis such as the California one in 2000-2001 (Joskow, 2002).

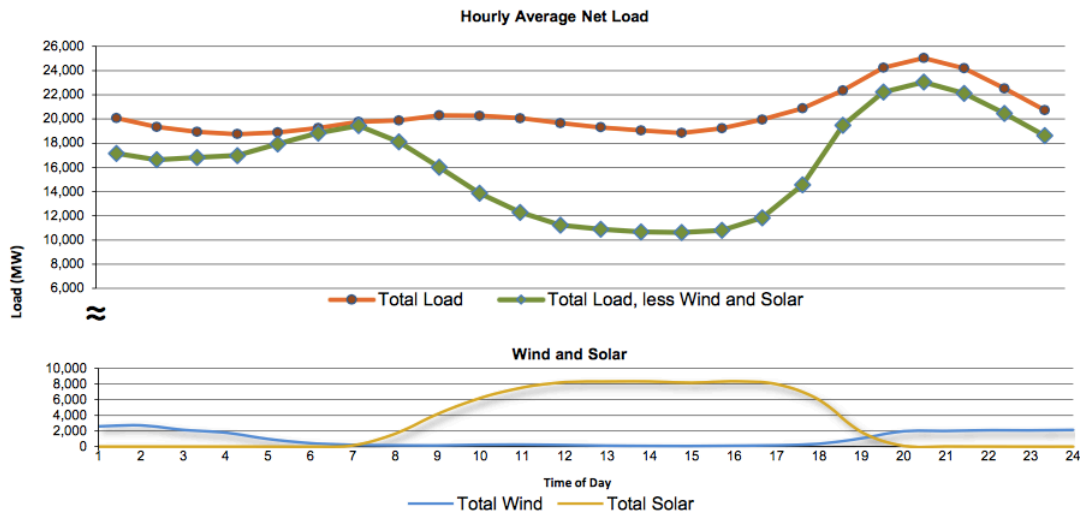


Figure 1.5: The duck curve (source: CAISO)

The best visualisation of the issue is illustrated by the now famous "duck curve". An example from the Daily Renewables Watch of CAISO is shown on figure 1.5 where we can observe that during the business hours (from 8:00 to 20:00), the consumption is low but the solar production may be high, creating a large difference between night and day hours highlighting the need for flexibility to handle the ramps. Flexibility may be provided by

activating a flexible asset or a demand-response contract.

The literature associates the demand-response with an increase of the welfare (Tirole and Joskow, 2006, Borenstein and Holland, 2003); however, some authors are sceptical regarding the implementation costs (Faruqui and al., 2010, Léautier, 2014).

A faster market

While renewables and demand response exogenously affect the market price, there also exists some endogenous transformations such as a change of market rules or the change of behavior of market participants. Even if the present thesis does not deal with those structural changes, they are worth mentioning as they impact the current market. While the power market is still preserve to the financialization in comparison to commodities like oil, the market has to adapt to structural transformations occurring in all exchanges. Speed is one example that could affect the trading. EPEX SPOT could observe, over the past years, the increase of the trading speed on the market, leading to an increasing number of orders and some very fast trading periods. Speed can also lead to an arm race (Budish and al., 2016) and should be taken seriously by exchanges and regulators. For example, EPEX SPOT introduced an order-to-trade ratio in order to avoid unnecessary order flows due to "robot fight"; they also increased the tick size on the continuous market (2016) from 1 cent to 10 cents. While those questions has been well documented in the financial literature, there is no study on the power market.

The importance of a proper market design

The current markets for power face new challenges, particularly due to the increasing renewable production. Regulation and market design should accompany the changes. In a liberalized power industry, regulation has two main goals : ensuring the security of supply and the competition of the market to avoid the exercise of market power. The aim of regulation is to give the right incentives to the actors in order to maximize the total welfare. Policies and laws are keys for a smooth and well functioning industry/market organization in order to avoid market failures. Market are not perfect this is why regulation designers should finely understand the incentives of all the actors following a policy change in order to reduce market frictions that may emerge. While regulation is in the hands

of the European or national institutions and governments, market design is a joint work between the same institutions and the exchanges that run the market. The main goal of market design is to give the right price signal (reflecting the fundamentals of the market) to market participants and efficiently allocate the assets. Exchanges should ensure to have detailed rules to facilitate trading and enhance market thickness or liquidity. Market rules have to incentivize the participants to reveal their true preferences. Market design should be adapted to the changes of the industry as well as the structural changes of market itself. The change in regulation has a direct effect on the market and vice versa and thus, regulation and exchanges have to work hand in hand to design an efficient power market for Europe and reduce market failures. The job of the energy economists today is to raise questions about the current or the future design of the markets but also find practical solution for those real world problems. Research should accompany the changes occurring in the industry.

This thesis is interested in some specific cases of market or regulation design in the power market.

The thesis

The present thesis can be split in two. The first part studies the German power spot market in details. It aims to bridge the gap between the microstructure (finance) and the power market literatures. Both literatures are dense but the research in finance did not yet get interested in power markets and energy economists in financial topics. One reason may be the barrier to entry into the complexity of electricity which has different features in comparison to more traditional financial markets. The power spot market is a B-to-B exchange with restrictive access for traders so it is not as known as the stock exchanges such as EuroNext or the London Stock Exchange - LSE. Another barrier may be the availability of the data, particularly order books, at the lowest granularity and the high frequency of the data. An obstacle to the development of this cross field is probably due to the fact that only continuous market may use the microstructure literature and this market is a European specificity limiting the interest of the out-of-Europe researchers; most of the studies on prices and volumes in power market study the day-ahead market which concentrates the vast majority of the liquidity of the spot market or the daily continuous index price. However, we can observe an increasing interest in the deep comprehension of

the markets, particularly the continuous one, from the industry and the academia. The work of the researchers from Duisburg-Essen (Weber, Ziel or Kiesel) or from the FiME lab (research project between Université Paris-Dauphine, Polytechnique, CREST and EDF R&D) start to fill this gap.

The aim of the second chapter is to get a deep understanding of the bid-ask spread in the German power market. I first study the evolution of the bid-ask spread over an average trading session of the continuous market. In a second part, I characterize the main drivers of this bid-ask spread on the German power market. While the question of the impact of an opening auction before a continuous market has been studied on various exchanges, it has never been studied in power markets which are not as liquid as the traditional financial markets and present some special features (maturity, non storability, ...). I use the introduction of a call auction before the start of the continuous market on the German power spot market as a natural experiment. I look at the impact on the continuous market in term of liquidity and volatility but also on the whole spot market in term of liquidity and competition.

The fourth chapter can be considered as the second part of the thesis. While the liberalization of the market put a lot of efforts on the competition of the supply side, the demand side remained unchanged and inelastic (Kirschen, 2003). The literature on demand-response is quite large but focuses on the effect of the demand on the equilibrium price; those researches admit that the supply side won't change its behavior consecutively to the adequacy of the market and the retail prices. However, in Europe, the former monopolies from before the liberalization remain vertically integrated and thus a change in the retail segment may impact their behavior on the market. In the fourth chapter, I theoretically study the impact of a regulatory change (the introduction of the possibility for suppliers to propose market based prices to their customers) on the behavior of the vertically integrated firms. This work was mainly made during my visiting in University Carlos III in Madrid and supervised by Pr. Fabra.

Chapter 2 - Electricity can be traded in the short-term bilaterally or in a centralized market. The quality of a market may be measured by its liquidity: the ability to quickly buy or sell power for an amount of time. This information is crucial for a market participant in its choice to participate in the centralized market because illiquidity may be interpreted as an implicit transaction cost. In this chapter, I examine the question of the

liquidity of a continuous market for electricity: when is the liquidity maximum during a trading session and what are the main drivers or it? In Germany, most of the short-term power trading (about 88% in 2015) is done the day before delivery during the day-ahead auction. The remaining volume is traded during a continuous based market – also called intraday continuous market, which occurs from after the day-ahead up to the delivery. The growth of the renewable generation capacity increases the uncertainty on the generation side which explains the increasing trend of the volume traded on the continuous market closer to delivery. This market is then an interesting case for continuous markets with increasing renewable generation, particularly in the context of the expansion of the continuous market in Europe thanks to the pan-European harmonization projects XBID. This research aims to bring the questions of the market microstructure literature to the power market literature. Using the complete order book of the German continuous power market, I measure the liquidity of the market using the bid-ask spread as a proxy. The bid-ask spread is the difference in price between the best seller offer and the best buyer offer. It can be interpreted as a premium in order to be immediately executed (Demsetz, 1968). In a first part, I reconstitute the order book of the market and represent the behavior of the bid-ask spread and market depths over an average trading session. I find that the bid-ask spread has a “L-shape” along the trading session: at the beginning of it, the bid-ask spread is large due to the uncertainty away from the delivery. As the trading session progresses, the bid-ask spread decreases. Most of the liquidity of the market is concentrated during the last hours of the trading session. This result is in line with the fact that 80% of the trading occurs during the last 3 hours of the trading session. On average, the local bid-ask spread is of 3€/MWh. In a second part, using a reduced-form equation, I express the bid-ask spread by its four main drivers: the volatility, the adjustment needs, the activity and the competition on the market. I find that an increase of the market volatility (measured by the weighted price standard deviation) increases the bid-ask spread. When there is a need for adjustment due to a load, solar or wind forecast errors, the bid-ask spread gets narrow. When there is more activity (measured by the load) or competition (measure by the Herfindahl Index), the bid-ask spread decreases.

Chapter 3 - A good market design is a key component of an efficient market. On the one hand, a trader willing to get quickly rid off an asset will prefer to submit a limit order on a continuous market in order to find a counter party in a minimum of time. On

the other hand, a trader interested in optimizing an asset would prefer to submit a bid in a uniform price auction to maximize her gain. While continuous trading permits an immediate execution and processes the market information, discrete trading creates a pool of liquidity and facilitates optimization. In the microstructure literature, some papers have investigated the effect of the creation of an opening auction on the continuous market with mitigated results on the improvement of market efficiency following the change. However, those papers focus on stock markets and the impact on the continuous market only. The contribution of this chapter is in threefold : (1) it studies a market different from stocks particularly interesting for its physical properties; (2) it examines the impact on the whole trading chain (auction and continuous market) ; (3) it adds the competition component to the analysis thanks to the details order books. This chapter quantifies the effect of the introduction of an auction before a continuous market in terms of liquidity, volatility and competition. I use the introduction of the 15-min call auction on December, 9 2014 as a natural experiment. Using order and trade books of the German quarter hourly contracts for power, I compute the mean-difference on variables linked to volatility, liquidity and competition. I find that the introduction of the auction decreased the volume traded on the continuous market (business-stealing effect) while it increased the total volume (auction and continuous). This limited effect is due to the complementary between the 2 trading mechanisms : most of the market participants did not specialized in one venue but started to trade on both the auction and the continuous market after the introduction of the call auction. Second, in most cases, the auction has no effect on volatility of the first hour of trading and even reduces it during the second hour of the session. Finally, after the introduction of the auction, we could observe, on the trading chain, an important increase of market participants and a decrease of the concentration.

Chapter 4 - Due to the intermittency of the renewable energy sources, there is a need for flexibility to compensate the variation of production. Flexibility can also come from the demand by the demand-response mechanism that gives the right price signal to end-consumers in order for them to reduce their consumption during peak price periods. Since the 80s, utilities propose this tariff to industrial consumers ; in recent years, the development of smart meters permits to apply real-time tariffs to residential consumers who hence can pay an hourly market based price for electricity. The literature is quite enthusiastic about demand-response and its effect on the market price. However, the

literature does not investigate the impact it may have on the market participants' behavior. While it won't have an impact on net producers or suppliers, the present chapter studies the impact of real-time pricing tariff on the vertically integrated firms' (whom produce and supply power to end-consumers) strategy. With real-time pricing tariff, the vertically integrated firms have a revenue dependent of the market price – which is not the case with fixed price ; in this sense, they have an incentive to increase the market price. This question of the incentives of vertically integrated firms is key for regulators to get the full picture of the impact of real-time pricing tariff. The present chapter theoretically studies this question. I use an oligopolistic model with one dominant firm and model the behavior of a vertically integrated dominant firm on two sequential markets (the forward and the spot market). The monopolist buys its supply commitment on the market and then sell it to its end-consumers at the price of the forward market. I find that vertical integration with fixed retail price, in sequential market, reduces market power in comparison to the case where the dominant firm is a net supplier. However, the result suggests that, in the case of the real-time pricing tariff, the vertically integrated firm has incentive to exercise more market power and hence increases prices on both the forward and the spot markets. In an extreme case where all the end-consumers are under real-time price tariff, the dominant firm extracts all the surplus from the end-consumers and the market prices are equivalent to the case where the dominant firm is a net supplier.

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Chapter 2

An empirical analysis of the bid-ask spread in the continuous intraday trading of the German power market

About this chapter

This chapter was my first PhD project. It was submitted to the Energy Journal and is now under a second revision, after resubmission. I want to thank the three anonymous referees for their comments that helped to improve an earlier version of the manuscript. I also want to thank EPEX SPOT as well as the chair European Electricity Market for their support. The last thank you goes to the participants of the following conferences for their constructive comments and remarks: 22nd Young Energy Economists and Engineers Seminar, 40th IAEE International Conference, 15th IAEE European Conference, EDFLab, Commodities Market Winter Workshop 2018 (Nantes, France), 13th Bachelor Colloquium on Mathematical Finance and Stochastic Calculus and the PhD. day at Dauphine University, particularly Marie Bessec for reviewing it.

Abstract

A sufficient amount of liquidity is decisive for a well-functioning market. This paper gives a better understanding of the liquidity of the German power market using the bid-ask spread as proxy. Based on the order books for hourly contracts, I first describe the evolution of the bid-ask spread and the market depths over the trading session. Further, I show the «L-shaped» behavior of the bid-ask spread during the trading session. Second, I identify the main drivers of the bid-ask spread. I find a positive relation between risk and the bid-ask spread as well as a negative relation between the bid-ask spread and the needs for adjustment, the activity, and the competition in the market.

Keywords: bid-ask spread, market depths, continuous market, power market.

2.1 Introduction

Liquidity is the major component of a well-functioning market. More liquid is a market, easier it is for a market participant to find a trading counterpart to match its requirements. The deep understanding of the liquidity of the German continuous power market is crucial because of its increasing attention in the public debate. The continuous market has been playing a growing role in the integration of renewable energy sources (RES); thus, the traded volume increased by about 170% over the past 6 years (from 2012 to 2018). It is also important to understand the liquidity of the market in the context of the European XBID (cross-border intraday) project where new countries are adopting continuous trading such as Spain or Italy.

This paper proposes a deep analysis of the liquidity of the German power market through the study of the market depths and the bid-ask spread. The market depth is the volume available at one point in the order book. It can be divided into the buy and the sell depths. They respectively are the total volume available on the buy and on the sell sides at one moment of the trading session. The bid-ask spread is the absolute difference between the best ask price (sell side) and the best bid price (buy side). This is the difference in price between the lowest price for which a seller is willing to sell a megawatt hour of electricity and the highest price that a buyer is willing to pay for it.

Market participants gain opportunities by exploiting the bid-ask spread which can be interpreted as a premium for immediate execution (Demsetz, 1968). The bid-ask spread is also an implicit transaction cost; the smaller the bid-ask spread is, the smaller the implicit transaction cost is for traders and so the end-consumers. Further, the bid-ask spread is a showcase for the quality of a market. Therefore, the bid-ask spread is of major importance for the market participants to their decision to participate or not in the market. This study is also relevant for the exchange to propose new products linked to the bid-ask spread in order to increase the market liquidity (ie. market making contracts).

The aim of this paper is to bring the questions of the market microstructure literature to the power market literature. Despite the various similarities between the continuous spot power market and the traditional financial markets, there are some major differences due to the physical aspect of the power market and its characteristics which makes it very interesting to financial researchers. For example, the power spot market is one of the most volatile commodity due to its non-storability and its highly inelastic demand (Dupuis et al., 2016). Both the market microstructure and power literature are dense, but the microstructure one mainly focuses on traditional financial markets such as securities or stocks while the power market literature does not deal much with microstructure issues. The present paper straddles on those two streams of literature and its contribution is twofold. First, it is the first study on the bid-ask spread of a power market. Second, the dataset used is unique as it includes information at the lowest granularity and information on the market participants behind each order.

In this article, I first do a dynamic analysis that studies the evolution of the bid-ask spread and the market depths over an average trading session at a granular level (microseconds). Second, I identify the main drivers of the bid-ask spread. Further, I am able to reconstitute the best order streams (best bid, best ask, and market depth) each time a new event occurs in the power market (i.e., new/modification/cancellation of an order in the order book). The model could be easily extended to other continuous markets.

The study yields three main findings. First, I show the "L-shaped" behavior of the bid-ask spread during a trading session. Second, I find a negative and significant correlation between the bid-ask spread and the market depths. Third, I identify four components in the spread: the risk, the adjustment needs, the activity, and the competition in the market. Using a fixed effect model, I find a positive relation between the risk and the bid-

ask spread as well as a negative relation between the bid-ask spread and the adjustment needs, the activity, and the competition in the market.

The paper is organized as follows: the second section is dedicated to the relevant literature, the third one is an overview of the current spot power market in Germany, the fourth section gives some statistical insights on the bid-ask spread and the market depth in the German intraday power market. The fifth part presents the data and the methodology used. Then, the sixth section displays the empirical results. The last section is the conclusion.

2.2 Relevant literature

The present paper straddles two streams of literature: the one on the continuously traded electricity market and the one on market microstructure.

While the literature on power markets is dense, the literature on continuous power markets is limited and mainly focuses on two issues: wind generation integration (how to handle forecast errors) and market design. The closest literature is on price formation in the intraday continuous market. Hagemann (2015), Hagemann et al. (2016), Karanfil and Li (2017) and Ziel (2017) work on explaining the price of the continuous market. Weber (2010) was the first to address the question on the liquidity in the continuous power market. He affirmed that the low liquidity might be the cause of a poor market design and/or the absence of a real need for a continuous market. However, those comments have to be balanced as the paper uses data from 2007 when the volume traded on the continuous market was 1.4 TWh - almost 26 times less than the volume traded in 2015. Also, the level of installed wind capacity more than doubled from 2007 to 2015 which increased the need to re-balance close to the delivery time and the importance of the market. Chaves-Avila et al. (2013) explain the low liquidity in the continuous power market as the preference of producers to commit their generation long ahead of time because of ramping-up costs and generation planning. Hagemann and Weber (2013) develop two models to explain the liquidity in the German continuous power market. To the best of my knowledge, the work of Hagemann and Weber (2013) is the first paper to talk about the bid-ask spread in the German continuous power market. However, their work neither uses the order books sent by the market participants or a reconstitution of the order books as input data for their

model. Neuhoﬀ et al. (2016) study the impact of an intraday auction before the opening of the continuous market. They find a negative relation between volatility and market depth as well as a positive relation between liquidity and market depth in the 15-minute intraday auction in Germany.

The microstructure can be defined as a branch of finance that deals with the trader’s behavior and market design. The study of the bid-ask spread is part of the microstructure literature, particularly of the sub-literature on price formation and price discovery.

Demsetz (1968) initiated the literature on the bid-ask spread. He defined market makers as immediacy providers in which the bid-ask spread is a premium paid by a market participant for immediate execution. The work of Demsetz highlights the negative relation between the volume and the bid-ask spread also raised in the paper of Copeland and Galai (1983) who developed a model of spread estimation by using the volatility and the level of trading as explanatory variables.

In the theoretical part of the literature, the spread reflects three components: transaction or order processing costs (Roll, 1984), adverse selection costs (Glosten and Milgrom, 1985), and inventory costs (Stoll, 1978). Glosten and Harris (1988) and Kim and Ogden (1996) have used models with both inventory and order processing costs. Glosten (1987) models the role of information asymmetries by separating the effect of order processing from the effect of adverse selection. The models of Stoll (1989) and Huang and Stoll (1997) present an estimation of the bid-ask spread with all three components. Hasbrouck (2004) proposes a Roll (1984) estimator using Markov chain and Monte-Carlo simulation. Chen et al. (2019) do an extension of the Roll model where only transaction price are needed as input.

The empirical literature also verify these three components of the spread. Schultz (2000) applies the Roll estimator¹ to a data set from the NASDAQ. The adverse selection paradigm was first empirically applied by Glosten and Harris (1988) to the NYSE based on an indicator variable for trade initiation. Madhavan et al. (1997) develop a model called MRR that decomposes the spread into two components: adverse selection and order process. This model has led to a multitude of papers on different markets such as future exchanges (Huang, 2004, Ryu, 2011), stock exchanges (Angelidis, and Benos, 2009), Exchange Trading Funds or ETS (Ivanov, 2016) and the European climate exchange

¹The Roll estimator is an estimation of the bid-ask spread using time series of trades.

(Mizrach and Otsubo, 2013). Many studies have found empirical evidence of the inventory cost such as Hasbrouck and Sofianos (1993), Manaster and Mann (1996), and Madhavan and Sofianos (1998). Huang and Stoll (1996) estimate and compare the spreads of the NASDAQ and NYSE from the three elements. Huang and Stoll (1997) quantitatively estimate the impact of the three components and find that order processing represents 61.8%, the average inventory cost 28.7%, and the average adverse-information represents 9.6%. McNish and Wood (1992) empirically estimate the bid-ask spread of the NYSE Stocks with four components: activity, risk, information, and competition based on the previous work of Schwartz (1988). The econometric model of this paper is inspired by the work of McNish and Wood (1992).

