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Liquidity in Intraday Markets for Electricity

An Empirical Analysis of the Swedish Bidding Area Reform

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Abstract

Congestion in electricity networks is a crucial challenge for European electricity markets, as the continent is moving towards an integrated, decarbonized power system. One potential solution to this problem is a zonal pricing approach, which divides large bidding areas into smaller zones. While this approach reduces congestion by taking into account a larger share of network constraints, it is criticized for reducing market efficiency due to smaller market size. This paper empirically analyzes the trade-off between congestion costs and market efficiency using the Swedish bidding area reform in 2011 as a natural experiment. A fixed effects estimation strategy is employed to test the effect of the reform on liquidity in the intraday market Elbas. We find that the bidding area reform did not have a consistent effect on liquidity in the Swedish intraday market. Thus, this study could serve as encouraging evidence for the use of bidding area reconfiguration as a congestion management tool.

Keywords: Liquidity, Congestion Management, Electricity Markets, Intraday Markets, Zonal Pricing, Electricity Market Reform

JEL: P18, L51, L94, Q40, Q42, Q41, Q48

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List of Abbreviations

CHP	-	Combined Heat and Power Plants
ELBAS	-	Electricity Balancing System (Nordic Intraday Market for Electricity)
ELSPOT	-	Electricity Spot Market (Nordic Day-Ahead Market for Electricity)
ENTSO-E	-	European Network of System Operators for Electricity
EPAD	-	Electricity Price Area Differentials
LMP	-	Locational Marginal Price
PJM	-	Pennsylvania-New Jersey-Maryland
TSO	-	Transmission System Operator

1. Introduction

The widespread adoption of renewable energy sources such as solar and wind energy is one of the most impactful developments of the early 21^{st} century. In combination with other policy measures, the expansion of renewable energy production has the potential to help solving pressing issues such as climate change, air pollution and resource depletion. For example, the European Union's goal to cut greenhouse gas emissions by 40%, compared to their 1990 level, requires the member states to more than double their share of renewable energy production, from 21% to 45% (European Commission, 2014).

However, the integration of renewable energy sources into existing electricity system creates challenges due to their scattered geographic distribution (*decentralized*) and infrequent production (*intermittent*). Historically, electricity has been produced by large-scale power plants, producing a stable and predictable supply of electricity. In contrast, the increasing generation of wind and solar power plants depends heavily on weather conditions (The Division of Energy Market Oversight, 2017). This creates challenges to the reliability of the system, which has not been constructed for such decentralized and intermittent generation. Thus, when the production unexpectedly spikes due to a sudden change in weather conditions, the demand for transmission of electricity might exceed the capacity of the transmission lines. This leads to so-called *congestion* in the transmission network, meaning that no more electricity can be transported through the constrained parts of the grid.

The problem of congestion is partially caused by the way electricity markets are designed. Most markets in Europe are structured as so-called *uniform price zones* and assume that no capacity limits exist between any two points. This creates a disconnect between the physical infrastructure and the market mechanism, which requires government agencies to intervene in the system. These interventions are expensive for society as the costs of congestion related interventions have increased from EUR 25 million in 2009 to EUR 186 million in 2014 in Germany alone (Egerer et al., 2016). However, they are necessary, because a failure in dealing with congestion would lead to a *black out* - or in other words, a break-down of the electricity system with high costs for a country's economy. For the Netherlands it has been estimated that an hour-long outage of electricity supply during working hours would lead to a welfare cost of EUR 159 million (de Nooij et al., 2007).

To bridge the disconnect between physical infrastructure and the market model, reforming the market design is discussed on a European level. Such a reform entails splitting one large bidding zone with a uniform price into multiple smaller zones along congested transmission lines. Hence, congestion is prevented by taking into account intra-zonal capacity constraints, creating efficient incentives regarding consumption and investments into network extensions (OFGEM, 2014). While such a market design is widely regarded as a valid solution for

more efficient congestion management, it has been criticized for introducing a variety of problems with regard to market power, liquidity and transaction risk. Of these problems, liquidity on intraday markets is especially crucial for the efficient functioning of a liberalized electricity market. Short-term markets such as intraday markets can only provide the required flexibility and efficiency of smoothing production imbalances if they are sufficiently liquid. The importance of this issue is highlighted by organizations such as Frontier Economics and Consentec (2013) and ENTSO-E, 2017, which call for an analysis of market liquidity in connection to bidding zone reconfiguration, which are currently being considered all over Europe.

In 2011, Sweden implemented such a reform of its electricity market design after losing a court case in front of the European Commission. This policy change functions as a natural experiment, which we exploit to study the implications of the introduction of smaller bidding zones. Thus, we contribute to the debate about a possible trade-off between liquidity and congestion costs by asking the question:

Did the bidding area reform decrease the liquidity of the Swedish intraday market?

We answer this research question empirically by building a dataset with trade data from the Nordic intraday market Elbas. We then use the Swedish policy change to identify if there has been an effect of market splitting on the liquidity of Elbas. To isolate the effect, we use Finland as a control group. With this empirical analysis we add to three distinct fields of literature with a focus on the Nordic electricity market. First, our paper contributes to the discussion about the efficiency of zonal pricing as a means to reduce congestion in liberalized power markets. Second, our paper adds to the body of literature on liquidity in intraday electricity markets. Finally, to the extent of our knowledge, this thesis is the first paper to empirically investigate the mechanisms of the Nordic intraday market Elbas.

The remainder of the paper is structured as follows. First, basic concepts of electricity markets, the problem of congestion and different congestion management tools are introduced. Additionally, the concept of liquidity in the context of electricity markets is discussed. Second, the Nordic market is introduced with a focus on the structure of its physical markets and the policy change in 2011. Third, the related literature is discussed in-depth. Fourth, based on the presented literature and concepts we develop testable hypotheses about the effect of zonal pricing on the liquidity of electricity markets. Fifth, our dataset and descriptive statistics for Nordpool's intraday market are presented. Sixth, we discuss our estimation strategy. Thereafter, we introduce and analyze the results of our empirical analysis. Finally, we conduct robustness checks, discuss the results and present policy implications.

2. Electricity Market Concepts

The Swedish bidding area reform presented policy makers with a trade-off: While the policy was supposed to reduce the problem of congestion in the Swedish electricity market, it was feared to induce market inefficiencies such as illiquidity. The following section discusses the three core concepts which created this trade-off. First, we introduce the general structure of electricity markets and the problem of congestion that arises from a disconnect between the market and the grid. Second, we explain how a bidding area reconfiguration can theoretically eliminate this disconnect. Finally, the concept of liquidity and its importance for electricity markets is introduced.

2.1. *Power Systems and the Problem of Congestion*

An electricity market consists of all actors involved in generating electricity and delivering the power to the end consumer. Historically, the entire value chain was operated by integrated monopolies, which were broken up by the liberalization of electricity markets in the late 1990's and early 2000's. This liberalization introduced competition at all levels of the electricity market, while also enhancing the complexity of coordinating all its actors to provide a stable and reliable supply of electricity (The Division of Energy Market Oversight, 2017).

Electricity is generated by profit maximizing firms that operate either *dispatchable* or intermittent generation sites. While dispatchable technologies, e.g. gas or coal fired power plants, produce a stable and predictable supply of electricity, intermittent generation, e.g. wind or solar power plants, exhibit a high volatility in production. After generation, the electricity is bought by suppliers on wholesale electricity markets, in order to distribute the power to the end-consumer (United States Department of Energy, 2014).

Market participants can buy and sell electricity on a variety of different markets which are typically distinguished by the time frame in which they operate. Most electricity is sold in auctions the day before it is delivered on so-called day-ahead markets. Additionally, generators can sell their electricity more short-term on so-called intraday markets. These intraday markets act as a supporting mechanism to the day-ahead market. They enable generators to sell electricity closer to delivery, thereby allowing them to adjust for unexpected deviations from their forecasted generation. Intraday markets have historically been less important, yet they are gaining market share due to the increasing amount of intermittent energy production (Stavseth, 2013).