This paper contributes to the literature by being the first paper which studies the bid-ask spread of a power spot market and by proposing the Herfindhal Index (HHI) as a measure of the competition on the market thanks to its very detailed dataset.

2.3 The intraday power market

In power markets, the financial flow goes along with a physical one. On the electricity spot market, the contract unit is the megawatt for a certain amount of time (15, 30 or 60 minutes). Contract are also called "product". Power trading can be divided into two categories: the one occurring bilaterally (Over-the-Counter - OTC) and the one taking place on an exchange. An exchange differs from the OTC because it is an organized marketplace with uniform rules and proposes standardized contracts (Geman, 2005). The trades that occur on an exchange are anonymous and transparent. The power spot market takes place between the long-term market (forwards, futures) and the balancing market operated by the Transmission System Operators (TSOs). The commodity spot trading differs from long-term trading because of the immediate delivery of the product (i.e., electricity, gas, gold, cotton, currencies, etc.) or with a minimum lag (due to technical constraints) between the trade and the delivery (Geman, 2005).

In Germany, the Energy Industry Act (1998) unbundled the generation and supply of electricity from the network segment. The German spot power market was created in 2000 by LPX - Leipzig Power Exchange, and is now operated by EPEX SPOT across Europe. It is the most liquid spot market in Europe: traders moved 302 TWh (terawatt-hour)

on the market in 2015 which represented 53% of the country's electricity consumption. The continuous intraday market (IDM) accounted for 36.3 TWh the same year and has increased since its creation as illustrated in 2.3.

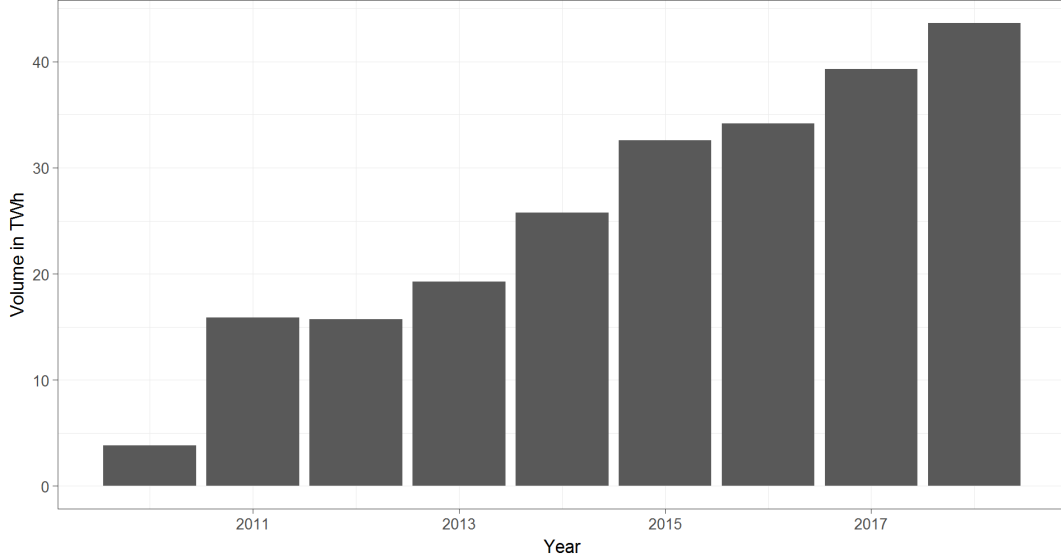


Figure 2.1: Transaction volume of the German continuous market

The German spot power market is divided into three sub-markets: the day-ahead market (DAM), the 15-minute intraday auction, and the continuous intraday market (IDM). The DAM is a uniform price auction that occurs every day at 12 am. The contracts exchanged on the DAM are hourly contracts (24) for the next day. The period called "intraday" starts right after the DAM and lasts until delivery. The 15 minutes call auction is a uniform price auction that occurs every day at 3 pm in Germany. The traded contracts (96) are 15-minute products for delivery on the next day. The continuous market for hourly contracts starts at 3pm the day before delivery and closes 5 minutes² before delivery. For example, the product 2 of tomorrow (D+1) (ie. hour of electricity between 1:00 and 2:00) is available for trading from 15:00 today until 00:55 tomorrow. The duration of the trading session for a contract is between 9 and 32 hours.

The continuous market runs continuously 24 hours a day, 7 days a week, all year long. Thus, a market participant can trade up to 32 hourly contracts at the same time. This

²Trading was first possible up to 45 minutes before delivery, then 30 minutes before delivery, and since June 2017 up to 5 minutes before delivery. This paper uses data from 2015 where the gate closure was 30 minutes before delivery.

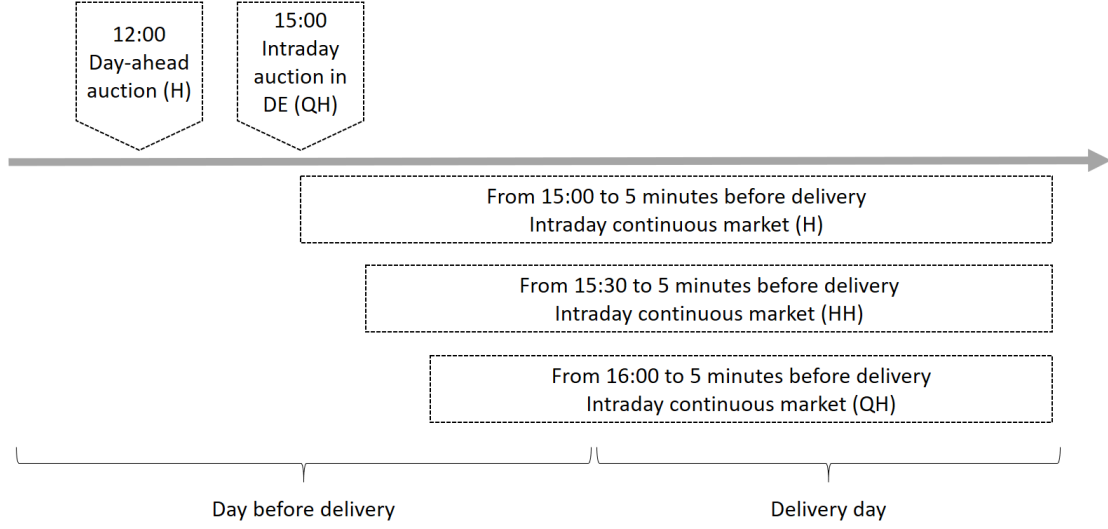


Figure 2.2: The German spot power market

market allows participants to re-balance and optimize their portfolios close to delivery. Scharff and Amelin (2016) justify the need for an intraday market in three points: it reduces unbalanced costs, it helps to optimize market participants' production and consumption schedules, and it promotes flexibility.

Market participants can submit limit price orders for a given contract to the exchange with a price-quantity at any time during the trading session³. The price is the minimum

³Orders can be sent as single orders or within a group of orders. Limit orders can have execution and validity restrictions. Execution restrictions include fill-or-kill (FOK - «either the order is immediately and entirely executed or cancelled in its entirety»), immediate-or-cancel (IOC - «the order is either immediately executed or automatically cancelled; the order can be partially executed and any unexecuted quantity is cancelled»), linked fill-or-kill (LFOK - «linked orders are either all immediately and entirely executed or all cancelled in their entirety»), and all-or-none (AON - «the order is executed completely or not at all»). Validity restrictions include «good for session» («the order is deleted on the trading end date and time of the contract unless it is matched, deleted, or deactivated beforehand»), «good-till-date» («the order is deleted on the date and time specified by the exchange member when placing the order unless it is matched, deleted, or deactivated beforehand»), or iceberg («large order is divided into several smaller orders which are entered in the order book sequentially»). Groups of orders can be of two types: block orders or basket orders. Block orders «combine several expiries with a minimum of two contiguous expiries on the same delivery day which depend on each other for their execution». A block order can be predefined or user-defined. In Germany, there are two predefined blocks: base-load that covers hours 1 to 24 and peak load that covers hours 9 to 20 during business days. User-defined block orders are designed by market participants. They can only use the same type of contract to compose their block. The execution

(maximum) price at which they are willing to sell (buy) the associated quantity. The IDM is continuous in its matching procedure⁴: orders are matched when they arrive in the order book if there is a counterpart in the market with whom price and volume requirements match⁵. Orders can either be fully or partially executed if only part of the match is possible. An order is executed at or above (under) the specified price for a seller (buyer), and there is no market price as each transaction that occurs on the IDM has a different price (pay-as-bid principle). If there is no possibility of a match, then the order remains in the order book. The orders are listed by price in the order book: increasing orders price on the sell side and decreasing orders price on the buy side. Members can also withdraw or modify their orders during the trading session.

The process that I have presented represents local (within a country) order books only; however, countries in Central Western Europe (CWE) are interconnected. Under the capacity constraint on a border, the capacity available will allow the best orders from the source country with a maximum volume of the capacity constraint to be visible in the order book of the sink country and vice versa⁶. The capacity is implicitly given and not priced in the market. The order book does not display if the orders are local or cross-border.

Table 2.1 displays some descriptive statistics on the trades of the German continuous market from January 1, 2015, to December 31, 2015. The mean daily price was 31.85€/MWh. The mean daily number of trades per contract was 267.5 while the mean

restriction AON is applied by default for blocks. Basket orders are a group of orders which allows users to submit a set of orders all at once (max. 100 orders). One basket can contain quarter-hourly as well as hourly and half hourly products. There are three possible constraints: linked («either all orders are fully executed or none at all»), valid («all orders must be valid, or all will be rejected»), and none («treat all orders in basket as separate orders»). The tool that I use does not take into account block orders as they have a different order book than the hourly products.

⁴Orders sent to the market are processed one at the time - serial processing, in general within milliseconds.

⁵A market participant is called "initiator" of the trade if he or she submits a new order in the order book and is called "aggressor" when he or she hits the price of an existing order in the order book.

⁶For example, the interconnection capacity available at time t for a specific product p is 20 MWh from Germany to France; so at that time, a volume of 20 MWh of the best sell orders from the German order book will be displayed on the French order book for product p . Simultaneously, a volume of 20 MWh of the best buy orders from the French order book will be visible on the German order book for the concerned contract.

	Min	Quartile 1	Median	Mean	Quartile 3	Max
Weighted price (€/MWh)	-84.60	25.12	31.53	31.85	39.52	120.16
Number of trades	14	169	247	267.5	345	907
Number of orders	109	599	945	1072	1373	6724
Active members on both side	29	43	51	50.95	59	77

Table 2.1: Descriptive statistics of the continuous market, per contract

daily number of orders per contract was 1072; it means that on average, a member sent 4 orders for 1 execution (trade). There was on average 51 active members⁷ in the market which represents around a quarter of the members registered on the market.

2.4 Bid-ask spread and market depth over the trading session

This section first provides the data description of the the bid-ask spread and the market depths of the German continuous electricity market. Then, I examine the behavior of these two variables over an average trading session. The data used for this dynamic analysis is fine-grained (milliseconds of the trading session).

2.4.1 Data

The gross order book contains only the German local orders and does not account for cross-border or block orders. It covers a period of a year from January 1, 2015 to December 31, 2015. Each line of the gross order books displays an order that a market participant sent to the power exchange during the continuous trading session (complete order books). It includes a range of variables such as the delivery date, the delivery instrument (specific hour, half hour, or quarter hour), the name of the member who sent the order, the side of the order (buy or sell), the day and time when the order was sent, and the day and time when the order was executed/cancelled/deactivated/expired/modified and the couple price-quantity of the member set. The gross order book serves as input for the reconstitution tool that was first developed by the Product and Market Development team of EPEX

⁷A market participant is considered as active if he send at least one order during the trading session.

SPOT by using the software R. I compute the best order stream (best bid and ask prices) and the market depths each time there is a change in the order book during the trading session. The R code sorts market orders and creates a row each time there is a change in the order book that affects the bid-ask spread and/or the market depths. Each line of the output displays the particular contract and the associated delivery date, the date and time of trading, the best buy (highest) and sell (lowest) prices at that time, the respective quantities - it can be the sum of two orders or more at the best price. The last information the output shows is the buy and the sell depths. The outcome of the reconstitution tool displays the first line of the order book and the market depths for both the buy and sell sides, which can be seen by the market participants at the time they trade. I compute the bid-ask spread at each moment of the trading session as the difference between the best ask and the best bid:

$$BAS_{it'} = \text{best ask}_{it'} - \text{best bid}_{it'} \quad (2.1)$$

where t' is a vector of three dimensions composed of the delivery date, the trading date, and the trading time; i is the contract concerned that equals to 1 to 24.

I use the raw values from the reconstitution tool for the buy and sell depths.

2.4.2 Descriptive statistics

Table 2.2 presents the descriptive statistics for the bid-ask spread and the market depths aggregated at the contract level (per delivery date and hour). Over the period, the mean bid-ask spread is 3.52 €/MWh which is slightly more than the mean bid-ask spread of 2.97€/MWh found by Hagemann and Weber (2013) . The mean bid-ask spread is about 350 times the tick size (0.01€/MWh). It is much bigger than the spread in the securities market which is only a few times the tick size; nonetheless it is smaller than the spread in the French intraday power market where the average bid-ask spread is about 1,100 times the tick size in 2015 for local order books⁸. Both of those values are overestimated due to the absence of cross-border orders in the data set. If cross-border data would be added, the spread would be impacted or would be lower because an order from a neighboring country could only decrease the bid-ask spread by either proposing a sell price lower than

⁸The value of the French local bid-ask spread is calculated by the author, using the EPEX SPOT data.

the best ask or a buy price above the best bid. The average bid-ask spread is higher during the weekend (+ 13%) because of the decrease in the load as well as the decrease in the number of participants. There is no significant pattern regarding the average bid-ask spread per contract. The distribution of the bid-ask spread is displayed in the appendices (figure 2.7). We can observe peaks of frequency of the bid-ask spread every 0.05€/MWh. This observation highlights the use of the 5 cents price steps by the members⁹.

I split the data in a subset where the spreads were the highest (above 4€/MWh). In this subset, lower depths exist (respectively -17% and -21% in comparison to the mean buy and sell depths) which is consistent with the negative correlation between the bid-ask spread and the depths found later in this section. Off-peak products (before 8:00 or after 20:00) and weekends are over-represented in the subset. This result is reasonable because during off-peak hours, the liquidity and the number of active participants are lower, which is also valid for weekends. From the observed subset, I also find a higher sell price (+8,5% on average) and a lower buy price (-2% on average).

	Min	Quartile 1	Median	Mean	Quartile 3	Max
Bid-ask spread (€/MWh)	0.96	2.51	3.14	3.52	3.99	31.09
Buy depth (MWh)	74.91	557.58	772.63	854.96	1156.92	4639.20
Sell depth (MWh)	111.9	540.9	758.5	828.6	1129.4	2049.0

Table 2.2: Descriptive statistics of the bid-ask spread and the market depths, per contract

In 2015, the buy and sell depths are respectively 855 and 829 MWh on average per contract and 25% of the time they are respectively above 1157 and 1129 MWh. The same argument on a lack of the cross-border data applies to the market depths which are underestimated - market depths can only be higher than the result as cross-border orders could only increase the volume in the order book. The mean depths are higher for baseload contracts (8:00 to 20:00). The distributions of the depths¹⁰ aggregated at the contract level show a bi-modal distribution. On the one hand, the subset including only the high mode (depth above 900 MWh), the spread is on average lower (2.58€/MWh), the forecast wind generation is higher (+ 12% in comparison to the overall mean), there

⁹In the period studied, the tick size of the continuous market was 0.01€/MWh and has been 0.10€/MWh since June 2016.

¹⁰The distribution of the buy and the sell depths are displayed in the figures 2.8 and 2.9 of the appendices.

2.4. BID-ASK SPREAD AND MARKET DEPTH OVER THE TRADING SESSION⁴¹

is an overrepresentation of business day and peak contracts. On the other hand, the subset including only the low mode (depth below 900 MWh), the reverse is true: higher bid-ask spread, lower wind generation forecast, overrepresentation of weekends and off-peak contracts.

Using observations at the milliseconds level, the correlations between the bid-ask spread and the market depths are weak: -0.16 with the buy depth and -0.11 with the sell depth. However, when aggregating the values at the minute level, the correlation increased particularly for the morning hours where the mean correlation for the contracts 1 to 11 is -0.66. These correlations are negative which is reasonable and consistent with the literature. I can also observe this negativity by looking at the evolution of the depths and the bid-ask spread over an average trading session¹¹. Aggregating at the hourly level of the trading session, the correlation between the bid-ask spread and the depths are high: -0.83 with the buy depth and -0.86 with the sell depth.

2.4.3 Dynamic analysis

This subsection describes the evolution of the bid-ask spread and the market depths over an average trading session.

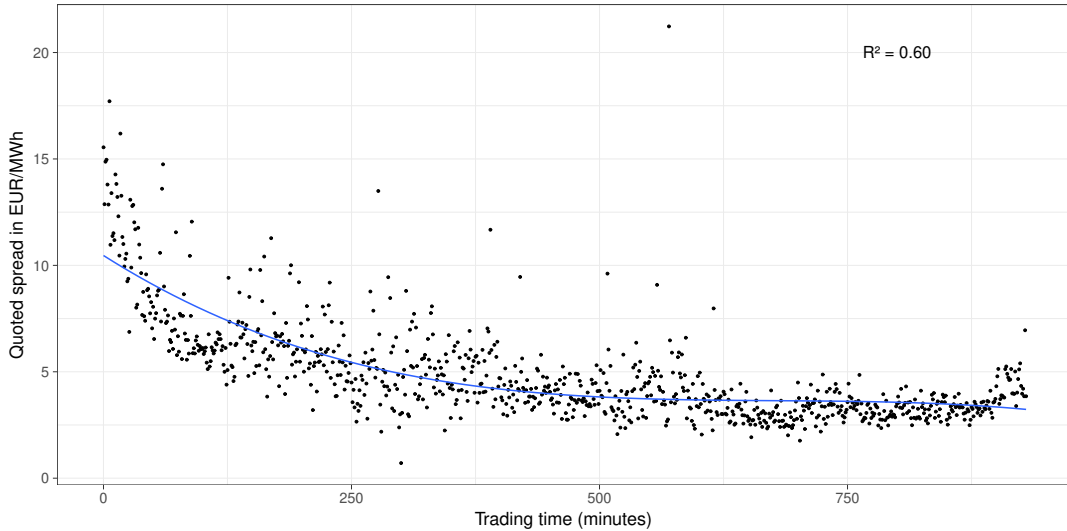


Figure 2.3: Bid-ask spread over an average trading session for the product 8

¹¹The figures 2.3 and the figure 2.4 illustrate the behavior of the bid-ask spread and the sell depth over an average trading session.

The figure 2.3 represents the evolution of the bid-ask spread over an average trading session aggregated at the minute level for the product 8 (60 minutes of power from 7:00 to 8:00)¹². The bid-ask spread decreases over the trading session no matter which contract is traded. This decrease might be because of the strong uncertainty away from the delivery time. During the last three hours in which the contract can be traded, I observe the lowest values of the bid-ask spread. As the contract gets closer to the delivery time, the uncertainty linked to the production decreases and so does the spread. The volume traded on the continuous market increases over time and 80% of the volume is traded during the last three hours of the trading session¹³. The continuous market is mainly used to adjust positions previously taken close to the real time due to the arrival of new information such as a new weather forecast, load forecast, or unplanned outages. The longer the trading session is (from 8,5 hours for the contracts 1 to 31,5 hours for the contract 24), the smoother is the curve of the bid-ask spread over time. At the end of the trading session, the bid-ask spread increases a bit due to the decrease of the volume of the orders book. The «L-shape» is consistent with the financial literature on microstructure but it is not straightforward due to the difference between financial and power markets, especially with the existence of a maturity in electricity contracts.

The figure 2.4 shows the evolution of the sell depth over an average trading session for the product 8¹⁴. The buy and the sell depths increase over the trading session. They have a reverse shape in comparison to the bid-ask spread. The correlation between the buy and the sell depths, using the data set at its lowest granularity (milliseconds), is of 0.95. As the contract gets closer to the delivery time, more quantities are added to the order book. The highest liquidity during the trading session occurs at the end. The reason behind this result is the growing need for trading because of the arrival of new information as well as the increasing need to be balanced. More liquidity means there are more opportunities for

¹²The figure 2.7 in the appendices illustrates the evolution of the bid-ask spread over an average trading session for the products 5, 9, 13 and 17. These contracts are different as the hours concerned have different profiles. For example, during contract 5, the demand for power is low and there is no solar generation. In contrast, product 13 represents the hour where solar production is the highest and the demand is high. The product 9 represents a peak hour where the demand is the highest.

¹³The figure 2.7 in the appendices shows the cumulative share of the volume traded during an average trading session.

¹⁴The figure 2.7 in the appendices illustrates the sell depth of the contracts 2, 9, 13 and 17.