In order to transmit the traded power from generators to the consumers, the physical infrastructure of the electricity grid is needed. The electricity grid is a system of power lines which is operated by the transmission system operator (TSO). The TSO is typically a highly

regulated natural monopolist that operates, expands and maintains the network. For example, the Swedish transmission network is operated by the state-owned enterprise Svenska Kraftnät which is supervised by the Swedish government. In order to prevent the company from misusing its monopolistic power, Svenska Kraftnät operates under a revenue cap that is determined every year by the supervising authorities (Swedish Energy Markets Inspectorate, 2017).

The transmission capacities of the power lines of the grid are limited due to technical specifications such as thermal and voltage constraints. These constraints are imposed by government agencies in order to ensure the stability and security of the power system (United States Department of Energy, 2014). An additional reliability constraint is introduced by the technical properties of the electricity system and the fact that electricity is a non-storable good[1]: All electricity has to be consumed immediately, and demand and supply of electricity have to be balanced at all times by the TSO. If this balance is disturbed, outages will occur which have detrimental effects on the economic activity of a region (United States Department of Energy, 2014).

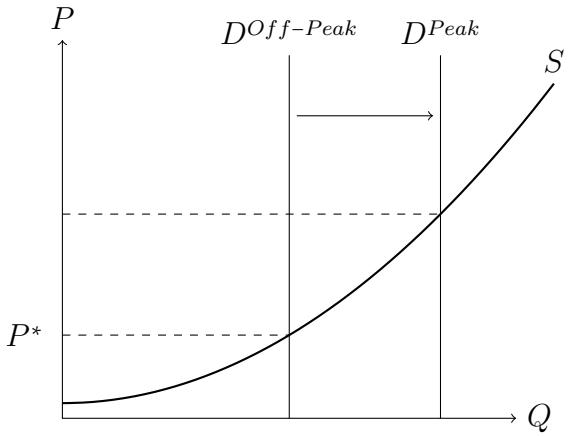


Figure 1: Bidding Curve with Different Demand Levels

Despite the existence of these capacity constraints, the largest share of electricity is traded on markets that ignore the capacity limitations of the grid. Instead, the markets operate under the so-called *copper plate assumption*. This means that unlimited transmission capacity between all points of the power system is assumed. For example, the dispatch of electricity on day-ahead markets is usually determined using a market mechanism know as the *merit order algorithm*. All generators submit bids consisting of both the price and quantity of electricity that they are willing to supply at each hour during the next day. The generators' bids are then stacked in ascending price order to create a supply curve and the resulting

[1]Even though it is technically possible to store electricity, it is not commercially viable on a large scale yet. For example, even though Norway is in a special position due to its vast availability of pumped hydro storage technology, it still has been a net importer of power in some recent years (Resources and Directorate, 2016).

supply curve is compared to the demand forecast for the respective hour. The intersection of demand and supply determines the uniform price: All generators whose bids fall below or equal to the determined equilibrium price are chosen to supply the electricity at the uniform price as can be seen in Figure 1. In this process, unlimited transmission capacity is a central assumption, as the geographic location of the producer is not taken into account.

Consequently, the copper plate assumption entails a disconnect between the physical characteristics of the grid and the market mechanism that determines the dispatch of electricity. This might result in dispatch schedules that are impossible to execute in practice as they create a problem that is known as *congestion*. Consider Figure 2 for a simplified example of the problem: It might happen that most generators chosen to dispatch are at point A, while most of the demand is at point B. As the merit order algorithm did not take into account the maximum transmission capacity from point A to point B, it might be technically impossible to transmit the scheduled amount between the two points. Thus, if the electrons were allowed to flow freely and according to the market mechanisms, the grid would break down and outages would occur.