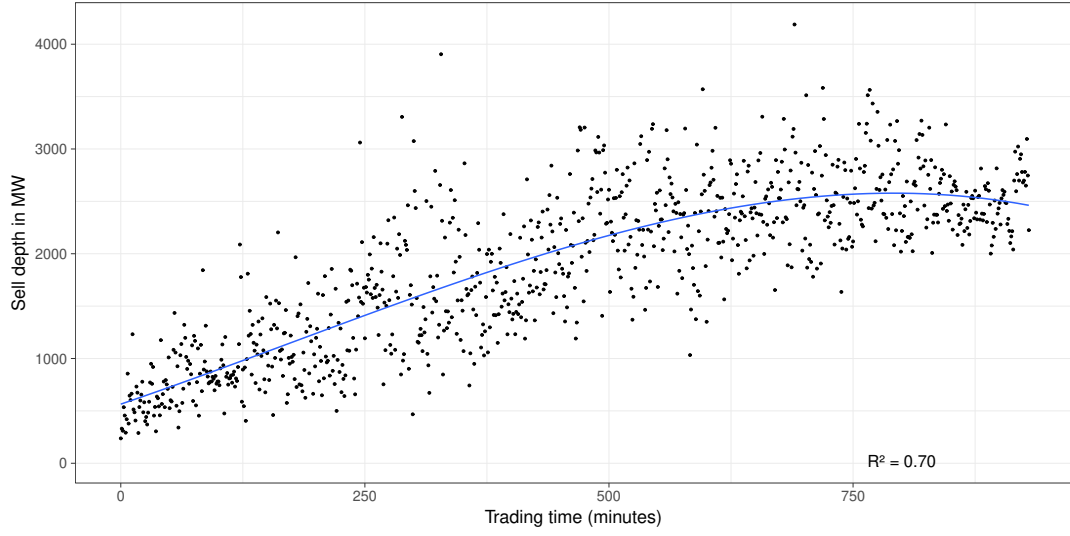


Figure 2.4: Sell depth over an average trading session for the product 8

matching, which is consistent with the fact that 80% of the trading volume is traded in the last three hours before delivery. At the opening of the trading session, market depths are around 500 MW (125 MWh) no matter what product is traded. For off-peak products, the average buy and sell depths are respectively 786 MWh and 769 MWh while for peak products, the average depths are respectively 936 MWh and 899 MWh. The market depths for off-peak products (before 8:00 and after 20:00) tend to increase to a lower level in comparison with peak products due to the lower economic activity in those hours. At the end of most trading sessions, I observe a decrease in the market depths 30 minutes before the gate closes due to the decrease in market opportunities as cross-border trading closes an hour before delivery. This decrease could also be explained by the traditional producers who want to fix their production at least an hour before delivery for operational purposes but also due to the large inflexibility of some power plants. It is also due to the absence of cross-border trading and so the decrease of market opportunities for a market participant.

2.5 Data and methodology

The present section is divided in two parts. The first subsection introduces the four hypothesis verified as well as the data sets that is used to check them. The second one is

dedicated to the methodology/econometrics specifications.

2.5.1 Hypothesis and data

This study uses data on firm-level energy bids of the continuous market (source: EPEX SPOT), day-ahead auction aggregated curves (source: EPEX SPOT), solar/wind forecast (source: Eurowind) and actual generation (source: EEX transparency platform) as well as forecast and actual load (source: ENTSO-E transparency platform). From the order book, I construct¹⁵ a novel dataset with the bid-ask spread and the market depths at each moment of each trading session of the year 2015. The order book data I use is highly confidential and includes market participants identifiers which permits me to compute the concentration ratio (HHI index). Due to the frequency of the data (from the milliseconds for the bid-ask spread to once a day for the actual wind generation), I aggregate all the variables at the daily level for each contract. In the rest of the paper, I will refer to t as the delivery date and i the contract.

The aim of the econometric specification is to find the main drivers of the bid-ask spread of the German electricity spot market. The bid-ask spread was chosen as a proxy for liquidity by representing an implicit transaction cost for market participants. From the outcome of the reconstitution tool, I compute the mean bid-ask per day and contract (s_{it}).

In order to find the main drivers of the bid-ask spread, I use the methodology from McNish and Wood (1992) who used the four following explanatory components: risk, information, activity and competition.

Hypothesis 1: There is a positive relation between the bid-ask spread and the risk and volatility in the market. When the volatility is high, there is more risk and uncertainty on the market; in this situation, the buyers are willing to buy at a lower price and the sellers are willing to sell at a higher price in order to hedge the risk linked to the volatility. Therefore, the bid-ask spread should increase. The volatility is measured here either as the elasticity of the supply curve of the day-ahead market, the elasticity of the demand curve of the day-ahead market and the weighted price standard deviation.

The slopes of the demand and the supply curves around the equilibrium point can be interpreted as their elasticities: when the elasticity on one side of the market increases

¹⁵The reconstitution is explained in section 4.1.

(slope tends to zero), the bid-ask spread decreases. When the inelasticity increases (slope tends to infinity), market participants are more sensitive to price variation: a small change in quantity means a strong change in prices which increases the volatility in the market and therefore the bid-ask spread increases.

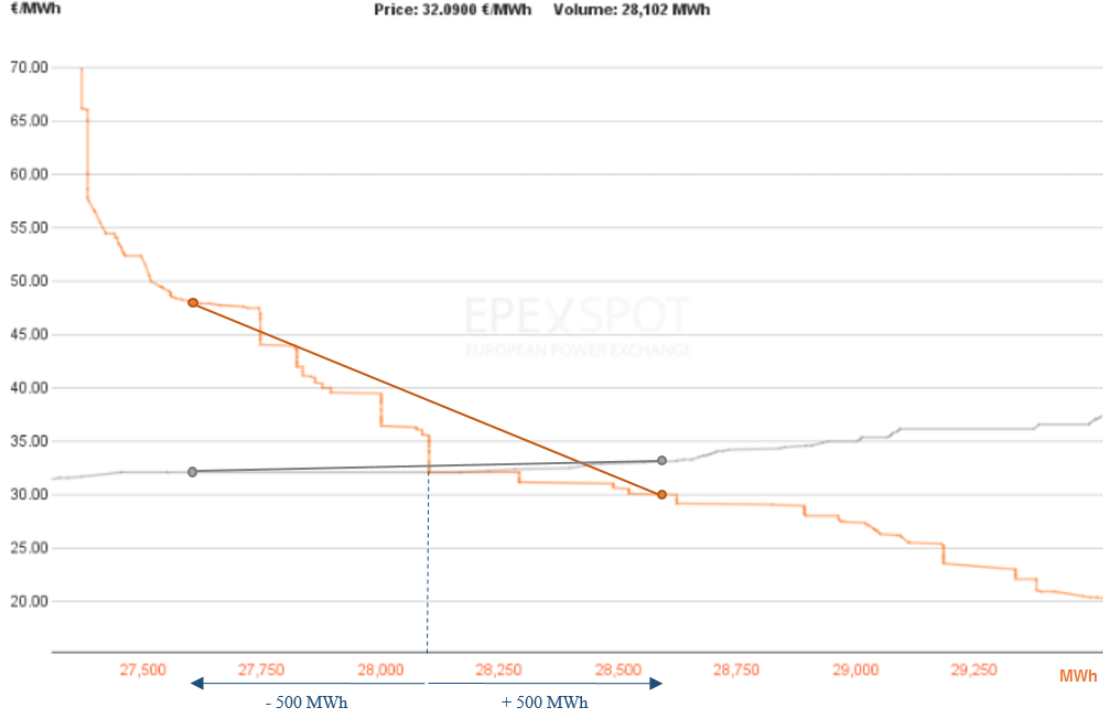


Figure 2.5: Example of aggregated curves of the DAM (25/10/2015 - product 9)

The price elasticity variables ES_{it} (supply elasticity) and ED_{it} (demand elasticity) are calculated using the aggregate curves of the German day-ahead market. Those variables represent an approximation of the elasticities around the equilibrium. The supply elasticity (respectively demand elasticity) is computed as the slope of a linear interpolation of the supply (respectively demand) curve between the two points corresponding to the equilibrium volume (Q^*) of the auction plus or minus 500 MWh. Figure 2.5 illustrates the concept of the calculation. The slopes are computed as follow:

$$ES_{it} = \left| \frac{[Q^* - 500] - [Q^* + 500]}{p^s(Q^* - 500) - p^s(Q^* + 500)} \right| \quad (2.2)$$

$$ED_{it} = \left| \frac{[Q^* - 500] - [Q^* + 500]}{p^d(Q^* - 500) - p^d(Q^* + 500)} \right| \quad (2.3)$$

where p^s is the supply price, and p^d is the demand price at the points (Q^*-500) and (Q^*+500) . The elasticity represents the average price variation around the equilibrium that corresponds to a quantity variation of 1 MWh.

The second proxy variable for the volatility is the weighted (by the volume) price standard deviation. It measures the variability around the average price. When the weighted price standard deviation increases, the volatility increases and the bid-ask spread gets wider as the price expectations of the sellers and buyers fluctuate more. It is computed as followed:

$$\sigma_p = \sqrt{\frac{\sum_{i=1}^N v_i (p_i - \bar{p}^*)^2}{\frac{M-1}{M} \sum_{i=1}^N v_i}} \quad (2.4)$$

where

$$\bar{p}^* = \frac{\sum_{i=1}^N v_i p_i}{\sum_{i=1}^N v_i} \quad (2.5)$$

The N is the number of observations, M the number of nonzero weights, v_i the volume (weight), p_i the price of the transaction, and \bar{p}^* is the weighted mean of the price.

Hypothesis 2: There is a negative relation between the bid-ask spread and the need for adjustment. When the demand or supply diverges from its initial forecast, the positions of some market participants will change, and they will need to balance their positions that therefore increases the volume in the market. The renewable production (wind and solar) and the load forecast errors are used to measure the need for adjustment from both the supply and the demand side.

Kiesel and Paraschiv (2017) found a significant effect of the wind and solar forecast errors on the price of the continuous market. When the supply (relative forecast error of the wind and the solar generation) changes, the bid-ask spread is expected to decrease. When an intermittent power supplier faces a positive shock in his production, he will produce more than he previously planned and so will need to sell the extra production. The reverse is also true: when an intermittent supplier faces a negative shock of her production; if she already sold her production, she will need to buy the difference to satisfy her production commitment.

In order to assess the impact of the forecast errors, I subtract the wind (solar) forecast (WF_{it} and SF_{it}) to the wind (solar) generation (WG_{it} and SG_{it}) as I admit that the

difference between the forecast 30 minutes before delivery (gate closure) and the actual generation is negligible. The chosen forecast is issued at 2 pm ("PREV4") the day before delivery as it is after the DAM and before the beginning of the intraday market (14:30 after the nomination to the TSOs). The relative forecast errors are expressed in percentage of variation. The relative forecast errors are defined as:

$$\Delta_{it}^W = \frac{WG_{it} - WF_{it}}{WF_{it}} \quad (2.6)$$

$$\Delta_{it}^S = \frac{SG_{it} - SF_{it}}{SF_{it}} \quad (2.7)$$

Inspired by Ziel (2017), I split the above equations depending on the algebraic sign of the shock. A positive shock is defined as:

$$W_{it}^{FE+} = \max\{\Delta_{it}^W, 0\} \quad (2.8)$$

$$S_{it}^{FE+} = \max\{\Delta_{it}^S, 0\} \quad (2.9)$$

and a negative shock is defined as:

$$W_{it}^{FE-} = \max\{-\Delta_{it}^W, 0\} \quad (2.10)$$

$$S_{it}^{FE-} = \max\{-\Delta_{it}^S, 0\} \quad (2.11)$$

When the demand (load relative forecast error) changes, I expect the bid-ask spread to decrease. The load forecast error is computed with the same methodology as the wind and solar forecast errors:

$$\Delta_{it}^L = \frac{LG_{it} - LF_{it}}{LF_{it}} \quad (2.12)$$

where LG_{it} is the actual load and LF_{it} the forecasted load taken at 14:00 the day before delivery. I then split the forecast error in a positive and a negative shocks:

$$L_{it}^{FE+} = \max\{\Delta_{it}^L, 0\} \quad (2.13)$$

$$L_{it}^{FE-} = \max\{-\Delta_{it}^L, 0\} \quad (2.14)$$

Hypothesis 3: There is a negative relation between the bid-ask spread and the activity on the market. I expect that when the activity on the market increases, the bid-ask spread

decreases. Indeed, when the load (retail demand) is high, the volume available on the market increases (higher liquidity) and therefore the bid-ask spread should be narrowed.

I use the forecasted load as a proxy for the activity on the market. This variable is well linked with seasonal variables such as business days or seasons. In this sense, I do not use seasonal control variable in the model.

Hypothesis 4: There is a negative relation between the bid-ask spread and the competition in the market. When the concentration of the market decreases, the competition increases on the market and so there is less asymmetry of information due to large market shares; the spread should then decrease.

To measure the concentration of the market, the Herfindahl-Hirschman Index (HHI) is computed on both side of the market. This index captures the concentration and measures the market competitiveness.

$$HHI = \sum_{i=1}^m s_i^2 \quad (2.15)$$

where

$$s_i = \frac{v_i}{\sum_{i=1}^m v_i} \quad (2.16)$$

where s_i is the market share (the volume traded by a firms in comparison to the total volume of the market) of the firm i and m the number of firms.

Table 2.3 gives the descriptive statistics of the variables described above for the year 2015. The data are at the contract level. The average bid-ask spread per contract is 3.5€/MWh which is about 10% of the weighted average price (WAP) for the same period. The mean weighted standard deviation of the price is 4.15€/MWh which means that the price variation within a trading session is 11.5% of the mean WAP. The mean slopes of the buy and sell curves of the DAM are equal to 0.026 and 0.010. The average hourly load is 247 GWh. The average concentration ratio is 1087 for the demand and 1034 for the supply.

Variable	Min	Quartile1	Mean	Median	Quartile3	Max	Skewness	Kurtosis
Bid-ask spread (EUR/MWh)	0,965	2,510	3,518	3,137	3,995	31,093	3,815	30,546
Weighted price std. dev. (EUR/MWh)	0,571	2,382	4,154	3,340	4,714	355,743	40,050	1 920,235
Demand elasticity	0,001	0,004	0,026	0,006	0,016	0,994	8,858	96,284
Supply elasticity	0,001	0,005	0,010	0,007	0,011	0,237	6,095	74,449
Positive solar forecast err. (%)	0,000	0,000	3 261,488	0,000	12,936	934 900,000	16,077	391,863
Negative solar forecast err. (%)	0,000	0,000	6,735	0,000	0,000	98,013	2,863	11,100
Positive wind forecast err. (%)	0,000	0,000	15,035	4,489	19,824	379,402	4,378	34,747
Positive wind forecast err. (%)	0,000	0,000	5,632	0,000	7,270	78,514	2,459	9,651
Positive load forecast err. (%)	0,000	0,000	1,560	0,277	2,405	19,713	2,739	13,820
Positive load forecast err. (%)	0,000	0,000	1,365	0,000	1,902	21,103	2,870	14,640
Load forecast (MWh)	135 802,000	211 292,000	246 932,926	246 841,000	285 548,000	325 957,000	-0,106	1,862
HHI - demand	401,008	753,707	1 087,434	966,065	1 279,941	5 747,157	1,978	9,838
HHI - supply	396,627	709,833	1 034,253	902,124	1 190,507	5 159,769	2,444	12,608

Table 2.3: Descriptive statistics of the variables (contract level)

2.5.2 Methodology

This subsection describes the econometric specification I use to explain the average bid-ask spread per contract.

Due to the configuration of the data set, panel data methods are the most appropriate because our data combines information on individuals' behaviors (contracts) and over time (delivery date). Contracts are independent as each of them are traded individually by the market participants. They also have their own specificities. Figure 6 shows the heterogeneity across contracts.

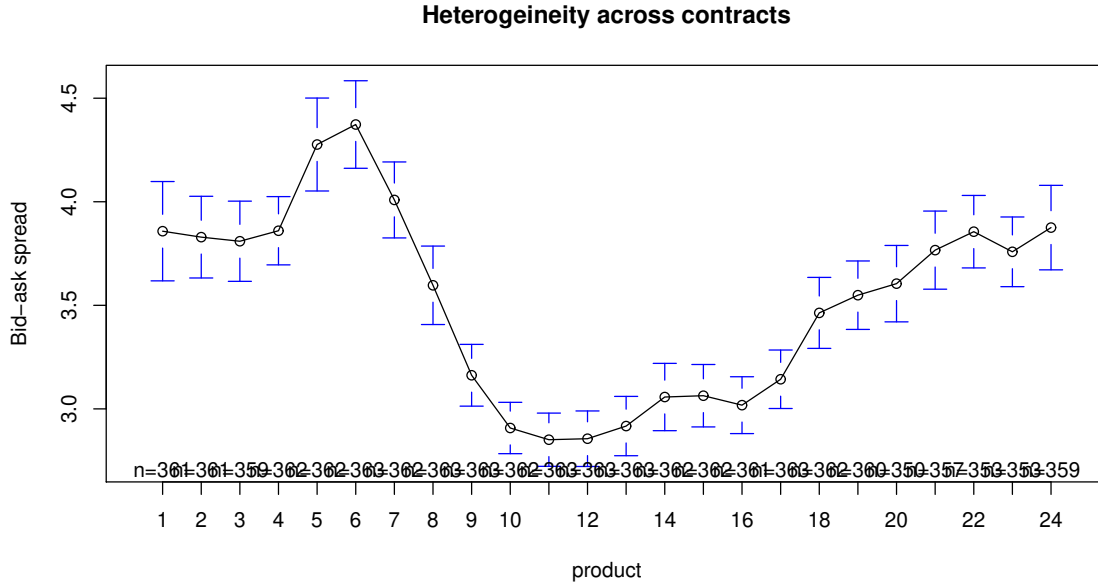


Figure 2.6: Heterogeneity across contracts

I compare the fixed effects model with the pooled OLS model using a F-test, and find that the the fixed model is a better choice. I then compare the fixed effect model with a random one using the Hausman test. The fixed effect is more appropriated. With fixed effects models, «within» or the first difference estimator can be used.

Using the Levin-Li-Chu test for panel data, I find that none of the variables have unit roots; however, applying stationarity test (Kwiatkowski-Phillips-Schmidt-Shin or KPSS test) for each group, I find that most of the variables are not stationary. In this sense, a first difference model is used to stationarize each variable. An additional KPSS test on each of the first difference variable confirms the stationarity of each variable.

The Breusch-Pagan test detects heteroskedasticity in the model. It can cause bias in the results of the standard deviations in the variables estimations that use an OLS estimator; I then produce HAC (Heteroskedasticity and Autocorrelation Consistent) standard errors for the OLS models. The Breusch-Godfrey/ Wooldridge test identifies serial correlation in the panel model. For this reason, a feasible generalized least square (FGLS) estimator is used as it "allows the error co-variance structure inside every group of observations to be fully unrestricted and is therefore robust against any type of intra-group heteroskedasticity and serial correlation" (Croissant and Millo, 2008).

To explain the daily average bid-ask spread per contract as a function of the volatility (weighted price standard deviation, elasticities), the need for adjustment (relative wind and solar forecast errors), the activity (weekends, load) and the competition (number of active members) on the market, I estimate the below equation:

$$\begin{aligned}
\Delta BAS_{it} = & \alpha_i \\
& + \beta_1 \Delta \sigma_{it} + \beta_2 \Delta ES_{it} + \beta_3 \Delta ED_{it} \\
& + \beta_4 \Delta W_{it}^{FE+} + \beta_5 \Delta S_{it}^{FE+} + \beta_6 \Delta W_{it}^{FE-} + \beta_7 \Delta S_{it}^{FE-} \\
& + \beta_8 \Delta L_{it}^{FE+} + \beta_9 \Delta L_{it}^{FE-} \\
& + \beta_{10} \Delta L_{it} \\
& + \beta_{11} \Delta HHI_{it}^D + \beta_{12} \Delta HHI_{it}^S \\
& + u_{it}
\end{aligned} \tag{2.17}$$

The seasonality variable is not included in the model as the load is correlated with the seasonality. The same argument also applies to the temperature.

One may be concerned about the endogeneity problem that may arise with the weighted standard deviation variable, particularly due to the aggregation at the daily level. Instrumental variables are commonly used to address this issue; however, I cannot find any robust instrumental variable for the volatility. I compute the correlation and the covariance between the weighted price standard deviation and the error term of the regression. Both are null. On top of that, I perform the Granger causality test using data at the millisecond level and found that volatility causes bid-ask spread. The reverse does not hold. For the reason mentioned above, I discard the endogeneity hypothesis in the model.

Notation	Definition
σ_{it}	Weighted price standard deviation of the trades (EUR/MWh)
ES_{it}	Elasticity of the supply
ED_{it}	Elasticity of the demand
W_{it}^{FE+}	Positive wind forecast error (% or MWh)
S_{it}^{FE+}	Positive solar forecast error (% or MWh)
W_{it}^{FE-}	Negative wind forecast error (% or MWh)
S_{it}^{FE-}	Negative solar forecast error (% or MWh)
L_{it}^{FE+}	Positive load forecast error (% or MWh)
L_{it}^{FE-}	Negative load forecast error (% or MWh)
L_{it}	Forecasted load (MWh)
HHI_{it}^D	Herfindahl index for the demand side
HHI_{it}^S	Herfindahl index for the supply side

Table 2.4: Definition of the notations

2.6 Results

This section describes and discusses the results of the panel data model. The model is first run on the whole dataset. Then, I split the data in peak (between 8 and 20) and off-peak (before 8 or after 20) contracts.

Volatility - The weighted price standard deviation has a positive impact on the bid-ask spread, particularly during off-peak hours. When the volatility increases by 1€/MWh, the bid-ask spread tend to increase by 5 cents. An increase of 1€/MWh during the trading session of an off-peak contract, increases the bid-ask spread by 13 cents per MWh; while, the impact will only be of 2 cents per MWh for peak contracts.

An increase of the elasticities of the demand and the supply also has a positive impact on the bid-ask spread. As the buy or the sell aggregated curves get more elastic, the price is more sensitive to a change in quantities; a small change in the quantity leads to an important change in prices. The higher the elasticity (slope tends to infinity) is, higher is the volatility and so the spread. The slope of the supply curve has a stronger effect on the bid-ask spread than the slope of the demand curve. Overall, when the slope of the supply curve increases by 0.1, the bid-ask spread increases by 1.25€/MWh while

	<i>Dependent variable: Bid-ask spread</i>		
	All	Peak	Off-peak
Weighted price std. dev. (EUR/MWh)	0,04831*** (0,00322)	0,02011** (0,00837)	0,12995*** (0,00557)
Demand elasticity	1,00748*** (0,15758)	0,28668 (0,52751)	0,56028** (0,24167)
Supply elasticity	12,52174*** (0,74737)	1,86613 (4,05236)	6,83013** (3,04588)
Positive load f.e. (%)	-0,00940*** (0,00320)	-0,02263*** (0,00734)	-0,01402* (0,00843)
Negative load f.e. (%)	0,01174*** (0,00293)	-0,00136 (0,01244)	-0,02293** (0,01151)
Positive solar f.e. (%)	-0,00000 (0,00000)	0,00000 (0,00000)	
Negative solar f.e. (%)	-0,00405*** (0,00038)	-0,00117 (0,00173)	
Positive wind f.e. (%)	-0,00569*** (0,00027)	-0,00204 (0,00141)	-0,00830*** (0,00171)
Negative wind f.e. (%)	-0,00129*** (0,00052)	0,00298 (0,00484)	-0,00320* (0,00173)
Load forecast (MWh)	-0,00001*** (0,00000)	-0,00001*** (0,00000)	-0,00001*** (0,00000)
HHI - demand	0,00009*** (0,00001)	0,00008*** (0,00003)	0,00007*** (0,00002)
HHI - supply	0,00034*** (0,00001)	0,00031*** (0,00006)	0,00031*** (0,00004)

Note:

*p<0.1; **p<0.05; ***p<0.01

Table 2.5: Results using the panel FGLS estimator.

an increase in the slope of the demand curve by 0.1 increases the spread by only 10 cents per MWh. This difference is due to the inelasticity of the demand. The elasticities do not have a significant impact on peak contracts.

Adjustment needs - The variation of the fundamentals (load, wind and solar) have a significant impact on the bid-ask spread. The uncertainty linked to the forecast errors brings additional volatility to the market but at the same time, a forecast error creates a need to trade and therefore an increase of the volume/market depths. This second explanation seems to gain over the first one. Looking at the results, we can see that most of the load, wind or solar forecast errors (positive or negative) have a negative impact on the bid-ask spread.

A negative load forecast error has a positive impact on the bid-ask spread while a positive load forecast error has a negative impact on the bid-ask spread. The positive impact may be due to the suppliers who will remove their orders from the order book as they will need to buy less from the market and so increase the bid-ask spread. However, this positive effect is not observed during off-peak contracts where both a negative and a positive forecast error have a negative impact on the bid-ask spread. For those contracts, a negative load forecast error has a stronger impact than a positive one. Only a positive load forecast error is significant for on-peak contracts.

When the wind positive (resp. negative) forecast error increases by 1%, the bid-ask spread tends to decrease by 0.6 cent/MWh (resp. 0.1 cent/MWh). A 1% negative solar forecast error has an impact of -0.4 cent per MWh on the bid-ask spread. A positive solar forecast error has a negative but negligible impact on the bid-ask spread. The difference between a positive wind and solar forecast error may be explained by the difference in behavior of the TSOs who market the solar production while the aggregators market the wind production. The aggregators may adjust their position on the market after a positive forecast error while TSOs may net their volume (for example, by using it to buy their grid losses). The difference between the positive and the negative wind forecast error may be due to the aggregators who are liquidity providers or trade's originators in the case of a positive forecast error (ie. they will send an order at a limit price in the order book) while they are more trade's aggressors or liquidity demanders (they will hit an order already in the order book) in the case of a negative forecast error in order to buy some volume. While the impact of forecast errors is not significant on peak contracts, it is for

off-peak contracts which contain most of the night hours. Ziel (2017) find a stronger impact of the forecast errors on prices during the night.

Activity - When the load increases by 1 GWh, the bid-ask spread decreases by 1 cent per MWh. When the load is high, during business days for example, there is an increase of the trading need and so more orders/volume are sent to the market. There is no specific pattern for peak versus off-peak contract.

Competition - When the concentration on the sell side increases by 100, the bid-ask spread also increases by about 3 cents/MWh while it only increases by 1 cent/MWh when the concentration on the buy side increases by 100. The bigger influence of the concentration on the sell side may be due to the inelasticity of the demand for power. This result is intuitive as an increase of the concentration goes along with a decrease of the market parties as well as an increase of the market power of some firms.

2.7 Remarks and conclusion

The continuous market is getting more and more attention in the literature as well as in the public debate thanks to (i) the growing renewable capacity that increases the willingness to trade very close to delivery and (ii) the XBID project which aims to harmonize the cross-border intraday trading across Europe. The market quality and so the liquidity is of major importance for institutions but also market participants. This paper brings to light the behavior of the liquidity along a trading session and find the main drivers of this liquidity.

I might have thought that the differences between the financial and the power market would lead to different results. However, I find a negative link between the bid-ask spread and the liquidity as well as a positive relation between the spread and the volatility, which is in line with the financial literature. Further, I observe a «L-shaped» behavior of the bid-ask spread over an average trading session similar to the financial markets (McInnish and Wood, 1992). I observe a strong dispersion of the bid-ask spread on the German intraday market at the beginning of the trading session which then diminishes as the delivery time approaches. The dispersion highlights the uncertainty away from the delivery time mainly due to the intermittent renewable generation. The reverse shape applies for the market depths, and increases over the trading session.

To sum up the econometrics part, the risk and volatility in the market increase the bid-ask spread. A fundamental (wind and solar) or load forecast error will lead to a decrease of the bid-ask spread by bringing more liquidity to the market except for the case of a negative load forecast error which has a positive effect on the bid-ask spread probably due to the strategy of the suppliers. Interestingly, we can observe that a demand (load) versus a supply (fundamentals) shock does not have the same impact on the bid-ask spread: a load forecast error has a stronger impact on the bid-ask spread than a fundamental one. When the activity on the market increases, the spread tends to decrease, in line with the positive link between the concentration on the market and the spread.

Further work might include an extension of the model to other intraday power markets. The model can also be enriched by including cross-border data. Last but not least, further work could characterize the determinants of the bid-ask spread in a less aggregated form over the trading session.

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Appendices

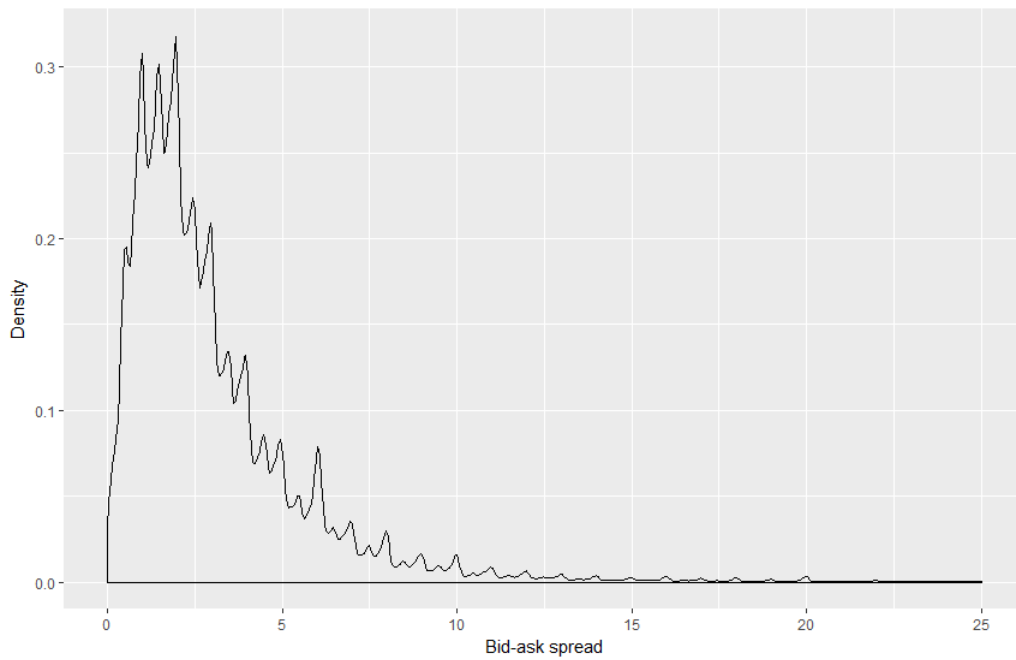


Figure 2.7: Distribution of the bid-ask spread

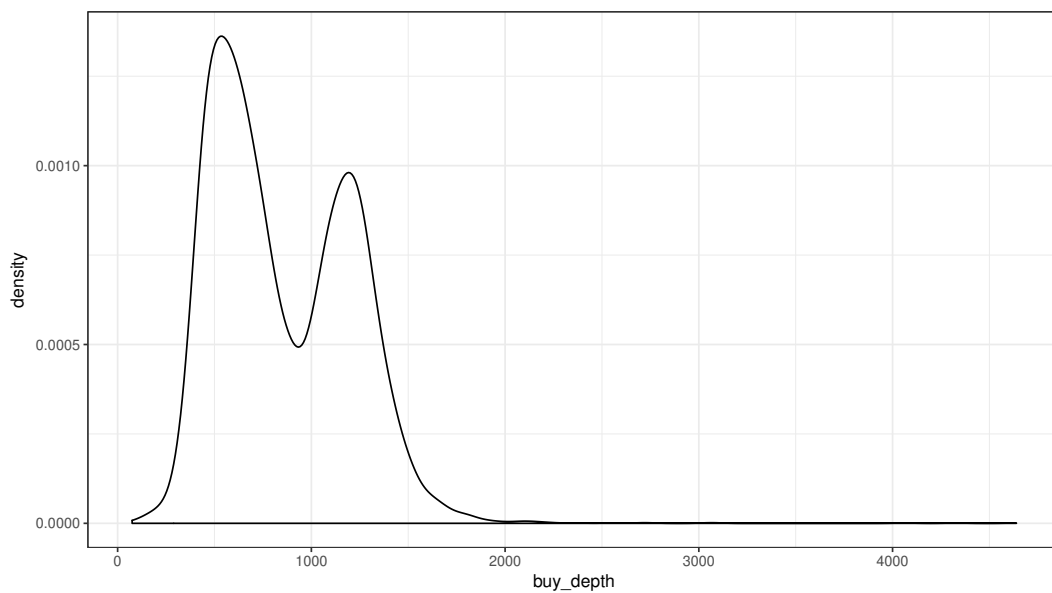


Figure 2.8: Distribution of the buy depth at the contract level

Abbreviation	Detailed factor
TWh	Terawatt-Hour
MWh	Megawatt-Hour
IDM	IntraDay Market
LPX	Leipzig Power Exchange
TSO	Transmission System Operator
NYSE	New-York Stock Exchange
MRR	Madhavan, Richardson and Roomans
NASDAQ	National Association of Securities Dealers Automated Quotations
OTC	Over-The-Counter
DAM	Day-Ahead Market
FOK	Fill-Or-Kill
IOC	Immediate-Or-Cancel
LFOK	Linked Fill-Or-Killed
AON	All-Or-None
CWE	Central Western Europe
BAS	Bid-Ask Spread
MW	Megawatt
WAP	Weighted Average Price
ED	Demand Elasticity
ES	Supply Elasticity
GWh	Gigawatt-Hour
OLS	Ordinary Least Squares
FGLS	Feasible Generalized Least Squares

Table 2.6: Abbreviations table

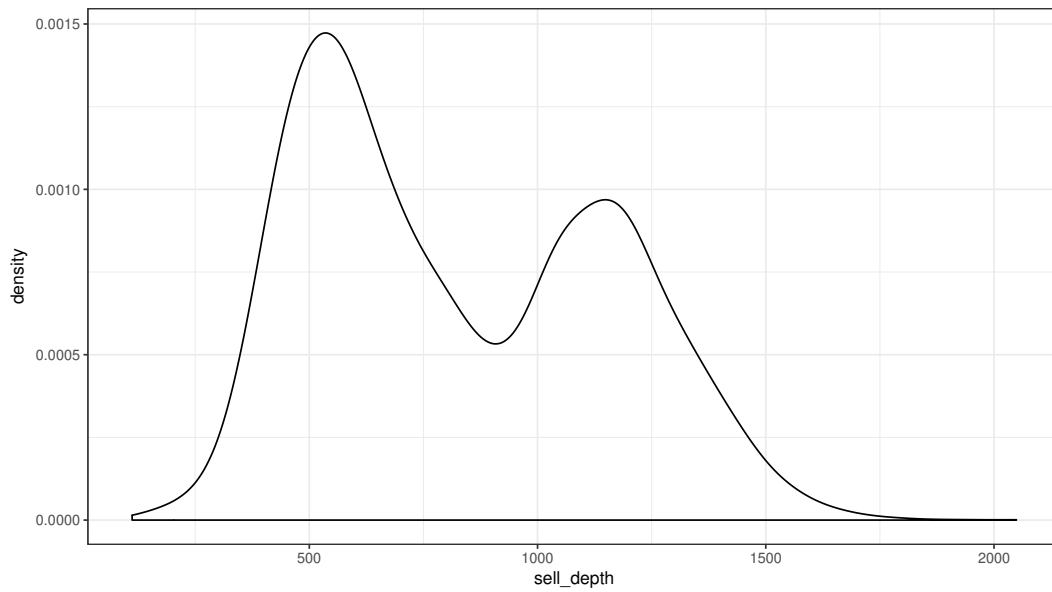


Figure 2.9: Distribution of the sell depth at the contract level

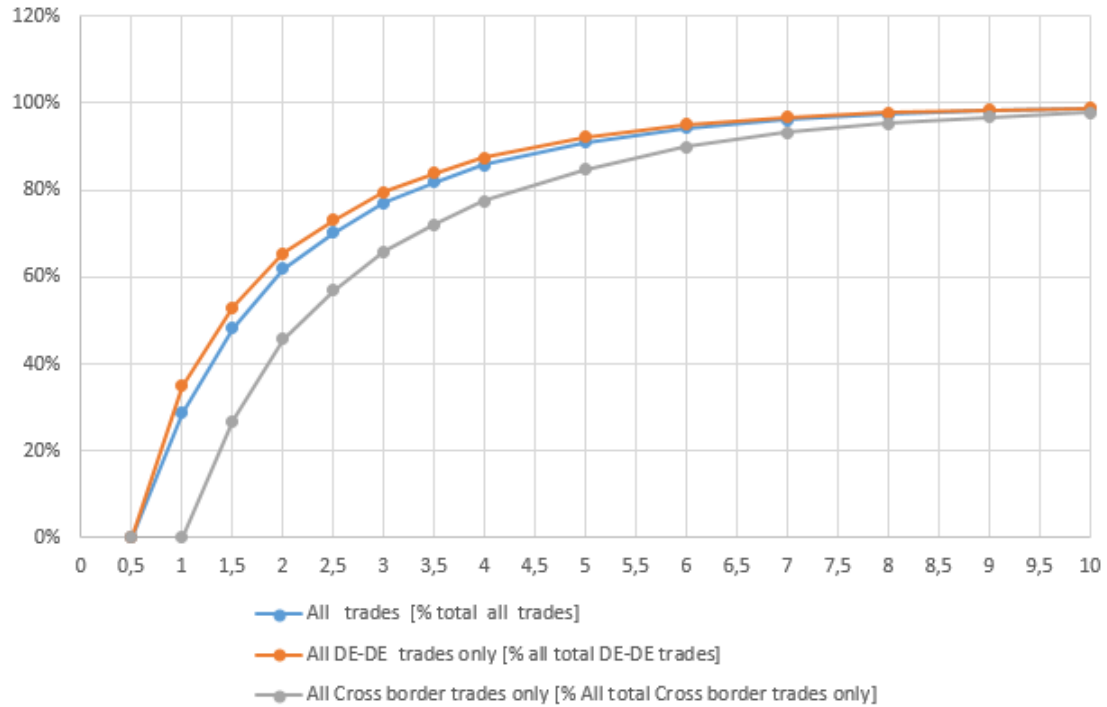


Figure 2.10: Cumulative share of the volume traded along an average trading session

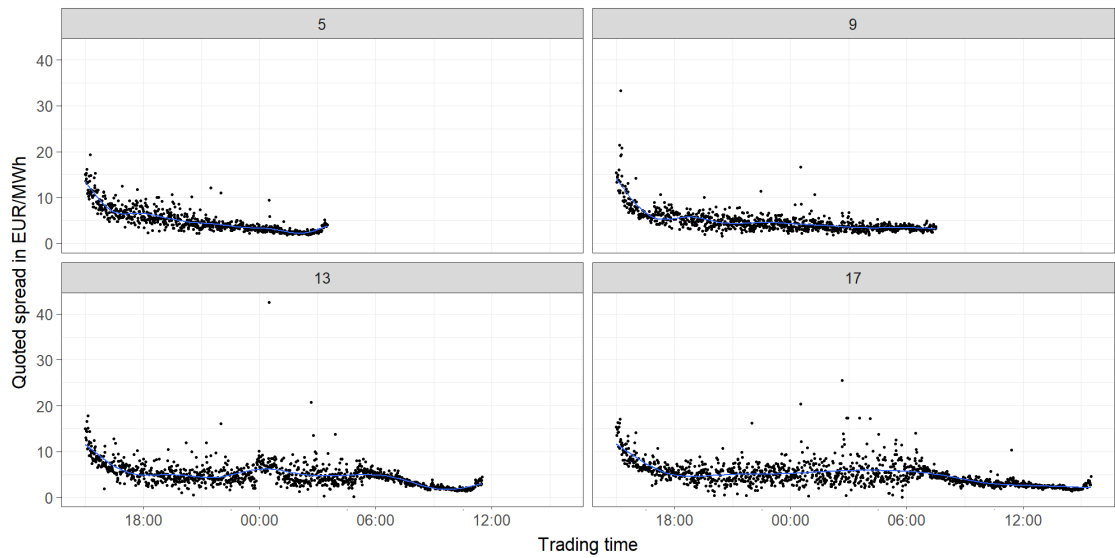


Figure 2.11: Bid-ask spread over an average trading session for various products

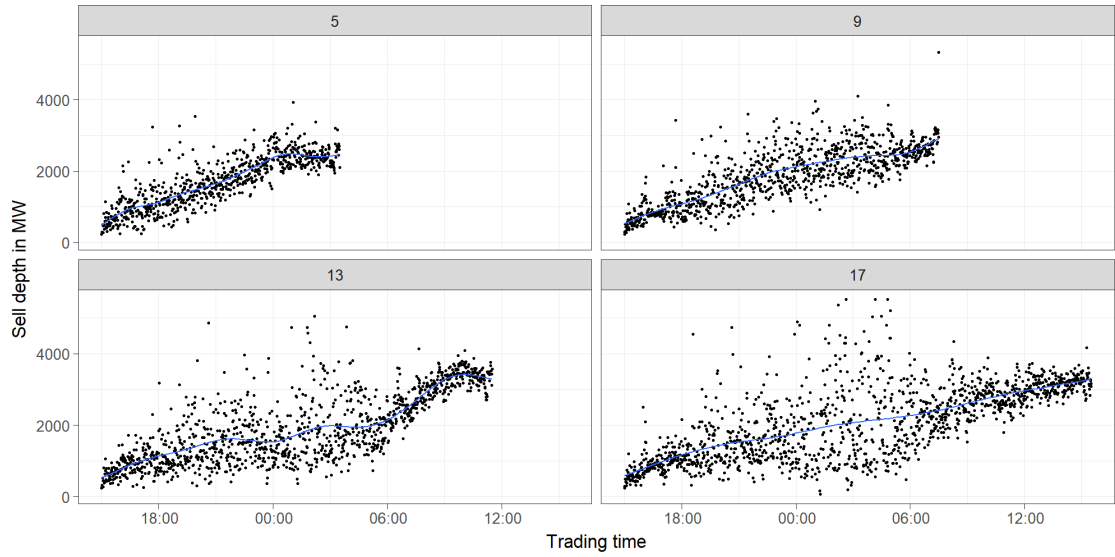


Figure 2.12: Sell depth over an average trading session for various products

	$\Delta\sigma_{it}$	ΔES_{it}	ΔED_{it}	ΔW_{it}^{FE+}	ΔS_{it}^{FE+}	ΔW_{it}^{FE-}	ΔS_{it}^{FE-}	ΔL_{it}^{FE+}	ΔL_{it}^{FE-}	ΔL_{it}	ΔHHI_{it}^D	ΔHHI_{it}^S
$\Delta\sigma_{it}$	1,000	0,056	0,024	0,006	0,047	0,004	0,005	-0,023	0,022	0,007	0,000	-0,017
ΔES_{it}	0,056	1,000	-0,003	-0,036	0,005	-0,016	0,030	0,018	0,013	0,051	0,014	-0,033
ΔED_{it}	0,024	-0,003	1,000	0,059	-0,015	0,006	0,015	-0,036	0,019	-0,121	0,023	0,057
ΔW_{it}^{FE+}	0,006	-0,036	0,059	1,000	-0,219	-0,010	-0,034	0,023	-0,055	-0,132	0,012	0,041
ΔS_{it}^{FE+}	0,047	0,005	-0,015	-0,219	1,000	0,012	0,040	0,009	0,045	-0,187	0,007	0,002
ΔW_{it}^{FE-}	0,004	-0,016	0,006	-0,010	0,012	1,000	-0,001	0,004	-0,010	0,012	0,008	0,030
ΔS_{it}^{FE-}	0,005	0,030	0,015	-0,034	0,040	-0,001	1,000	-0,028	0,025	-0,033	-0,008	-0,001
ΔL_{it}^{FE+}	-0,023	0,018	-0,036	0,023	0,009	0,004	-0,028	1,000	-0,290	0,010	0,078	-0,124
ΔL_{it}^{FE-}	0,022	0,013	0,019	-0,055	0,045	-0,010	0,025	-0,290	1,000	-0,016	-0,078	0,099
ΔL_{it}	0,007	0,051	-0,121	-0,132	-0,187	0,012	-0,033	0,010	-0,016	1,000	-0,112	-0,211
ΔHHI_{it}^D	0,000	0,014	0,023	0,012	0,007	0,008	-0,008	0,078	-0,078	1,000	0,030	0,030
ΔHHI_{it}^S	-0,017	-0,033	0,057	0,041	0,002	0,030	-0,001	-0,124	0,099	-0,211	0,030	1,000