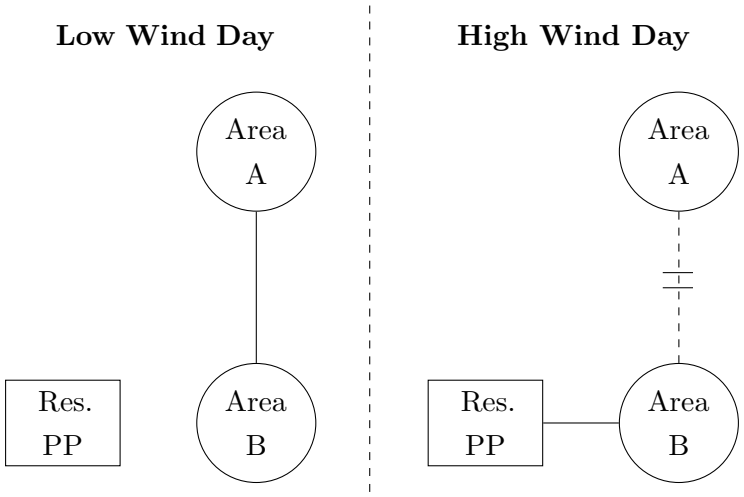


Figure 2: Simplified Model of Congestion

To prevent outages and guarantee consistency of supply, the system operator has the authority to intervene in the case of congestion. In the following section we will present a variety of approaches to solve the issue of congestion.

2.2. *Solutions to Mitigate Congestion*

The logic behind all types of congestion management approaches is similar. Generators in the low-price, low-load area – at point A – have to dispatch less, and generators in the

high-price, high-load area – at point B – have to generate more.[2] This is done in practice by the rescheduling of power plants. The network operator curtails the generation in area A, and instead increases generation of reserve power plants in area B (Appunn, 2016). This process is called redispatch and is expensive, because ramping up a generation unit short-notice or even providing the flexibility to do so is costly for the generator. Furthermore, the generator whose production is curtailed is typically paid the same price as if she had actually supplied the electricity (Holmberg et al., 2015).

Apart from relying on rescheduling production short notice in order to manage congestion, one could also invest in the grid by reinforcing existing or building new transmission lines. This would make the grid resemble a copper plate more closely and reduce the probability of congestion by increasing transmission capacity. Alternatively, the TSO could be given the authority to manage the location of new power stations more closely by setting the right incentives through price signals or auctions. This would lead to a controlled extension of the generation capacity that is in accordance to the existing grid structure. Thus, it would avoid congestion by adjusting the generation side to the physical infrastructure (Frontier Economics and Consentec, 2013).

Finally, the approach that is assessed in this thesis aims to solve the problem of congestion by reforming the market design. This entails a reorganization of the electricity market in a way that reflects both the transmission constraints and the physical characteristics of generation and demand. For example, one could envision a market in which a different price is determined at each point of the electricity grid (*node*). Thereby, the market mechanism could take all limitations of available transmission capacity into consideration. Such an approach is called *nodal* or *locational marginal pricing* (LMP). At each node, the locational marginal price reflects the marginal cost of electricity by taking into account local transmission constraints and limits in generation capacity (Hogan, 1992). Apart from eliminating congestion, this sets efficient incentives for market participants: At a high-price node, generators have an incentive to produce more, while consumers have an incentive to consume less. The opposite is true for a low-price node which incentivizes an increase in consumption. An example for a market employing a nodal pricing scheme is the American PJM market (OFGEM, 2014).

Most of the theoretical literature argues that nodal pricing would be the first best solution to eliminate congestion in electricity markets. Yet, policy makers fear that its theoretical advantage is reduced by negative side-effects related to the decreased number of market participants at each node. The concern is that fewer players will lead to increased market power and decreased market liquidity (ENTSO-E, 2017). Additionally, the implementation

[2] Alternatively, the demand side could adjust their behaviour. Consumers in area B could reduce their consumption in order to reduce the load and ensure the electricity system's balance. However, this thesis will focus on supply side rather than demand side management approaches to mitigate congestion.

of a nodal pricing regime is unfeasible in the current European context as it conflicts with regulations that forbid discriminating consumers based on their location (Olmos et al., 2015).