Table 2.7: Correlation matrix

<i>Dependent variable: Δ Bid-ask spread</i>				
	All	All	Peak	Off-peak
W. price s.d. (EUR/MWh)	0.026** (0.012)		0.015** (0.008)	0.146*** (0.037)
Demand elasticity	0.486** (0.189)	0.626*** (0.211)	0.191 (0.184)	0.608** (0.294)
Supply elasticity	8.921*** (2.579)	9.492*** (2.727)	4.413*** (1.295)	18.674*** (6.855)
Positive load f.e. (%)	-0.014** (0.006)	-0.012** (0.006)	-0.020*** (0.004)	-0.014 (0.012)
Negative load f.e. (%)	0.005 (0.014)	0.011 (0.014)	0.018* (0.009)	0.016 (0.025)
Positive solar f.e. (%)	0.00000*** (0.00000)	0.00000*** (0.00000)	0.00000*** (0.00000)	0.00000 (0.00000)
Negative solar f.e. (%)	-0.002 (0.003)	-0.002 (0.003)	-0.004 (0.003)	0.008*** (0.002)
Positive wind f.e. (%)	-0.003*** (0.001)	-0.003*** (0.001)	-0.003*** (0.001)	-0.002** (0.001)
Negative wind f.e. (%)	-0.0001 (0.002)	0.0002 (0.002)	0.002 (0.003)	-0.005 (0.003)
Load forecast (MWh)	-0.00001*** (0.00000)	-0.00001*** (0.00000)	-0.00001*** (0.00000)	-0.00001*** (0.00000)
HHI - demand	0.0001** (0.00004)	0.0001** (0.00004)	0.0001 (0.0001)	0.0001* (0.00005)
HHI - supply	0.0003*** (0.00004)	0.0003*** (0.00004)	0.0003*** (0.00005)	0.0004*** (0.0001)

Note:

*p<0.1; **p<0.05; ***p<0.01

Table 2.8: Results using the panel OLS estimator.

Chapter 3

Auction and continuous markets: complements rather than substitutes? The case of the German power spot market for quarter hourly contracts

About this chapter

I want to thank EPEX SPOT for the support as well as the participant of the following conferences for their constructive comments and remarks that helped to improve the chapter: the Financial econometrics seminar (Nantes, France), the 41th IAEE International Conference, the International Ruhr Energy Conference and the 24th Young Energy Economists and Engineers Seminar.

Abstract

A good market design is a key component of an efficient market. This paper quantifies the effect of the introduction of an auction before a continuous market in terms of liquidity, volatility and competition. Using order and trade books of the German quarter hourly contracts for power, I find that the introduction of the auction decreased the volume traded on the continuous market (business-stealing effect) while it increased the total volume (auction and continuous). This limited effect is due to the complementarity between the 2 trading mechanisms. Second, the introduction has no effect on the volatility during the first hour of trading and reduces it during the second hour of the session. Finally, after the introduction of the auction, the number of market participants more than doubled and the concentration of the market decreased on the trading chain (auction and continuous market). This research contributes to the literature by using order books in their finest details to assess the impact of the introduction of an auction in complement to a continuous market as well by monitoring the effect on the competition.

Keywords: auction, continuous market, power spot market.

3.1 Introduction

On the one hand, a trader willing to get quickly rid off an asset will prefer to submit a limit order on a continuous market in order to find a counter party in a minimum of time. On the other hand, a trader interested in optimizing an asset would prefer to submit a bid in a uniform price auction to maximize her gain. While continuous trading permits an immediate execution and processes the market information, discrete trading creates a pool of liquidity and facilitates optimization. The difference between the two mechanisms is also in term of execution priority (auction gives the priority to the price while the continuous gives it to the time), price (auction yields to a uniform price whilst continuous trading is based on the pay-as-bid principle) and so strategies. While one may want to oppose the two venues, this paper investigates how they can work together. I examine in the present study the question of the complementarity between a continuous market and an auction, particularly the impact of the introduction of a uniform price sealed bid auction

in addition to a continuous market.

From a theory perspective, the launch of a uniform sealed-bid auction is supported by the following arguments: it facilitates the price discovery process (Schwartz, 2012, Ko et al., 1995 and Pagano and Schwartz, 2003) and reduces the adverse selection at the beginning of the continuous market (Biais, 1993, Domowitz and Madhavan, 2001). It also permits a pool of liquidity (Madhavan, 1992), creates a price reference and larger volumes can be sent to the market at once as the bids of other participants are unknown. The continuous market works as the pay-as-bid principle where each participant negotiates a price and a volume for each transaction, in the auction, the participant is price-taker and optimizes its portfolio with the market price. However, continuous time trading has the advantage of the immediate execution. This flexibility is very important in power markets close to delivery as participants should be balanced at delivery.

There exists a literature on the question of discrete versus continuous trading in the early literature with the work of Madhavan (1992), Economides and Schwatz (1995), Pagano and Roell (1996) or more recently with the paper of Budish et al. (2015) which adds the high frequency dimension. This vast literature is a good base for the present study as it includes many variables I monitor; however, it opposes the two market mechanisms. Opening and closing auctions literature looks at the two venues as complementary. The vast majority of this literature found an increase of the market efficiency following the introduction of a call auction. Gerace et al. (2015) and Agarwalla et al. (2015) study the impact of the creation of an opening auction respectively at the Shanghai Stock Exchange and at the Indian Stock Exchange. They both find an increase of the liquidity following the introduction of the call auction. Pagano and al. (2013) and Comerton-Forde et al. (2007) look at the impact of the introduction of an opening and a closing auction respectively at Singapore Stock Exchange and at the NASDAQ. Both papers found an increase of the market quality with a decrease of the volatility. The paper of Chang et al. (2008) found a better price discovery and market quality after the introduction of an opening auction in the Singapore Stock Exchange. They found that the benefits were more important for the most liquid stocks. Angel and Wu (2001) and Ellul et al. (2008) have a more contrasted conclusion regarding the opening auction. Angel and Wu (2001) found that centralized market may perform worse due to the order imbalance while Ellul et al. (2008) found that the opening auction at the LSE was not beneficial for medium

and small sized stocks. The analysis of Biais and al. (1999) on the preopening period at EuroNext or the paper of Coa et al. (2000) give some good insights on price formation. Ibikinle (2015) studies the opening auction mechanism at the London Stock Exchange and found that failure depends on the volume of the auction. Another interesting study is the one of Kalay et al. (2002) which studies the change of mechanism in the Tel Aviv Stock Exchange from a call auction to a continuous venue. They observed an increase of the liquidity following the transition. The paper of Neuhoff and al. (2016) introduces this question in the power market. Using the same data source as Neuhoff and al. (2016), I include two more dimensions to the study: the volatility and the competition. This paper contributes to the literature by studying a completely new market that is closer to commodities than stocks by the nature of the product such as the existence of maturity. On top of that, electricity is way less liquid than the previous studied markets. To the best of my knowledge, it is the first research which monitors the competition before and after the introduction of an auction due to the scarcity of detailed data on market participants.

This article assesses the impact of the introduction of an auction in complement of a continuous market in term of liquidity, volatility and competition. The introduction of the 15-minute call auction in the German power continuous market for quarter hourly contracts is a great natural experiment to empirically answer this question. Three hypothesis are tested in the actual paper:

Hypothesis 1: The creation of the auction has a business-stealing effect on the liquidity of the continuous market. The launch of the auction adds a new trading venues and some market participants would prefer to trade in the auction for different reasons: earlier trading, optimization purposes, etc. The volume in the continuous should decrease, particularly during the first hours of the trading session where the need of adjustment of the position taken in the auction is very low. It is due to the time proximity between the auction and the continuous market (only one hour is in between). However, the business-stealing effect should be limited as the two trading mechanisms are complements more than substitutes: they propose two different mechanisms and so different strategies are applied to them. In this sense, the overall volume (auction and continuous) should increase.

Hypothesis 2: The creation of an auction before a continuous market decreases the price volatility at the beginning of the trading session. The auction creates a price index

on which the market participants of the continuous market can use it as a price reference. Before the introduction of the auction, market participants had little information about the prices of the contracts and the variance of the estimations could have been high. At the opening of the trading session, the participants that were eager to trade before the introduction of the auction, then can trade in the auction so there is less urge to trade at the beginning of the continuous market and so the price variation should be lower.

Hypothesis 3: The creation of the auction increases the competition for the contract in both markets. The creation of a new trading facilities increases the trading opportunities and so more market participants are willing to participate in either one or both markets which increases the competition for the contract. However, the competition on the continuous market itself should decrease as some market participants will move part of their volume in the auction.

This paper tests those hypothesis with the mean-difference method using the order and trade books of the German quarter hourly contracts for electricity. First, I find that the introduction of the auction decreased the volume traded on the continuous market (business-stealing effect) while increased the total volume for the contract (auction and continuous). Second, it did not have a significant impact on the price volatility during the first hour of trading and decreased it during the second hour of the session. Finally, after the introduction of the auction, the number of market participants decreased (resp. increased) on the continuous (resp. on both markets) as well as the concentration of the market.

The article is organized as follow: the first section is dedicated to the presentation of the power spot market in Germany, the data and the methodology used in the paper. The second section gives the results of the analysis and discuss it. Finally, the last section is the conclusion.

3.2 Background, data and methodology

3.2.1 Market structure

The German spot power market is today the most liquid power market in Europe with a volume traded equivalent to 53 % of the German power consumption or 302 TWh in 2015. EPEX SPOT SE operates the main trading platform for power in Germany since

the merger between PowerNext and EEX AG in 2008. The market runs all year long, 24/7 and proposes 3 contracts lengths: 15, 30 and 60 minutes of electricity.

The continuous market for quarter hourly contracts was created in 2011 in order to answer the network balancing need every 15 minutes in Germany. With the increasing intermittent generation, producers needed smaller duration contracts in line with the balancing granularity: if market participants are not balanced at delivery, they get penalties and may even be exclude "from the grid". The contract duration of 15 minutes promotes flexibility due to its short duration. The solar eclipse of March 2015 was a great example of the flexibility that the 15 minutes contracts can provide (EPEX SPOT 2015). Negative prices were observed few quarter hours before and after the eclipse - due to the ramps of the flexible plants and very high prices were observed during the eclipse when there were no solar production at all.

The continuous market refers to the continuous matching procedure (pay-as-bid principle). The market opens at 4pm the day before delivery and closes 5 minutes before delivery for the 15 minutes contracts. Market participants send limit orders to the exchange within the price range comprise between -9999€/MWh and 9999 €/MWh. The order can either be matched with an existing order in the order book, creating a trade or remains in the order book. In this case, the market participant who hits the order in the order book is called "aggressor" while the other market participant is called "originator". The execution price is the one posted by the order already in the order book (originator). If there is no match possible, the order remains in the order book.

On December 9, 2014, EPEX SPOT SE introduced a uniform sealed-bid auction for quarter hourly contracts which takes place the day before delivery at 3pm for the 96 quarter hours of the next day - an hour before the start of the continuous market for quarter hour contracts. This introduction was encouraged by the peak of number of trades at the beginning of the trading session as illustrated on the figure 3.1. This peak reflected the urge to trade as soon as the trading session started. On top of that, continuous trading is very costly in term of human resources as the continuous market runs 24/7, all year long while an auction is once a day during business hours and bids may be submitted in advance.

In order to participate in the auction for one of the 96 contracts, participants have to send couples of price-quantity between -3000€/MWh and 3000€/MWh. Then, the

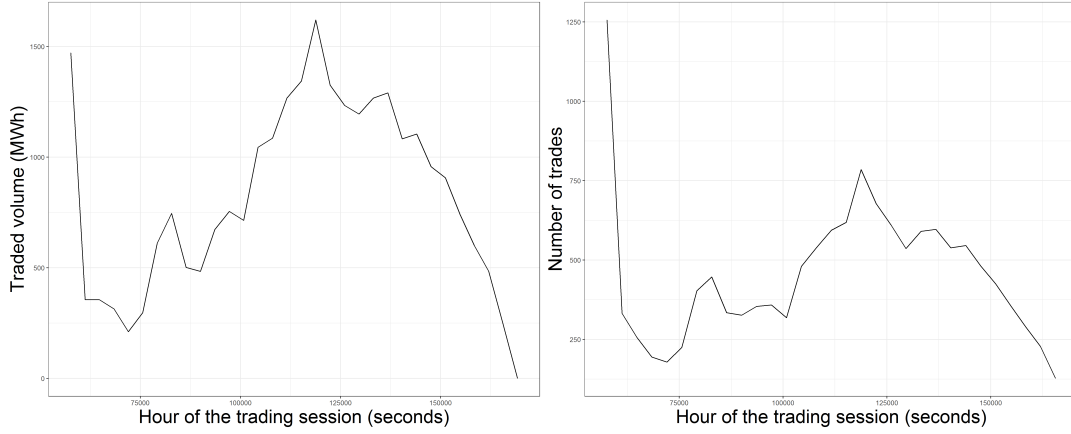


Figure 3.1: Traded volume and number of trades per hour of the trading session for 15 min contracts

algorithm compiles the orders of the market participants and constructs a supply and a demand curve which give the equilibrium price and market volume. The auction is local and is not interconnected with other markets: only German members can participate.

Various categories of market participants trade power on the German spot market. The most active participants in term of volume on the continuous market for quarter hourly contracts are trading houses followed by utilities/aggregators and Transmission System Operators (TSOs)¹. The last two categories have the largest renewable portfolio in Germany: the TSOs mainly use the market to buy grid losses or sell the solar production under Feed-In-Tariff (FIT); utilities have a large renewable portfolio in Germany due to their core activity and the aggregators take care of most of the renewable production under direct marketing scheme².

The table 1 compares the mean price, the annual volume, the mean number of trades and orders as well as the average number of market participants per trading session for the continuous (quarter hourly contracts only), the day-ahead market and the 15-min call auction for the years 2014 and 2015. The number of trades, orders and market participants are the averages per trading session. We can observe an homogeneity of prices across markets each year. The 15-min call auction was created at the beginning of December 2014 which explains the values' difference with the two other markets for the year 2014.

¹Those results are from the author's computation for the year 2014.

²The Figure 3.4 in the appendices shows the share of direct marketing scheme over time; the share of Feed-In-Tariff compensation scheme are the difference between 1 and the share of direct marketing.

		2014	2015
Mean price (€/MWh)	Continuous (QH)	32,59	31,80
	Day-ahead market	32,76	31,63
	15-min call auction	27,68	31,66
Yearly volume (TWh)	Continuous (QH)	4,85	3,95
	Day-ahead market	262,92	264,13
	15-min call auction	0,09	3,96
Number of trades (daily)	Continuous (QH)	6 110,13	6 714,85
Number of orders (daily)	Continuous (QH)	20 095,71	29 441,84
Number of market participants	Continuous (QH)	35,59*	29,56
	15-min call auction	47,00	82,00

* Data from 09-30-2014 to 12-31-2014 only.

Table 3.1: Facts about the spot power market

The volume traded on the day-ahead market in 2015 was 67 times higher than the volume traded on the 15-min call auction or the volume of the continuous market for quarter hourly contracts. We can observe a similar volume on the continuous market and on the 15-min call auction in 2015. Despite the decrease of volume on the continuous market for quarter hourly contracts, the number of trades and orders increased from 2014 to 2015. In line with this finding, the average trade volume decreased between the 2 years. The number of market participants almost double on the 15-min call auction while decreased on the continuous market. A market participant is defined as a participant who makes at least one trade during a specific trading session.

3.2.2 Data

The data used for the analysis is composed of the trades and orders of the European Power Exchange - EPEX SPOT. The variables are expressed at the contract level; a contract is 15 minutes of power for a specific delivery day. For example, 10MW of power from 15:00

to 15:15 on January 24, 2015. The period chosen before and after the introduction of the 15-min call auction is of 2 months before (from October, 9 2014 to December, 9 2014 - not included) and 2 months after the introduction of the auction (from January, 9 2015 to March, 9 2015 - not included). The period of two months was chosen in order to capture the direct effect while not compromising the amount of data needed for robust results. A shorter period would be exposed to specific events that may distort the result due to the high weight on each individual days. A longer period would less capture the direct effect of the introduction of the call auction. The lag between the introduction of the auction and the period "after" was chosen in order to take into account the learning process from the market participants as well as avoid the Christmas and New Year holiday period which is a special period of trading due to the public holidays. The variables are computed per day and contract (delivery date and time) and then averaged.

3.2.3 Methodology

I compare some volatility, liquidity and competition related variables before and after the introduction of the 15-min call auction. For a deeper understanding of the impact, I split the dataset in various categories. For some variables, it is interesting to look at the impact on the whole trading session while for some others, I expect the impact to be relevant only at the beginning of the trading session; thus, I concentrate my analysis during the first two hours of the session for most of the variables. For some others, it is also interesting to study their behavior over the whole trading session. I then perform the analysis by splitting the data in three categories:

- Business day versus week-end. As the load being lower during week-end due to a smaller economic activity, it is interesting to compare the behavior of the market on this different days.
- Per liquidity. I cluster the contract per liquidity and use the average daily volume of each contract between January, 1 2012 and December, 1 2014 to assess the four groups. The first group is composed of the 24 less liquid contracts while the fourth group has the 24 most liquid contracts.
- Per delivery time. I split the contracts in 4 groups depending on their distance to gate closure. It is also interesting to make this split as it also highlights the peak

(8:00-20:00) and off peak periods (00:00-8:00 and 20:00-00:00). Peak products are usually the most traded ones as the power consumption at those hours is the biggest during the day.

Then, I check the significance of these means using a paired t-test. The Student t-test can be used even if the distribution of the variables are not Normal as the sample is large enough. For some variables, a Welch t-test is computed as the variance before and after are not equals. The t-test measures if the mean before and after the introduction of the auction are significantly different.

Volatility

I first compute the weighted price standard deviation of the trades which corresponds to the mean of the daily standard deviation of the price weighted by the volumes. It measures the price volatility of the trades on the continuous market. The volatility captures the price variation of a contract during a trading session.

$$\sigma_p = \sqrt{\frac{\sum_{i=1}^N v_i (p_i - \bar{p}^*)^2}{\frac{M-1}{M} \sum_{i=1}^N v_i}} \quad (3.1)$$

where

$$\bar{p}^* = \frac{\sum_{i=1}^N v_i p_i}{\sum_{i=1}^N v_i} \quad (3.2)$$

N is the number of observations, M the number of nonzero weights, v_i the volume (weight), p_i the price of the transaction and \bar{p}^* the weighted mean of the price. The variable price standard deviation is calculated during the first two hours of the trading session - from 4pm to 6pm the day before the delivery in order to quantify the effect at the very beginning of the trading session. The variable is computed at the 10 minutes level of the trading session then averaged over the whole trading session for an individual contract.

In order to monitor all other things being equal, I also compute the relative price standard deviation weighted by the volume. I use this variable as a proxy for volatility. It is equal to the weighted standard deviation over the absolute value of the weighted average price. The absolute computation is used in order to avoid negative standard deviation due to negative prices in power market.

$$\sigma_p^R = \frac{\sigma_p}{|\bar{p}^*|} \quad (3.3)$$

The second variable used to monitor volatility is the realized volatility. It is computed as the price range of the trades relative to the price. This variable is calculated every 10 minutes of the trading session. The liquidity of the power market is not comparable to the one on the financial market in general and so there is not enough transaction made per minute to compute a robust indicator. The realized volatility formula is:

$$rv_i = \left| \frac{\max(p_i) - \min(p_i)}{\text{mean}(p_i)} \right| \quad (3.4)$$

where i is a time interval of 10 minutes of the trading session for a specific contract. Due to the possibility of negative prices on the power market, I choose to use the absolute value of the realized volatility.

The time series of the weighted price standard deviation and the realized spread does not display any trend or seasonality. No trend are visible on the plot of the serie. However, seasonality may be not easily seen graphically so I compute a Webel-Ollach (WO) test (Ollach, 2018) and reject the null hypothesis of seasonality. Thus, I do not detrend or deseasonalized the series.

Liquidity

Liquidity variables can be split in two categories: the ones linked to the activity on the market (volume, number of orders) and the ones linked to the implicit transaction cost (bid-ask spread).

Market activity

The first variable used for market activity is the mean number of orders on each side of the order book (buy and sell) per contract. The individuals order IDs are used to compute the variable.

Due to a limited dataset on orders, I cannot detrend or deseasonalize the serie. However, it is a realistic hypothesis to assume that the trend and the seasonality of the number of orders is similar to the trend and seasonality of the volume. In this sense, we expect an increasing trend as well as a decreasing seasonality when comparing the months of October-November with the months of January-February. The effect on the result is then ambiguous.

ous and not very different from the results we will get without detrend/deseasonalized as both coefficients are more or less similar.

The volume related variables monitored are: the volume of the continuous market and the total volume for the 15 minutes products (auction and continuous market). The volume of the continuous market is the mean volume traded during a trading session across contracts. I compare the variable during the first and the second hour of the trading session as well as over the complete session.

We observe clearly an increasing trend of the volume over the years. Also, we can see a monthly seasonality in the volume exchanged. In order to remove the seasonality, I create a monthly coefficient of seasonality per contract using data from January, 1 2012 to December, 1 2014. Due to the increasing amplitude of the seasonality, I choose to use a multiplicative model where the deseasonalized volume is computed as follow:

$$vd_{idmy} = \frac{v_{idmy}}{sc_{im}} \quad (3.5)$$

where v is the volume, sc the seasonal coefficient, i is a contract ($i=1, \dots, 96$), d a delivery date, m a delivery month, y a delivery year. sc is computed as the mean daily volume per month over the studied period. I then detrend the time serie using the moving average method and remove it from the deseasonalized serie:

$$vdd_{idmy} = \frac{v_{idmy}}{sc_{im} * st_{imy}} \quad (3.6)$$

where st is the trend coefficient. In order to compute it, I first detrend the serie between January, 1 2012 and December, 1 2014; then I regress the detrend variable against its first lag, per contract to forecast the detrend coefficient during the studied period. I choose this method to avoid to include the analysis period in the computation and thus avoid the detrend coefficient to absorb the effect of the introduction of the call auction.

$$st_{imy} = \alpha + \beta st_{i(m-1)y} + u_{imy} \quad (3.7)$$

An AR(1) model was chosen as it presented the best Aikake Information Criteria (AIC) in comparison to some other ARMA(p,q) models. It has a R^2 above 95% for each individual contract. I then use this regression to forecast the detrend coefficient during the period studied.

Implicit transaction cost

The variables representing the transaction costs are linked to the bid-ask spread. The variable bid-ask spread (or quoted spread) represents the mean bid-ask spread per contract (delivery date, quarter hour). It is weighted by time (each second of the trading session).

The bid-ask spread is the difference between the best price a seller is willing to sell (or ask price) a quart hourly contract of power and the best price a buyer is willing to buy the same contract (or bid price). It is measured in euro per megawatt hour and can interpreted as an implicit transaction cost: a premium to pay in order to be immediately executed (Demsetz, 1968).

$$qs_t = |a_t - b_t| \quad (3.8)$$

where a is the ask price and b the bid price. In the spot power market, the quoted spread may be negative due to the AON ("All-Or-None") restriction. This restriction imposes the order to be fully matched or remain in the order book.

The relative spread is the quoted spread relative to the price level (mid-quote) at one moment of the trading session. It is another measure of liquidity. The relative spread is the absolute value of the quoted spread over the mid-quote due to the possibility of negative prices³.

$$rs_t = \left| \frac{qs_t}{\frac{a_t + b_t}{2}} \right| \quad (3.9)$$

In order to avoid very extreme values especially high spreads at the beginning of the trading session, I decide to remove the top 5% and the bottom 5% values from my sample.

Regarding any trend or seasonality, I did not observe any trend or seasonality in the variables bid-ask spread or relative bid-ask spread.

Competition

To measure the concentration of the market, the Herfindahl-Hirschman Index (HHI) is computed on both side for each contract. This index captures the concentration of the market. It measures the market competitiveness.

$$HHI = \sum_{i=1}^m s_i^2 \quad (3.10)$$

³Submitted prices on the continuous market should be in between -500 and 3000€/MWh

where

$$s_i = \frac{v_i}{\sum_{i=1}^m v_i} \quad (3.11)$$

where s_i is the market share (the volume traded by a firms in comparison to the total volume of the market) of the firm i and m the number of firms.

I do not detrend or deseasonalized the variable on competition as from month to month, there is not a significant change; neither a particular pattern over the year.

3.3 Results

This section presents the results of the study then discuss them. I compare the mean before and after the introduction of the call auction and the variation associated.

3.3.1 Volatility

In order to assess the impact of volatility, the weighted price standard deviation as well as the realized volatility variables are used as a proxy. The volatility over the whole trading session may be affected by more than the introduction of the auction; in this spirit, I choose to only observe the volatility at the beginning of the trading session, where the impact of the call auction is the strongest.

The analysis is firstly done on the whole dataset that I split in period of 15 minutes of the trading session to get a more detailed analysis of the impact. I then split the dataset by liquidity, delivery time and business days. For the categories just listed, the data is then split in two: first and second hours of the session. The tables 3.2 and 3.3 display the results of the analysis.

Whole data - While most of the mean-differences are not significant, we observe an increase of the volatility during the first quart hour of the trading session as well as a decrease of it between 17:45 and 18:00. Even if the values are not significant, a pattern seems to emerge: across contracts, the volatility increases between the opening of the trading session at 16:00 and 16:30 (in the case of the realized volatility) and 16:45 (for the weighted price standard deviation); the volatility then decreases in comparison to the period before the introduction of the call auction.

Liquidity - The mean-difference is not significant during the first hour of the trading session and decreases during the second one in comparison to the period prior to the introduction of the 15-min auction. Most of the differences during the second hour of the session are significant at the 1% level for the weighted price standard deviation; however, only the group 4 (highest liquidity) and the group 2 are significant for the realized volatility. During the second hour of the trading session, we cannot see a clear pattern.

Table 3.3 displays the results for the split by delivery time and business days versus week-ends. Across the categories, we can observe the same pattern as before: most of the time, there is no significant variation or an increase of the volatility in the first hour of the trading session and a decrease of the volatility in the second hour.

Delivery time - During the first hour of the trading session, the weighted price standard deviation almost doubled for the peak contracts (8:00-20:00) and is not significant of off peak contracts (before 8:00 and after 20:00). During the second hour of the session, a decrease of the volatility for both variables is observed during off peak hours. During on peak contracts, there is no significant change.

Business day versus weekend - There is no significant difference in volatility when looking at the trading days type (business days or weekend) except during the second hour of the trading session of business days: there is a decrease of almost 57% of the quoted spread and a decrease of 77% of the realized volatility.

To sum up, we observe that most of the time, there is no significant difference for the first hour of trading. During the second hour of the session, the volatility decreases after the introduction of the call auction. There is no pattern regarding the liquidity of the contract; however I find that the volatility tends to increase during the first hour of the peak contracts (8:00-20:00) and to decrease during the second hour of the session of off peak contracts.

	Trading time	Weighted price standard dev.				Realized volatility			
		Before	After	Difference (%)	t-test	Before	After	Difference (%)	t-test
Whole data	16:00-16:15	0,057	0,137	141,200		0,195	0,288	47,415	**
	16:15-16:30	0,032	0,044	38,205		0,076	0,179	134,379	
	16:30-16:45	0,032	0,054	71,010		0,206	0,091	-55,666	
	16:45-17:00	0,026	0,014	-45,387		0,066	0,041	-37,929	
	17:00-17:15	0,017	0,015	-13,972		0,045	0,043	-3,454	
	17:15-17:30	0,014	0,011	-26,629		0,055	0,036	-35,091	
	17:30-17:45	0,012	0,016	28,856		0,692	0,046	-93,334	
	17:45-18:00	0,024	0,004	-84,848	***	0,073	0,011	-84,382	***
Liquidity	4 (highest)	0,112	0,125	10,849		0,414	0,481	16,280	
	17:00-18:00	0,065	0,025	-61,415	***	0,175	0,073	-58,492	***
	3	0,082	0,127	55,498		0,339	0,303	-10,661	
	17:00-18:00	0,024	0,015	-35,917	*	0,073	0,053	-27,663	
	2	0,113	0,211	87,378		0,399	0,531	32,992	
	17:00-18:00	0,040	0,020	-50,013	**	0,178	0,052	-71,020	*
	1 (lowest)	0,097	0,297	205,945		0,339	0,577	70,204	
	17:00-18:00	0,026	0,028	5,413		0,505	0,090	-82,177	

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.2: Mean-difference for the volatility

Delivery time	Trading time	Weighted price standard dev.				Realized volatility			
		Before		After		Before		After	
		Difference (%)	t-test	Difference (%)	t-test	Difference (%)	t-test	Difference (%)	t-test
	00:00-8:00	16:00-17:00	0,175	0,337	92,841	0,715	0,707	-1,079	
		17:00-18:00	0,066	0,031	-52,457	0,567	0,093	-83,608	
	8:00-12:00	16:00-17:00	0,041	0,078	91,421	0,143	0,266	85,943	**
		17:00-18:00	0,021	0,012	-41,157	0,065	0,032	-49,993	*
	12:00-20:00	16:00-17:00	0,050	0,102	102,292	0,174	0,350	101,550	*
		17:00-18:00	0,015	0,014	-4,242	0,045	0,046	3,218	
	20:00-24:00	16:00-17:00	0,103	0,117	14,433	0,314	0,395	25,759	
		17:00-18:00	0,039	0,011	-71,286	0,129	0,037	-70,945	**
	Business day	16:00-17:00	0,104	0,114	10,234	0,392	0,371	-5,301	
		17:00-18:00	0,043	0,019	-56,810	0,235	0,053	-77,608	*
Week-end	16:00-17:00	0,104	0,294	181,887	0,393	0,665	69,194		
	17:00-18:00	0,051	0,035	-31,030	0,166	0,114	-31,454		

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.3: Mean-difference for the volatility

3.3.2 Liquidity

Market activity

The market activity is measured with the average daily volume traded per contract. As clearly shown on the figure 3.2, the introduction of the call auction decreased a bit the volume of the continuous market while the overall volume (auction and continuous market) for the 15 minutes contracts doubled when comparing the month of October 2014 to the month of March 2015.

Looking at the behavior of the market participants, the increase is mainly due to the large members (top 25% in term of volume, based on their trades before the introduction of the auction) who increased on average their volume by 590.8 MWh per day. However, in term of variation, the smaller members (bottom 25%) had the biggest growth: +560% while the top 25% got only an increase of 80%. Before the introduction of the auction, the volume during the first hour of trading session had a mean of 720 MWh while the average volume of the auction was 14 050 MWh during the period from February 9th 2015 to March 9th 2015.

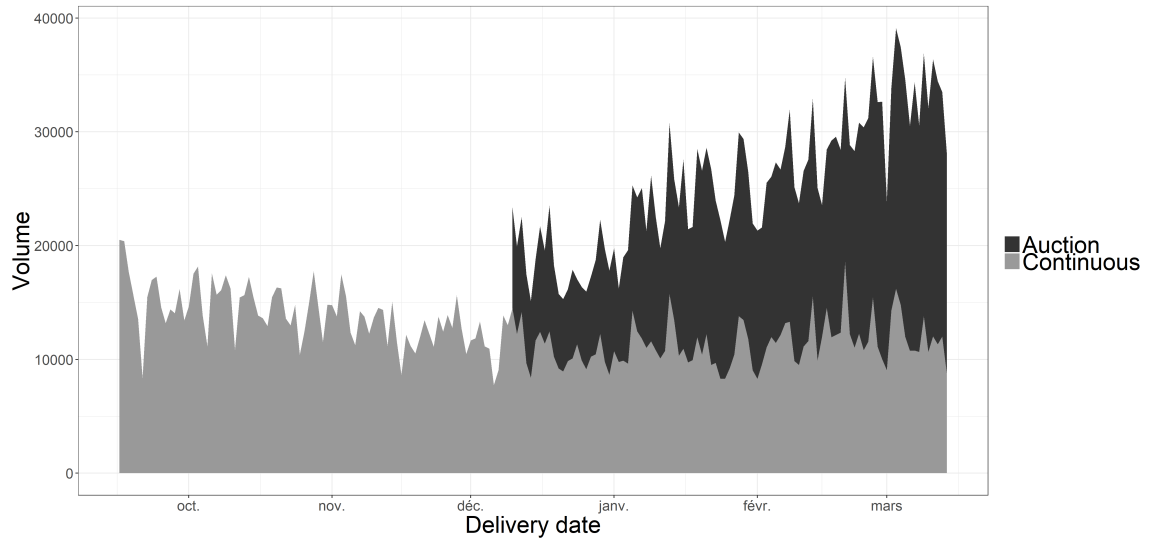


Figure 3.2: Evolution of the volume for quarter hourly contracts

Looking a little bit deeper in the volume transfer, 95% of the members who traded on the continuous market before the introduction of the auction, still trade either on the auction (A), on the continuous market (C) or on both (CA) after the introduction of

the call auction. 29.5% (resp. 30.8%) of the buyers (resp. sellers) continued to trade exclusively on the continuous market while 59.0% (resp. 60.3%) of them start trading on both markets. The remaining 6.4% (resp. 3.8%) of the buyers (resp. sellers) switched their trading from the continuous to the auction. On the buy side, the market participants who only trade in the auction after December 9, 2014 were for 40% local suppliers or consumers, 40% trading companies and for 20% utilities or aggregators. Still on the same side, buyers using both markets were split as followed: 12.5% aggregators, 29.2% local suppliers or large consumers, 25% trading companies and 33.3% utilities or aggregators. On the sell side, the market participants who only trade in the auction after December 9, 2014 were for 50% local suppliers or consumers and 50% trading companies. Still on the same side, sellers using both markets were split as followed: 12% aggregators, 36% local suppliers or large consumers, 24% trading companies, 4% Transmission System Operators (TSO) and 24% utilities or aggregators.

More than half of the market participants (52.56%) who traded on the continuous before December 9, 2014 started trading a lower volume⁴ on the continuous market after the introduction of the call auction. 70.7% (resp. 68.3%) of the buyers (resp. sellers) who decreased their volume of the continuous after the introduction of the auction, started to trade on the auction a volume bigger than the one lost on the continuous. 17.2% (resp. 10.7%) of those buyers (resp. sellers) only choose to trade in the auction only while the remaining 82.8% (resp. 89.3%) started trading on both markets (auction and continuous).

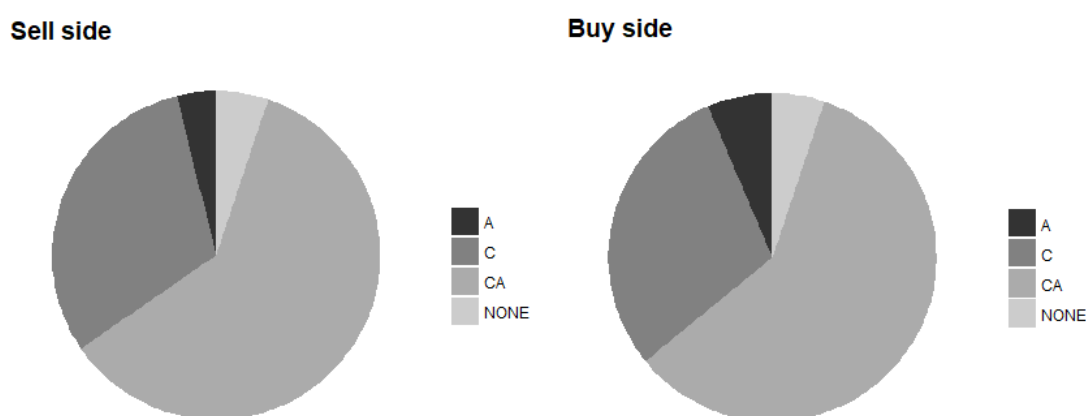


Figure 3.3: Share of the venues used after the introduction of the call auction

⁴A volume is considered lower if the volume traded on the continuous after the introduction of the call auction is strictly lower than the volume traded before the introduction of the call auction minus 10%

The tables 3.4 and 3.5 display the comparison of the volume, detrended and deseasonalized, before and after the introduction of the call auction during the whole trading session as well as during the first two hours of the session. The data set is split by liquidity, business days versus weekend and delivery time. All differences are statistically significant at the 1% level.

Liquidity - Over the whole trading session, the volume traded on the continuous market decreased with a most important decrease for the second and fourth (most liquid contracts) categories. This pattern is also observed during the first and the second hours of the trading session. The decrease during the first hour of the trading session is a little bit higher than the one for the whole trading session and the decrease during the second hour of the session is smaller than the one during the first hour. We observe an increase of the liquidity during the second hour of the session for the least liquid contracts. However, there is no clear pattern: liquidity changes after the introduction of the call auction seems independent of the liquidity of the contract.

Business day versus weekend - The decrease of volume during the first hour of the trading session as well as during the whole trading session is more important during weekends in comparison to business days. We also observe the same behavior as in the previous case (split by liquidity): the drop of the traded volume in the second hour of the trading session is smaller than the one during the first hour of the session or during the whole session.

Delivery time - Over the whole trading session as well as during the first hour of the session, we observe a more important decrease of the volume during off peak contracts (before 8:00 or after 20:00). The decrease of the volume during the first hour of the trading session is similar, although bigger, to the decrease over the whole session. For the contracts with a delivery after 8:00, there is a drop of the volume during the first hour of the trading session which seems to be more important when the delivery is later during the day - and so the trading session longer. The reason may be that the market participants already traded in the auction, just an hour before the start of the continuous market and so do not have different forecasts at the opening of the session; while before the introduction of the call auction, there was a urge to trade at the beginning of the session to adjust the position at the quarter hour granularity. In this sense, the drop of volume is more important for the first contracts of the day. During the second hour of the trading session,

we observe an increase of the traded volume for peak contracts and a decrease (however, smaller than during the first hour of the session) of the volume for the off peak contracts.

To sum up, we observe a decrease of the volume of the continuous market during the first two hours of the trading session as well as during the whole session. The decrease is more important during the first hour of the session than the second one. The difference is even positive for peak contracts during the second hour of trading. It may be due to the increasing arbitrage opportunities thanks to the auction. The decrease of the volume during the first hour of trading may be due to the lower urge to trade at the opening of the continuous market. There is a stronger decrease during weekends in comparison to business days and for off peak (before 8:00 or after 20:00) contracts in comparison to peak contracts. There is no specific pattern regarding liquidity that could be highlighted.

	Trading time	First 2 hours of the session				Whole session				
		Before		After		Before		After		
			Difference (%)		t-test		Difference (%)		t-test	
Liquidity	1 (lowest)	16:00-17:00	0,833	0,679	-18,490	***	0,852	0,687	-19,363	***
		17:00-18:00	0,898	0,924	2,864	***				
	2	16:00-17:00	0,981	0,695	-29,205	***	0,984	0,709	-27,887	***
		17:00-18:00	0,954	0,812	-14,901	***				
	3	16:00-17:00	0,884	0,675	-23,661	***	0,880	0,692	-21,415	***
		17:00-18:00	0,889	0,865	-2,782	***				
	4 (highest)	16:00-17:00	0,942	0,679	-27,948	***	0,941	0,689	-26,713	***
		17:00-18:00	0,908	0,772	-15,011	***				
	Weekend	16:00-17:00	0,906	0,653	-27,910	***	0,911	0,667	-26,790	***
		17:00-18:00	0,892	0,796	-10,772	***				
	Business day	16:00-17:00	0,942	0,748	-20,575	***	0,940	0,759	-19,231	***
		17:00-18:00	0,966	0,898	-6,974	***				

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.4: Mean-difference for the volume

	Trading time	First 2 hours of the session				Whole session				
		Before		After		Before		After		
		Difference (%)	t-test	Difference (%)	t-test	Difference (%)	t-test			
Delivery time	00:00-8:00	16:00-17:00	0,842	0,531	-36,924	***	0,853	0,542	-36,467	***
		17:00-18:00	0,895	0,618	-31,002	***				
	8:00-12:00	16:00-17:00	0,917	0,832	-9,272	***	0,915	0,843	-7,897	***
		17:00-18:00	0,890	1,042	17,071	***				
	12:00-20:00	16:00-17:00	1,004	0,837	-16,602	***	1,005	0,859	-14,534	***
		17:00-18:00	0,963	1,125	16,769	***				
	20:00-24:00	16:00-17:00	0,933	0,515	-44,798	***	0,927	0,522	-43,690	***
		17:00-18:00	0,918	0,644	-29,906	***				

Note: *: t<0.1; **: t<0.05; ***: t<0.01

Table 3.5: Mean-difference for the volume

The tables 3.6 and 3.7 display the comparison of the average number of orders per trading session (specific delivery date and time).