Therefore, most European countries operate under a *zonal pricing* approach. Zonal pricing describes the mechanism of determining a single price for electricity within a specific area - the so-called bidding zone. A bidding zone is defined as the geographic area within which electricity can be traded without taking into account transmission constraints (OFGEM, 2014). While the single price zone avoids price discrimination, it leads to inefficient incentives for renewable energy production as it does not take into account transmission constraints which typically increase in bidding zone size (Hu et al., 2018). Examples of countries that are currently organized as a single bidding zone are Germany, France and Austria (ENTSO-E, 2018).

A compromise between zonal and nodal pricing is the introduction of multiple bidding zones. These are constructed by clustering the prices of nodes both in front and behind the points of congestion in order to better reflect the underlying transmission constraints (OFGEM, 2014). Examples of countries that currently operate multiple bidding zones are Italy, Sweden and Norway. In a perfect scenario, introducing multiple bidding zones is a way of reducing the complexity of a nodal pricing approach while minimizing the amount of intra-zonal congestion. However, the division of markets into bidding zones is far from trivial and necessarily results in nodes with different characteristics inside the same zone (Holmberg et al., 2015).

Thus, smaller bidding zones are hardly able to fully eliminate congestion, but can move the physical system closer to efficiency. Smaller bidding zones might, however, introduce negative side-effects related to market efficiency. This trade-off makes the question of bidding zone reconfiguration a highly relevant topic from a policy standpoint. At the heart of the European process of energy market integration is the vision of a unified market with bidding zones that are not delineated by national borders. Therefore, the European Network of Transmission System Operators for Electricity (ENTSO-E) is currently reviewing the design of European bidding zones with regard to a variety of factors including market efficiency. Under the broad term of market efficiency the ENTSO-E considers different aspects such as market liquidity, market power and the possibility for long-term hedging (Regional Group Baltic Sea, 2018).

In this thesis, we will further investigate the effect of zonal pricing on market liquidity. In particular, we are interested in how the Swedish bidding area reform in 2011 affected the liquidity of the Nordic intraday market. Thus, in the following section we introduce the concept of market liquidity and discuss its role as an indicator of the efficiency of electricity markets.

2.3. *The Importance of Liquidity*

Liquidity in general is a concept that is used for a variety of economic aspects reaching from describing money markets, to discussing the state of a business to assessing the efficiency of financial markets (Barnes, 2007). With regard to its many areas of application, the observation that there "[...] is no single, unambiguous, or universally accepted definition of liquidity" (Baker and Center, 1996) seems reasonable. On financial markets, there are multiple definitions of liquidity. Foucault et al. (2013) define liquidity as "the degree to which an order can be executed within a short time frame at a price close to the security's consensus value". This definition focuses on how convenient in terms of speed and cost it is to trade a good on the market. Similarly, Frontier Economics and Consentec (2013) define liquidity on electricity markets as the ability of market players to always find parties to trade with, as well as the inability of single trades to affect the price. A similar definition is used in a variety of papers related to this thesis.

Commonly used liquidity indicators are tightness, immediacy, depth, breadth, and resilience. A market is said to be *tight* if it has low transaction costs as measured by a small bid-ask-spread. *Immediacy* refers to the speed of the settlement process, measuring how quickly the sale of a product can be finalized. *Market depth* is observed with a large amount of trades taking place, while *market breadth* describes the size of these orders. The last characteristic is *resilience*, which means that a product with a price that deviates from its efficient value due to an order imbalance quickly converges back to its efficient level (Lybek and Sarr, 2002). In practice, the ENTSO-E suggests to look at similar indicators for the assessment of market liquidity such as market depth, trading volume, number of trades per day, churn rates or bid-ask spreads (Regional Group Baltic Sea, 2018). Given the data available for this paper, we will use the indicators of market depth, market breadth and resilience as is discussed in Section 6.

According to the ENTSO-E, the analysis of liquidity with relation to market splitting is especially relevant for the intraday and forward markets. In line with assumptions made in the literature by Trepper et al. (2015), the organization expects a decrease of intraday market liquidity as a result of market splitting based on a survey of member associations (ENTSO-E, 2018). This notion confirms the relevance of this thesis for current policy debates and subsequent decisions on the optimal market design on a European level.