Whole trading session

Delivery time - Later is the gate closure, more important is the increase of the number of orders. The trading sessions opens at 16:00 the day before delivery and closes 30 minutes before delivery. Longer is the trading session higher is the number of new information during the trading session and so the need to adjust the initial position. For the first contracts of the day (before 8:00), the number of orders decreased due to the same reason as the decrease of volume: traders already fulfilled their commitment in the auction that occurs an hour before the start of the trading session so there is no or very small adjustments to make before the delivery that occurs few hours later.

Liquidity - The variation of the number of orders over the whole trading session by liquidity is not significant.

First two hours of the continuous market

The results for the first two hours of the trading session are available in the table 3.7.

First two hours of the session - We cannot observe a clear pattern in the difference of the number of orders before versus after the introduction of the call auction. The number of orders during the first 15 minutes of the trading session increased by almost 40% after the introduction. We then can observe fluctuation of the number of orders before versus after December, 9 2014.

Business day versus weekend - Over the first two hours of the trading session, on average, there is a decrease by about 20% for both day types. During the first hour of the trading session, the number of orders decreased for weekend contracts while increased for business day. Interestingly, the number of orders during the second hour of the trading session decreased twice more for Monday to Friday contracts.

Delivery time - Farther is the delivery time, more important is the decrease of the number of orders during the first hour of the trading session except for the contracts between 8:00 and 12:00 (not significant). The decrease of the number of orders is more important during the second hour of the session compared to the first hour. We can also observe a larger decrease for the first 12 hours of the day (00:00-12:00) in comparison to the last 12 (12:00-00:00).

Liquidity - During the first hour of the trading session, an overall decrease of the

number of orders by 7-10% is observed across contracts' liquidity with no specific pattern. During the second hour of the trading session, we observe a more important increase for the top 50% (groups 3 and 4) contracts in term of liquidity in comparison to the bottom 50%.

To sum up, over the whole trading session, there is no significant difference when splitting the data by liquidity; however, we can observe a decrease of the number of orders send to the market for the first contracts of the day (before 8:00) and an increase for the rest. During the second hour of the trading session, we observe a more important decrease of the number of orders. When delivery time increases, we can observe a more important decrease of the number of orders; the reverse can be seen during the second hour of the session.

		Before	After	Difference (%)	t-test
Delivery time	00:00-8:00	179,477	168,045	-6,370	***
	8:00-12:00	294,362	299,181	1,637	*
	12:00-20:00	290,038	295,518	1,890	*
	20:00-24:00	226,368	232,430	2,678	*
Liquidity	1 (lowest)	211,933	209,084	-1,344	
	2	239,065	242,124	1,280	
	3	254,466	255,984	0,596	
	4 (highest)	261,382	258,430	-1,130	

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.6: Mean-difference for the number of orders

Bid-ask spread

The tables 3.8 and 3.9 display the results of the analysis for the bid-ask spread and the relative spread during the first two hours of the trading session. Overall, we can observe an increase of the quoted and relative spreads.

Business day versus weekend - After the introduction of the 15-min call auction,

the bid-ask spread increased at the beginning of the session. We observe a stronger increase of the spread (either quoted or realized) during the weekend in comparison to business days. The realized spread during the second hour of the trading session is not significant; however, during weekends, the quoted spread seems to increase even more during the second hour of trading which is the reverse from Monday to Friday.

Delivery time - During the first hour of the trading session, for both variables, we observe that longer is the distance between the opening and the closure of the market, smaller is the increase of the spread for the contracts after 8:00. Knowing that 80% of the trading is done during the last three hours of the trading session, it is not surprising to see a smaller impact for the "late" contracts. We observe a larger increase of the spread for the peak contracts (8:00-20:00) during the first hour of the trading session. A smaller increase is found during the second hour of the session for the bid-ask spread during business day and a more important increase of the spread during the second hour of the session during weekends. The mean-difference of the relative spread during the second hour of the session is not significant.

Liquidity - During the first hour of the trading session, it seems that there is a pattern regarding the liquidity: more liquid is a contract, smaller is the increase of the quoted spread. This intuition is not valid for the bottom 25% contracts (group 1) probably as it includes the contracts for the first hours of the day; however, if we split the contracts into 2 homogeneous groups depending on their liquidity, we can see that the most liquid contracts face a lower increase of the quoted spread during the first hour of the trading session than the least liquid ones. There is no significant pattern when looking at the relative spread. During the second hour of the continuous market, there is no specific pattern for the quoted spread. The realized spread is not significant during the second hour of the session except for the second group.

To sum up, the spread increased during the first two hours of the trading session. During the first hour of the session, the increase is more important for contracts with a delivery on weekends. We observed a more important increase of the spread when the delivery time is later during the day or when the contract is more illiquid - except for the first contracts of the day (before 8:00). There is no significant pattern during the second hour of the trading session.

		Trading time	Before	After	Difference (%)	t-test
Trading session		16:00-16:15	3,371	4,700	39,428	***
		16:15-16:30	2,976	2,939	-1,231	
		16:30-16:45	2,844	2,880	1,248	
		16:45-17:00	2,938	2,209	-24,801	***
		17:00-17:15	2,426	2,452	1,060	
		17:15-17:30	3,218	2,247	-30,170	***
		17:30-17:45	2,238	2,396	7,063	**
		17:45-18:00	2,803	2,640	-5,812	*
Delivery time	Week-end	16:00-17:00	8,120	6,369	-21,566	***
		17:00-18:00	5,991	4,747	-20,776	***
	Business day	16:00-17:00	8,326	9,736	16,933	***
		17:00-18:00	5,766	3,238	-43,838	***
	00:00-8:00	16:00-17:00	7,831	7,066	-9,766	***
		17:00-18:00	6,712	4,449	-33,721	***
	8:00-12:00	16:00-17:00	8,467	8,209	-3,048	
		17:00-18:00	5,987	4,241	-29,167	***
	12:00-20:00	16:00-17:00	8,148	7,288	-10,560	***
		17:00-18:00	5,086	4,243	-16,565	***
	20:00-24:00	16:00-17:00	8,578	7,139	-16,770	***
		17:00-18:00	5,399	4,105	-23,972	***
Liquidity	1 (lowest)	16:00-17:00	7,175	6,419	-10,526	***
		17:00-18:00	5,407	3,980	-26,389	***
	2	16:00-17:00	7,709	7,007	-9,106	***
		17:00-18:00	5,171	4,133	-20,065	***
	3	16:00-17:00	8,423	7,844	-6,881	
		17:00-18:00	6,104	4,319	-29,253	**
	4 (highest)	16:00-17:00	9,141	8,128	-11,087	***
		17:00-18:00	6,839	4,638	-32,172	***

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.7: Mean-difference for the number of orders

Delivery time	Trading time	Quoted spread in EUR per MWh				Relative spread			
		Before		After		Before		After	
			Difference (%)		t-test		Difference (%)		t-test
Business day	16:00-17:00	6,224	8,903	43,042	***	0,208	0,291	40,259	***
	17:00-18:00	4,902	6,932	41,425	***	0,181	0,246	35,999	
	16:00-17:00	6,607	9,857	49,206	***	0,295	0,459	55,965	***
	17:00-18:00	5,431	8,753	61,170	***	0,251	0,390	55,362	
00:00-8:00	16:00-17:00	6,914	9,656	39,659	***	0,341	0,443	30,005	
	17:00-18:00	5,485	8,267	50,728	***	0,299	0,389	30,327	
	16:00-17:00	4,870	7,857	61,340	***	0,134	0,243	82,127	***
	17:00-18:00	4,552	6,585	44,654	***	0,134	0,217	62,209	
12:00-20:00	16:00-17:00	6,222	9,103	46,311	***	0,170	0,283	66,607	***
	17:00-18:00	4,961	6,895	38,966	***	0,143	0,225	56,727	
	16:00-17:00	7,524	10,131	34,648	***	0,273	0,356	30,421	***
	17:00-18:00	5,109	8,217	60,835	***	0,202	0,304	50,488	**

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.8: Mean-difference for the bid-ask spread

	Trading time	Quoted spread in EUR per MWh				Relative spread				
		Before		After		Before		After		
					Difference (%)	t-test			Difference (%)	t-test
Liquidity	1 (lowest)	16:00-17:00	5,525	8,244	49,209	***	0,245	0,352	43,802	***
		17:00-18:00	4,767	6,759	41,789	***	0,218	0,299	37,415	
	2	16:00-17:00	5,439	8,215	51,050	***	0,190	0,287	50,909	***
		17:00-18:00	4,289	6,605	54,004	***	0,158	0,243	53,615	**
	3	16:00-17:00	6,846	9,669	41,247	***	0,263	0,358	35,796	***
		17:00-18:00	5,365	7,833	46,005	***	0,224	0,311	38,854	
	4 (highest)	16:00-17:00	7,357	10,348	40,655	***	0,238	0,361	51,421	***
		17:00-18:00	5,771	8,603	49,080	***	0,211	0,309	46,183	

Note: *: t<0.1; **: t<0.05; ***: t<0.01

Table 3.9: Mean-difference for the bid-ask spread

3.3.3 Competition

In this section, I compare the level of competition on the continuous market before versus after the introduction of the auction using the Herfindhal index (HHI) as a proxy for the market concentration. I also compare the concentration before versus after on both markets (auction and continuous) as it represents the level of concentration for a contract no matter where the contract is traded (auction or continuous market). I split the variable for each side of the market (buy, sell).

The table 3.10 displays the mean-difference of the competition level before versus after the introduction of the 15-minute call auction on the continuous market as well as on the whole trading chain (auction and continuous market).

Continuous market

On the continuous market, the concentration increased by about 10.5% no matter the trading side. There is no particular difference in the results depending if the contract is peak or not. This result is in line with the decrease in number of active members⁵ on the continuous market per contract by 17.89% after the introduction of the call auction. In term of liquidity, we do not observe a specific pattern on the sell side; however, on the buy side, it seems that more liquid is a contract (except for the last category), more important is the increase of the concentration.

Auction and continuous market

On the whole trading chain, the concentration decreased by 7.68% on the buy side and 5.62% on the sell side while the overall number of active members on both markets increases by 93% over the period studied. We observe an important decrease for peak products and a negligible one for off peak contracts (-2% on the buy side and -1.6% on the sell side). It seems that there is a decreasing pattern with the increase of liquidity: more liquid is the contract, higher is the drop of the market concentration. However, this result has to be balanced as the third group does not seem to behave in that direction.

To sum up, following the introduction of the 15-min call auction, we observe an increase of the concentration on the continuous market. However, the concentration of the whole trading chain decreased thanks to the increase of the number of active market participants.

⁵A market participant is considered as active if it sends at least one order during the trading session. It does not matter if the order is executed or not.

	Buy side				Sell side				
	Before	After	Difference (%)	t-test	Before	After	Difference	t-test	
Continuous market	Whole data	0,168	0,185	10,358	***	0,168	0,186	10,520	***
	Peak	0,158	0,173	9,199	***	0,159	0,175	10,172	***
	Off peak	0,177	0,197	11,417	***	0,178	0,197	10,839	***
	1 (lowest)	0,191	0,206	7,987	***	0,193	0,211	9,270	***
	2	0,165	0,180	8,895	***	0,166	0,178	7,379	***
	3	0,156	0,176	12,789	***	0,156	0,177	13,077	***
	4 (highest)	0,158	0,177	12,287	***	0,157	0,177	12,690	***
	Whole data	0,168	0,155	-7,685	***	0,168	0,159	-5,622	***
	Peak	0,158	0,136	-14,135	***	0,159	0,143	-10,204	***
	Off peak	0,177	0,173	-2,022	**	0,178	0,175	-1,628	*
Auction and continuous	1 (lowest)	0,191	0,180	-5,583	***	0,193	0,182	-5,765	***
	2	0,165	0,149	-9,862	***	0,166	0,154	-7,115	***
	3	0,156	0,143	-8,424	***	0,156	0,149	-4,578	***
	4 (highest)	0,158	0,139	-11,753	***	0,157	0,144	-8,260	***

Note: *: $t < 0.1$; **: $t < 0.05$; ***: $t < 0.01$

Table 3.10: Mean-difference for competition

3.4 Remarks and conclusion

This article investigates the impact of the introduction of an auction before the start of a continuous market. The introduction of the 15-min call auction before the start of the continuous market for power in Germany is used as a natural experiment for the study. Using the mean-difference method, I quantify the effect on the volatility, the liquidity and the competition of the market. The contribution of this chapter is in threefold: (1) it studies a market different to the previous study by its inherent properties, (2) it studies the market participants' behavior after the introduction of the auction, (3) it assess the impact on competition thanks to the detailed order books. The table 3.11 in the appendices summarizes the results for the continuous market.

The implementation of the call auction has a mitigated effect on the continuous market. The liquidity deteriorated: the traded volume decreased and the spread increased during the first two hours of the session. In line with the decrease of the liquidity, we could observe an increase of the market concentration. While, in most cases, we find no significant change in the market volatility during the first hour of the trading session, the volatility decreased during the second hour of the session.

The liquidity decrease and the market concentration increase could be expected as the introduction of the auction permitted market participants to trade earlier so there is then less need to trade at the opening, especially for the first contracts of the day where the time between the auction and the market gate closure is the smallest. The lower volatility is due to the price reference that the auction created: before the introduction of the call auction, market participants did not have quarter hour price indexes.

While the auction has a "business-stealing" effect on the continuous market, it is clear that the effect is limited (about 16% after detrend and deseasonalize the serie). The overall volume for quarter hourly contracts almost double, highlighting the complementary between the two venues. This result is also supported by the fact that, after the introduction of the call auction, most of the market participants started to use both venues. If the auction and the continuous market were substitute, participants would specialized their trading in either one or the other. Indeed, the auction attracted volume that wasn't from the continuous. We could observe a growing interest for the 15 minutes contracts following the introduction of the auction materialized by the increasing number of mar-

ket participants on the spot market for quarter hourly contracts. In line with that, the concentration ration (HHI) of the spot market for quarter hourly contracts decreased.

While the literature found that the market quality increased on the continuous market following the introduction of an opening auction, this paper found that the quality of the continuous market was deteriorated due to a business-stealing effect of the auction. However, it highlights the improvement of the market quality of the whole trading chain for 15 minutes contracts. Overall, the introduction of the call auction had a positive effect: it decreased a bit the market quality of the continuous market but significantly increase the quality of the trading for 15 minutes contracts.

This result contrasts with the literature probably due to the properties of the power trading: there is an existence of maturity, power is not storable in comparison to some other commodities, market participants should be balance responsible, ... All those features make the power market less liquid in comparison to the stocks that were studied in the previous literature. On top of that, the physical aspect of electricity preserves its market from an important financierization and limits the arbitrage behaviors between the auction and the continuous market.

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Appendices

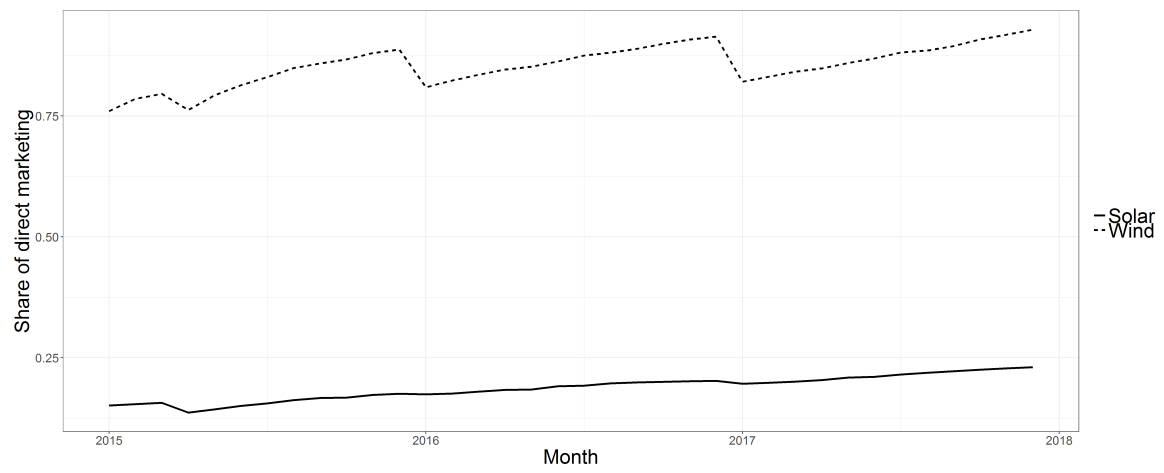


Figure 3.4: Share of direct marketing compensation scheme for wind and solar capacity

		Volatility	Volume	Spread	Concentration
Week-end	16:00-17:00	0	-	+	+
	17:00-18:00	0	-	+	+
Business day	16:00-17:00	0	-	+	+
	17:00-18:00	-	-	+	+
00:00-8:00	16:00-17:00	0	-	+	+
	17:00-18:00	0 or -	-	+	+
8:00-12:00	16:00-17:00	+	-	+	+
	17:00-18:00	0 or -	+	+	+
12:00-20:00	16:00-17:00	+	-	+	+
	17:00-18:00	0	+	+	+
20:00-24:00	16:00-17:00	0	-	+	+
	17:00-18:00	-	-	+	+
1 (lowest)	16:00-17:00	0	-	+	+
	17:00-18:00	0	+	+	+
2	16:00-17:00	0	-	+	+
	17:00-18:00	-	-	+	+
3	16:00-17:00	0	-	+	+
	17:00-18:00	0 or -	-	+	+
4 (highest)	16:00-17:00	0	-	+	+
	17:00-18:00	-	-	+	+

Table 3.11: Results' summary: impact of the call auction on the continuous market

Chapter 4

Vertical integration, real-time pricing and market power

About this chapter

This chapter was mainly realized in Madrid during my visit at the EnergyEcoLab of Carlos III university under the supervision of Pr. Natalia Fabra. I want to warmly thank Pr. Fabra for her precious comments, suggestions and time as well as Pr. Juan Pablo Montero, Imelda and David Andres Cerezo for the fruitful discussions we had during my stay in Madrid. I also want to thank Pr. Creti for her comments on a first version of the chapter.

Abstract

While the literature studies the question of real-time pricing from a demand perspective, this paper theoretically investigates it from the supply point of view. I use an oligopolistic model with a vertically integrated dominant firm whom proposes a real-time pricing scheme to its final consumers - i.e. supply power at the hourly price of the forward market. I find that vertical integration in sequential market reduces market power when the retail price to end-consumers is fixed. However, the result suggests that the real-time pricing scheme gives incentives to the dominant firm to exercise more market power and hence increases prices on both the forward and the spot markets.

Keywords: vertical integration, real-time pricing, market power, power market.

4.1 Introduction

The increase of the non-flexible generation capacity due to the rapid development of the renewable energy sources (RES) and the peaks of consumption may create high prices on the power market as well as congestion issues. To avoid those issues, there is a concern about giving the right signal to the end consumers by a willingness of adequacy of the market and the final prices. The emergence of smart meters for residential consumers lets consumers to pay the real price of electricity based on the hourly market prices. This scheme allows end-consumers to adjust their consumption in line with the market price and thus reduce peak prices on the market while reducing their bill. It also permits to reduce the costs for producers, operators and retailers (Verrier, 2018, IEA, 2003, Faruqui and Georges, 2005, Spees and Lave, 2007, Albadi and El Saadany, 2008). In a setup with only one market, this tariff scheme won't change the incentive of the vertically integrated firms: as they produce and supply power, they will buy power on the market at price p and sell it to their end-consumers at price p plus a margin. However, in a setup with sequential markets, end-consumers' price will only be based on the first market as the second market will be too close to the delivery and consumers need to be informed in advance of the price they will pay¹. This may change the incentive of the vertically integrated firm whom

¹For example, in Spain, the regulator publishes the hourly prices for end-consumers the day before delivery at 20:00.

participates in the two sequential markets. This scheme is for example in place in Spain where the regulated tariff is based on the hourly market price. With the expansion of smart meters and the increasing willingness to give the right signal to end consumers, the question of the incentives of vertically integrated firms is key for regulators in order to design proper tariff schemes.

While most of the literature studies the question of real-time pricing from a demand perspective, the aim of this paper is to look at the impact of real-time pricing on the strategy of vertically integrated firms.

This paper relates to two streams of literature: the one on vertical integration and the one on real-time pricing. Many researchers such as Mansur (2004) or Hogan and Meade (2007) demonstrate the positive impact of vertical integration on the exercise of market power especially in the case of power market. Bushnell et al. (2004) argues that the surge of electricity prices in California in 2000/2001 is due to the absence of vertical integration of the dominant firms. Kühn and Machado (2004) show the positive effect of vertical integration in the Spanish market. While there exists a consensus on the positive impact of vertical integration on single markets, the present article contributes to the literature by theoretically investigating the impact of vertical integration in a sequential market setup, closer to the reality.