3. The Swedish Electricity Market

A market that has undergone such a change is the Swedish electricity market. In this study, we add to the analysis of market liquidity on intraday markets by empirically assessing the Swedish bidding area reform in 2011. In the following section, we first introduce the

regulatory and economic environment in which the policy change took place. To begin with, we introduce the Swedish electricity market and thereafter focus on the different electricity markets that operate in the Nordics.

3.1. *Structure of the Nordic Electricity Sector*

The Swedish electricity market is mostly dominated by nuclear and hydro power plants. In 2016, the two generation types produced 80% of Swedish electricity. Meanwhile, wind power is only responsible for 10% of Swedish electricity generation but has increased from below 1% in 2007. The Swedish generation sector is fairly concentrated. The largest producer, Vattenfall, produces over 40% of electricity, and together the three largest producers generate nearly three quarters of Swedish power (Swedish Energy Markets Inspectorate, 2017). An overview of the development of the Swedish generation mix can be found in Figure 7 of the appendix.



Figure 3: Nordic Bidding Zones
Source: Swedish Energy Markets Inspectorate (2017) - modified

?? in the appendix shows the structure of the Swedish transmission networks. It can be observed that the grid is built to transfer the cheap hydropower electricity from the North to the more densly populated demand centers in the South, which is, in fact, the prevalent direction of electricity flows within Sweden (Figueiredo et al., 2016). As can be seen in Figure 3, the Swedish transmission grid is linked to its neighboring countries. In addition to being physically connected through transmission lines, the Nordic countries also operate

under the joint market framework of the *Nordpool* market.

The Nordpool electricity market was set up in 1993 as a power exchange for Norway and became the joint electricity market for Sweden and Norway in 1996. In the following years Finland and Denmark joined, creating an integrated Nordic market (Nordic Energy Regulators, 2010). Recently, Nordpool has been extended through the addition of the Baltic countries Estonia, Lithuania and Latvia. Today, Nordpool consists of 13 bidding zones because Sweden, Denmark and Norway are split into multiple bidding areas (Stavseth, 2013). The national bidding areas are operated by the respective national TSO (Nordic Energy Regulators, 2007). Additionally, Nordpool is linked to the German and British market, and via transmission lines to Poland and Russia (Regional Group Baltic Sea, 2018).

Before 2011, only Norway and Denmark were divided into several bidding zones to allow effective management of internal and cross-border congestion. Meanwhile, Sweden made up a single bidding zone delineated by its national borders. Under the existing Nordpool market framework, congestion is mitigated through the two mechanisms of market splitting and counter trading. First, the pricing algorithm on ELSPOT considers transmission constraints between the bidding zones. Thus, when those constraints are binding, the area prices on both ends of the bottleneck diverge. Second, counter trading means that the system operator pays for increasing production in the low production area and curtailing production on the other side of the point of congestion (Swedish Energy Markets Inspectorate, 2017). Hence, the price in each region reflects the underlying grid constraints between zones (Svenska Kraftnät financial information, 2013).

3.2. *Elspot, Elbas and Balancing: The Nordpool Markets*

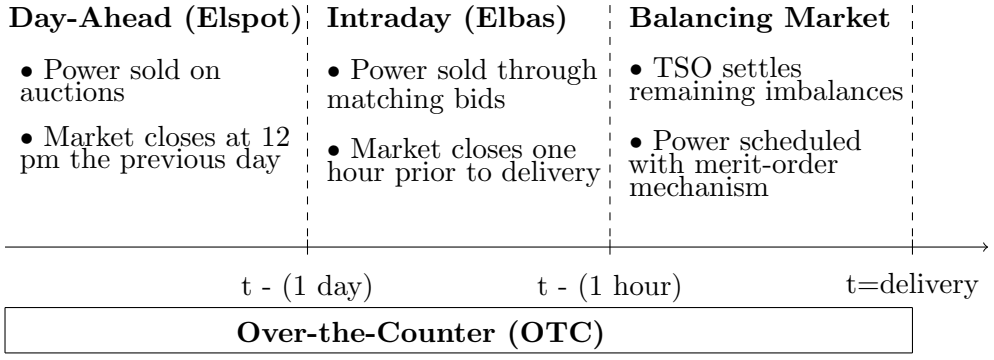


Figure 4: Overview of Nordpool Markets

The Nordpool market combines a physical and financial market for the trading of electricity. The financial market is accessed through commodity exchanges, which provide a range of financial contracts, e.g. future or area price contracts. All contracts on the financial market

are settled financially without physical delivery taking place. Instead, the contracts provide a hedging opportunity that complements the physical market. In 2016, 96% of the total Nordic production of electricity was traded on Nordpool (Swedish Energy Markets Inspectorate, 2017). The physical market Nordpool is structured along a time line as illustrated in Figure 4, and consists of a day-ahead market (Elspot), an intraday market (Elbas) and an additional balancing market for flexibility.

a. Selling Power One Day Ahead: Elspot

On the physical day-ahead market Elspot both buyers and sellers of electricity can place their bids for electricity each day before noon. The market operator then employs a merit order mechanism and allocates generation schedules to all producers that bid below the uniform price. There are two types of prices on Elspot. The *system price* is calculated by assuming unlimited transmission capacity throughout the entire market and serves as a reference point for the financial market. However, it is merely theoretical. The actual prices paid to producers are the *area prices*. These are calculated for each bidding zone separately by taking the transmission restrictions between areas into consideration, as well as the generation technologies and loads of each individual bidding area in Nordpool (Stavseth, 2013).

b. Trading Same Day Electricity: Elbas

In addition to the day-ahead market, Nordpool operates the intraday market Elbas. Elbas was originally created in 1999 as the joint intraday market for Sweden and Finland (Stavseth, 2013). On Elbas, power can be traded up to one hour before delivery at a known price. Market participants trade on Elbas because of a variety of reasons. First, it is used to reduce imbalance costs due to forecast errors. Second, it can be used for the optimization of production and consumption schedules if buying power on Elbas is cheaper than producing the scheduled electricity oneself. Finally, the intraday market is used to offer flexibility in consumption and production to other market participants in need of such flexibilities (Scharff and Amelin, 2016). Thereby, Elbas allows producers to optimize their delivery schedules and increase their revenue (Stavseth, 2013). In 2011, 105 actors were actively trading on Elbas. Those participants are generation companies, electricity retailers and large industrial companies (Mauritzen and Tangerås, 2014).

There is no uniform price on Elbas. Instead, the price is determined for each trade individually by matching buy and sell bids (Nordpool, 2018*c*). Its continuous trading stands in contrast to the auction-based trading on the day-ahead market Elspot. Trading on Elbas can thus be thought of as resembling the activities on a stock market (Mauritzen and Tangerås, 2014). However, contrary to the financial electricity markets, trades on Elbas

entail physical delivery and are not settled purely financially (NordREG, 2014). Similar to other intraday markets, ELBAS is expected to gain in importance as it is a way of providing flexibility to the electricity system. As the share of intermittent production capacity increases the market's need for flexibility is expected to rise (Per Klevnäs, 2016). This is because intraday markets enable intermittent power producers to balance sudden deviations from their previously assigned production schedules. These frequent deviations are typically caused by imperfect weather forecasts, which make dispatch from wind and solar power plants less reliable (Hagemann and Weber, 2013).

c. Clearing Your Imbalances: The Balancing Market

Furthermore, the Nordic electricity market consists of the balancing market. This market is used to ensure reliable electricity supply despite the existing imbalances. These imbalances are caused by generators or consumers when they deviate from the assigned generation or consumption schedules. If not settled, such imbalances could create grid disturbances such as congestion and ultimately lead to outages. The balancing market works as follows: After ELSPOT is cleared, market participants can submit bids to the TSO, indicating how much up- or down- regulating capacity they can offer to the balancing market and at which price. During the delivery hour, the TSO settles remaining imbalances that were not settled on the intraday market in real time, using the capacity provided by the balancing providers. It chooses which balancing providers will be up- or down-regulated according to a merit order mechanism. This determines different prices for up- and down-regulation. After the operating hour, the TSO calculates the differences between the capacity offered by the balancing provider and the capacity used by the TSO for balancing purposes, and then settles the differences. Participants on the balancing market are price takers because they will only know their price after delivery (Stavseth, 2013).