Regarding real-time pricing, the broad literature focuses on the impact of the tariff scheme on the market demand (Alcott, 2012) or the end-consumers' behavior (demand-response) but does not look at the impact on the supply, particularly on the bid strategy of the vertically integrated firms. Even if part of literature on real-time pricing is very enthusiastic about the right signal it gives to the demand side (Borenstein and Holland, 2003, Joskow and Tirole, 2006, Borenstein, 2013), some results are mitigated due to the low financial gain for residential consumers versus the cost of installation of smart meters (Borenstein, 2005, Holland and Mansur, 2006, Léautier, 2014 or Faruqui et al., 2010). Some papers (Ruff, 2002, Chao, 2010, Crampes and Léautier, 2010) also highlight the issues that may arise with real-time pricing such as double payment, moral hazard or adverse selection. This paper contributes to the literature by theoretically studying the impact of market based tariff scheme for end-consumers on the supply.

I develop a theoretical framework with a vertically integrated dominant firm who can sell power to its end consumers at a fixed price or at the forward market price. The

model is inspired by the paper of Ito and Reguant (2016) itself based on the work of Allaz and Vila (1993) for the sequential markets and by the work of Coase (1972) for the non sophisticated or impatient consumers. It challenges the hypothesis of Weber (1981) that markets prices should converge in expectation. In their paper, they show that a systematic price difference between the forward and the spot market arises due to the exercise of market power even in the presence of arbitrage. In this paper I am not interested in price difference neither arbitrage but rather in the prices themselves, under different tariff scheme of electricity. However, the methodology of their model is a good base to answer to my research question. In comparison to their model, I add the vertical integration dimension of the dominant firm and the possibility to propose real-time pricing scheme to its end consumers. In this paper, the dominant firm wants to maximize its profit with respect to its net position on the market and not only its supply quantity. In Ito and Reguant (2016), the dominant firm is a net supplier.

I find that the vertical integration of the dominant firm reduces market power: prices are reduced in comparison to the model without vertical integration due to the increase of the supply. However, the vertically integrated firm has incentives to exercise market power in the context of real-time pricing as the price of the forward market will positively impact their revenue which is not the case with a fixed price. Interestingly, the price of the spot market also increases due to the the increase of the demand.

The paper is structured as follows. Section 2 describes the model I am inspired by and the framework I developed with vertical integration. Then, section 3, discusses the results and section 4 is the conclusion.

4.2 Models

4.2.1 Ito and Reguant, 2016

Consider a producer who wants to maximize its profit by backward induction. In the spot market, the monopolist problem is:

$$\begin{aligned} & \max_{p_2} p_2 q_2 - c(q_1 + q_2) \\ \text{s.t. } & D_2(p_1, p_2) = (p_1 - p_2)b_2 \\ & D_1(p_1) = A - b_1 p_1 \end{aligned}$$

where q_i , $i=1,2$ is the quantity supplied by the dominant firm in the first (resp. second) market, p_i the market price in the i th market and c the linear cost function. D_i is the demand and b_i the slope of the demand curve on the i th market. A is the total demand of the end-consumers.

In the first stage or forward market, the monopolist problem is:

$$\begin{aligned} \max_{p_1} & p_1 q_1 + p_2(p_1) q_2(p_1) - c(q_1 + q_2(p_1)) \\ \text{s.t. } & D_1(p_1) = A - b_1 p_1 \end{aligned}$$

Assuming that the monopolist is a net seller, they found the following results:

$$p_1^* = \frac{2A + 2cb_1 - cb_2}{4b_1 - b_2} \quad (4.1)$$

$$q_1^* = \frac{(A - -b_1 c)(2b_1 - b_2)}{4b_1 - b_2} \quad (4.2)$$

$$p_2^* = \frac{c(3b_1 - b_2) + A}{4b_1 - b_2} \quad (4.3)$$

$$q_2^* = \frac{b_2(A - cb_1)}{4b_1 - b_2} \quad (4.4)$$

$$p_1^* - p_2^* = \frac{A - cb_1}{4b_1 - b_2} \quad (4.5)$$

They show that the price on the forward market is above the price on the second market ($p_1 > p_2$) as well as the quantities ($q_1 > q_2$). They also find that the price difference between the two markets ($p_1 - p_2$) is increasing in A , decreasing in b_1 and increasing in b_2 .

4.2.2 The model

In this section, I develop a theoretical sequential model based on the framework developed by Ito and Reguant (2016).

Consider a vertically integrated firm which decides how much to sell and to buy on two sequential markets: the forward and the spot markets. The firm has a dominant position on the market, commits to produce a certain quantity and has to answer the demand of its

end-consumers. There is no transaction fee in the model and the firm cannot internalize its supply meaning that it needs to buy all its demand from the market. The problem of the dominant vertically integrated firm is to find its net position and how much to produce in the forward market at price p_1 and in the spot market at price p_2 .

The dominant vertically integrated firm wants to maximize its joint profit (generation and retail profits) by backward induction, under the constraint of the residual demand of the market, with respect to its net position in both markets Q_1 and Q_2 . Its net position is defined as its production commitment to the market i $i = 1, 2$ minus a share of its commitment to its end-consumers that it wants to buy on the market i $i = 1, 2$.

Forward market - In the forward market, the monopolist's problem is:

$$\begin{aligned} \max_{p_1} & p_1 Q_1 + p_2(p_1) Q_2(p_1) - c(Q_1 + Q_2(p_1) + \theta) + \varphi \theta p_1 + (1 - \varphi) \theta p_F \\ \text{s.t. } & D_1(p_1) = A - \theta - b_1 p_1 \end{aligned}$$

where $Q_1 = q_1 - \alpha \theta$ and $Q_2 = q_2(p_1) - (1 - \alpha) \theta$ are respectively the net positions of the monopolist on the forward and on the spot market. q_i is the supply quantity of the firm on market i and α is the share of the demand faced by the monopolist answered in the forward market. θ is the demand that the dominant firm faces on the retail market. The cost of production c is linear for simplicity². This is because the impact of the cost on price will be the equal in the two models and then will be cancelled in the comparison of the models. $\varphi \theta$ is the demand faced by the firm under real-time pricing scheme and $(1 - \varphi) \theta$ the demand under fixed tariff. In other words, $\varphi \theta$ represents the end consumers who have a dynamic tariff and so pay their electricity based on the hourly market price.

In order to incentivize the end-consumers to reduce their demand during peak hours - where the electricity is the most expensive, the regulator displays the market price that will be applied to residential customers the day before on a transparency platform. In doing so, only the forward market price p_1 is taken into account in the real-time tariff.

The profit of the vertically integrated firm is subject to the residual demand it faces Q_1 which is the total demand of the market A minus the demand it faces θ and the demand answered by a fringe of suppliers $b_1 p_1$. b_1 corresponds to the slope of the supply curve of the fringe. The demand of the market (A) is inelastic.

²I have tried to put a quadratic cost function, closer to reality but it doesn't change the results of the paper.

Spot market - In the spot market, the monopolist' problem is:

$$\begin{aligned} \max_{p_2} & Q_2(p_1) - c(Q_1 + Q_2(p_1) + \theta) + \varphi\theta p_1 + (1 - \varphi)\theta p_F \\ \text{s.t. } & D_1(p_1) = A - \theta - b_1 p_1 \\ & D_2(p_1, p_2) = (p_1 - p_2)b_2 \end{aligned}$$

where Q_2 is the residual demand in the second market. In this setup, the fringe of suppliers may oversell in the first market and buy the difference on the second market. b_2 is the slope of the supply curve of the fringe in the second market. It is assumed that $b_2 < b_1$ as the supply is less elastic closer to delivery.

4.3 Results

In this section, I resolve the model described above.

4.3.1 Sequential markets and vertical integration

Assume that the dominant firm is vertically integrated with a large capacity of production which is above the demand of its end-consumers (θ) and that it sells electricity at a fixed rate ($\varphi = 0$, no real-time pricing).

Solving the above model with $\varphi = 0$, I find the following results:

$$p_1^* = \frac{2(A - \theta) + 2cb_1 - cb_2}{4b_1 - b_2} \quad (4.6)$$

$$Q_1^* = \frac{(A - \theta - b_1c)(2b_1 - b_2)}{4b_1 - b_2} \quad (4.7)$$

$$q_1^* = Q_1^* + \alpha\theta = \frac{(A - \theta - b_1c)(2b_1 - b_2) + \theta\alpha(4b_1 - b_2)}{4b_1 - b_2} \quad (4.8)$$

$$p_2^* = \frac{c(3b_1 - b_2) + A - \theta}{4b_1 - b_2} \quad (4.9)$$

$$Q_2^* = \frac{b_2(A - \theta - cb_1)}{4b_1 - b_2} \quad (4.10)$$

$$q_2^* = Q_2^* + (1 - \alpha)\theta = \frac{b_2(A - cb_1) + \theta[1 - \alpha - b_2]}{4b_1 - b_2} \quad (4.11)$$

$$p_1^* - p_2^* = \frac{A - \theta - cb_1}{4b_1 - b_2} \quad (4.12)$$

The price of the forward market decreases by $\frac{2\theta}{4b_1 - b_2}$ in comparison to the model without vertical integration (Ito and Reguant, 2016). The supply of the dominant firm q_1 depends on the share of the demand it faces that it will buy in the first market ($\alpha\theta$). If α is below $\frac{2b_1 - b_2}{4b_1 - b_2}$ then the supply will decrease in order to avoid an important decrease of the price due to the lower demand (low α); however when the share of the demand answered in the first market ($\alpha\theta$) is above the threshold, the vertically integrated monopoly will want to increase the supply to lower the price on the forward market as it will need to buy a lot from it. In a simplest setup where $b_1 = b_2 = b$, the threshold is $\alpha = 1/3$ and thus, when the monopolist buys more than a third of the demand it faces on the forward market, it will increase its supply above the level in the case where it is only a net producer - initial model of Ito and Reguant (2016). Therefore, it exists an arbitrage for the vertically integrated dominant firm between selling at a "high" price and buying at a "low" price depending on the quantity it has to buy on the forward market. This quantity is defined exogeneously by the market rules.

The price on the spot market decreases by $\frac{\theta}{4b_1 - b_2}$ in comparison with the model without vertical integration of the dominant firm. As in the first market, the supply of the vertically integrated monopoly decreases if the share of the demand of the monopoly answered in the second market ($1 - \alpha$) is below $\frac{b_2}{4b_1 - b_2}$ and increases if it is above the threshold. The reason behind this is the same as in the forward market: the firm adjusts its supply depending on the volume it will need to buy on the market. In this sense, when the demand of the dominant firm is low (high), it will produce less (more) in order to increase (decrease) the market price.

The price difference between the two markets decreased by $\frac{\theta}{4b_1 - b_2}$ in comparison with the initial model of Ito and Reguant (2016). This negative relationship implies that: higher is the demand faced by the monopolist, smaller is the price difference between the two markets and so softer is the exercise of market power.

As the monopolist maximizes its joint profit and in doing so, it thinks in term of net position. The share of the demand answered in the first market (α) will only have an effect on the quantities supplied and not the prices. When the vertically integrated firm

has the obligation to buy all its demand in the first market ($\alpha = 1$), it will then supply more in the first market and decrease its supply on the second market.

Result 1. In sequential markets, the vertical integration of the dominant firm reduces its incentive to exercise market power. The prices of both markets will be reduced in comparison with the model without vertical integration.

This result is explained by the fact that the dominant firm is not only a producer but also faces a demand to whom it has to buy electricity from the market. In this sense, it is now on both side of the market and does not want to use as much market power as before on both markets because the price of the market is not only a revenue but also a cost.

4.3.2 Vertical integration and real-time pricing in sequential markets

Assume that the monopolist is vertically integrated with a large capacity of production which is above the demand of its end-consumers and that it sells electricity either at a fixed rate or at a real-time tariff ($\varphi > 0$).

Solving the model, I find

$$p_1^* = \frac{2(A - \theta) + 2\varphi\theta + 2cb_1 - cb_2}{4b_1 - b_2} \quad (4.13)$$

$$Q_1^* = \frac{(A - \theta - b_1c)(2b_1 - b_2) - 2\varphi\theta b_1}{4b_1 - b_2} \quad (4.14)$$

$$q_1^* = Q_1^* + \alpha\theta = \frac{(A - \theta - b_1c)(2b_1 - b_2) + \theta[\alpha(4b_1 - b_2) - 2\varphi b_1]}{4b_1 - b_2} \quad (4.15)$$

$$p_2^* = \frac{c(3b_1 - b_2) + A - \theta(1 - \varphi)}{4b_1 - b_2} \quad (4.16)$$

$$Q_2^* = \frac{b_2(A - \theta(1 - \varphi) - cb_1)}{4b_1 - b_2} \quad (4.17)$$

$$q_2^* = Q_2^* + (1 - \alpha)\theta = \frac{b_2(A - cb_1) + \theta[1 - \alpha - b_2(1 - \varphi)]}{4b_1 - b_2} \quad (4.18)$$

$$p_1^* - p_2^* = \frac{A - \theta(1 - \varphi) - cb_1}{4b_1 - b_2} \quad (4.19)$$

The real-time pricing scheme increases the price of the forward market by $\frac{2\theta\varphi}{4b_1-b_2}$ in comparison to the model without real-time pricing (section 4.3.1). This price increase is due to the capacity withholding (decrease of the supply) of the vertically integrated monopoly by $\frac{2\varphi b_1}{4b_1-b_2}$. However, in comparison to the basic model without vertical integration (section 4.2.1), the price of the forward market decreases by $\frac{2\theta(1-\varphi)}{4b_1-b_2}$.

The price of the spot market increases by $\frac{\theta\varphi}{4b_1-b_2}$ in comparison to the model without real-time pricing. However, the dominant firm supplies more capacity q_2 in the spot market which increases by $\frac{\theta b_2\varphi}{4b_1-b_2}$. The price increase is due to the increase in price difference between the two markets by $\frac{\theta\varphi}{4b_1-b_2}$ to answer a higher demand compared to the framework in 4.3.1.

Result 2. In sequential markets with a vertically integrated dominant firm and the possibility for it to propose a real-time pricing scheme to their end-consumers, the dominant firm has an incentive to exercise more market power in comparison to the framework without real-time pricing. However, in this setup the dominant firm does not exercises as much market power as in the model without vertical integration.

While the real-time pricing scheme has a positive effect on the demand side (cf. literature), it distorts the incentives of a vertically integrated firms who has an incentive to exercise more market power in both the forward and the spot market. We can observe that the price increases, particularly in the forward market. In the extreme case where all the end-consumers are under real-time pricing scheme ($\varphi = 1$), on the spot market, the setup fully cancels the positive effect of the vertical integration and the prices in the forward and the spot market are equal to the prices of the initial model without vertical integration.

4.4 Discussion

While the benefit of real-time pricing on the demand is proved by various academic contributions (Joskow and Tirole, 2006, 2007, Wolak, 2007, Alcott, 2011), I show in the above section that the effect may be negative due to the change in supply strategy following the introduction of real-time pricing. In the present section, I will give insights to the question: can the positive effect from the demand side overcome the negative effect from the supply side ?

The total demand of the market (A) and the share of demand of the vertically integrated monopolist under real-time pricing scheme ($\theta\varphi$) has a positive effect on the prices. I want to know the level of demand-response that cancels the negative impact of real-time pricing from the supply. In order, for the price to remain the same as in the case with no real-time pricing (fixed price), an increase of the share of the demand under real-time pricing ($\varphi\theta$) of 1 megawatt hour (MWh) should be compensated by a decrease of 1 MWh of the new total demand (A'): $A = A' + \varphi\theta$.

We now want to find the lower level of demand-response $t \in [0; 1]$ needed in order to compensate the increase of price due to the exercise of market power from the supply side. We want the prices in both markets with real-time pricing (equations (4.13) and (4.16)) to be respectively below or equal to the prices in the model without real-time pricing (equations (4.6) and (4.9)): $(1 - t)A - \theta + \theta\varphi \leq A - \theta$. We can rewrite the previous equation as $(1 - t)A + A\omega\varphi \leq A$ where ω is the share of the total demand answered by the monopolist: $\theta = \omega A$. We then want $t \geq \omega\varphi$ to sustain the change of tariff without affecting the benefit of vertical integration. When the share of the demand answered by the vertically integrated monopolist (ω) increases, t should also increase in order to keep the same price level. There is also a positive relation between the level of end-consumers under real-time pricing scheme (φ) and the level of demand-response needed to compensate the increase in price due to the exercise of market power.

Back of the envelop computation - The four main vertically integrated firms in Spain represent about 70% of the market share (Ito and Reguant, 2016): $\omega = 0.7$. The real-time pricing scheme is the regulated and so it is the default tariff. I could not find the value of the share of end-consumers under real-time pricing scheme but knowing that most industrial consumers are under this tariff and that it is the regulated one for households, I will approximate it to 70%: $\varphi = 0.7$. I also make the computation for a low case scenario ($\varphi = 0.55$) and a high case scenario ($\varphi = 0.85$) Then, in order to compensate the change in supply due to market power, the demand should decrease by 49% in the main case, 38.5% in the low case scenario and 59.5% in the high case scenario.

This result seems quite large knowing that the demand response potential in the IEA's Sustainable Development Scenario (SDS) from the World Energy Outlook 2018 is of 26%. However, with the rapid expansion of the technology related to demand-response as well as the decrease in concentration of the power market thanks to the liberalization, this

value should increase in the future.

Going further, an interesting question may be to investigate the issue using the data of the Spanish spot power market. A more rigorous analysis of the arbitrage between supply and demand decrease due to real-time pricing in order to properly assess the overall impact of the tariff scheme.

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Chapter 5

Conclusion

The present thesis is interested in the operation of the current European spot market. It aims to better understand this market, particularly the continuous one. I also study the impact of some special cases of regulatory or market design changes: the creation of an auction before a continuous market and the change in tariff for the end-consumers from a fixed price to a dynamic one based on the hourly market prices. It is a very interesting to study the spot market as it is getting more attention due to the increasing (intermittent) renewable production.

The first part of the thesis studies the liquidity formation on the continuous market. It highlights the "L-shape" behavior of the bid-ask spread over an average trading session. First, I find that there is a positive relationship between the bid-ask spread and the volatility. Then, I show that there is a negative relationship between the bid-ask spread and the market activity, the competition as well as the supply and demand forecast errors.

The second part focuses on a natural experiment from the European Stock Exchange - EPEX SPOT, which introduced a call auction before the start of the continuous market. The results suggest that while the auction harmed the quality of the continuous market, the deterioration was limited: there is no effect on the volatility and the business-stealing effect of the auction was modest. However, the overall quality (auction and continuous market) increased: we could observe a significant increase of the liquidity and a decrease of the concentration.

The last part studies the impact of real-time pricing (ie. end-consumers pay a dynamic price based on the hourly market price) on the supply of vertically integrated dominant

firms. The result indicates that the dominant firms have an incentive to exercise more market power and thus increase the market price. The explanation behind this argument is that, with real-time pricing, the retail price is a revenue for the firm.

Further personal researches imply the improvement of the chapters to then submit them in peer-review journal. From a more global perspective, the study of the price formation of the power spot market should be deeply investigated. The field of market design still has unanswered questions related to the new challenges of the industry such as the congestion issues.

RÉSUMÉ

Cette thèse s'intéresse aux marchés spot de l'électricité et plus particulièrement à l'organisation et la conception de ces derniers. En effet, l'industrie électrique fait face à de nouveaux défis dues à l'augmentation de la capacité de production renouvelable mais également dues à des changements plus structurels liés aux comportements des acteurs. La régulation et les plateformes d'échange doivent s'adapter à ces changements afin de veiller à l'efficacité du marché dans son ensemble.

Le premier chapitre de la thèse étudie en détails la formation de la liquidité sur le marché continu allemand. Il s'intéresse particulièrement à l'évolution de la fourchette bid-ask au cours d'une session d'échange et les facteurs qui l'influencent. Dans un second chapitre, j'évalue quantitativement l'effet de la création d'une enchère avant le début d'un marché continu sur la liquidité, la volatilité et la concentration du marché. La dernière partie de la thèse étudie théoriquement l'impact de l'intégration verticale dans des marchés séquentiels ainsi que l'impact de la tarification en temps réel pour les consommateurs finaux sur le comportement des acteurs du marché.

MOTS CLÉS

Electricité, marché spot, enchère, marché continu, intégration verticale, tarification en temps réel

ABSTRACT

The present thesis is interested in the power spot market, particularly its organization and design. The electricity industry faces new challenges due to the increasing intermittent renewable capacity but also due to the structural transformations linked to the changes of participants' behaviors. Regulation and exchanges should adapt to those changes in order to ensure the efficiency of the market.

The first chapter of the thesis extensively studies the liquidity formation on the German continuous market. It analyzes the evolution of the bid-ask spread along a trading session and the main drivers of it. In a second chapter, I quantitatively evaluate the effect of the introduction of a call auction before the start of a trading continuous session in terms of liquidity, volatility and competition. The last chapter of the thesis theoretically studies the impact of vertical integration in sequential markets as well as the impact of the real-time pricing on market participants' behavior.

KEYWORDS

Electricity, spot market, auction, continuous market, vertical integration, real-time pricing