3.3. *The Swedish Bidding Area Reform in 2011*

In 2009 the European Commission started to investigate the Swedish system operator, Svenska Kraftnät, on antitrust charges. This was triggered by the Danish TSO, which complained that Svenska Kraftnät was exploiting the market power that resulted from its central geographic location. Svenska Kraftnät was accused of restricting export of electricity across its borders, with the goal to mitigate internal congestion and to maintain a Swedish uniform system price. This conduct was seen as discriminating European consumers in favor of Swedish citizens. To comply with the Commission's decision, Sweden offered to split its market into two or more bidding zones by 2011, in order to deal with congestion without unfairly limiting the export capacity of cross-border trades (Svenska Kraftnät financial information, 2013).

The key criterion for the new market design was to comply with European Union competition

rules as was ordered by the European Commission after investigating the case. On November 1^{st} of 2011, Svenska Kraftnät started the operation of four separate bidding zones instead of one uniform price zone. The borders of each bidding area were chosen to reflect the underlying transmission constraints, instead of the national border of Sweden. Figure 3 provides an overview of the Nordic bidding zones after the policy change. This delineation was successful in decreasing costs related to congestion. Already in 2012, Svenska Kraftnät reported a year-on-year decrease in capacity charges from 77 MSEK in 2011 to 26 MSEK in 2012. This reflects a lower cost in counter trading, the prevailing congestion management tool used in Sweden (Svenska Kraftnät financial information, 2013).

The bidding areas are structurally different in their power generation mix. While the northern bidding zones contain most of the country's hydroelectric facilities, the southern areas contain the nuclear and thermal facilities (Mauritzen and Tangerås, 2014). Similarly, all major populations centers are located in the two southern bidding areas. This results in demand being highest in those zones. In fact, between 2012 and 2015 demand in bidding zone SE2, which includes Stockholm, was 1.6 times the demand in all remaining areas (Figueiredo et al., 2016). In 2016, the bidding areas had a common price in 76% of the entire year with most price divergences created by congestion or production shortfalls in the southern bidding area SE4 (Swedish Energy Markets Inspectorate, 2017).

4. Related Literature

This thesis adds to three distinct fields of the economics literature on electricity markets: the efficiency of electricity market designs, the topic of liquidity in electricity markets, and the mechanisms of intraday markets. In the following paragraph we present the literature on each of the three topics. Additionally, we discuss how our study relates to the research that serves as the basis for developing our hypotheses in the following section.

4.1. *Efficiency of Electricity Market Designs*

First, this thesis contributes to the body of literature on the efficiency of zonal pricing. Most of the papers on this topic have a theoretical focus, and construct stylized models or employ large-scale simulation models of the electricity market in order to investigate the efficiency of existing or planned market designs. To this literature on the issue of electricity market design, the paper adds an empirical evaluation of a recent policy change.

There is a general consensus in the literature that nodal pricing leads to a welfare maximizing outcome. Green (2007) shows positive welfare effects through decreased market power in a nodal pricing simulation for the English and Welsh power systems. Others find these positive effects to be especially true when assuming an increasing amount of renewable energy sources

in the generation mix. For example, Neuhoff et al. (2013) simulate the introduction of LMPs for continental Europe under the scenario of an increasing feed-in of renewable energy. They find significant operation cost savings and more efficient use of grid capacity, especially in high wind scenarios. This confirms the findings of Leuthold et al. (2008) who show that nodal pricing in high-wind scenarios would lead to more system efficiency in Germany and Barth et al. (2009), who find inter-country cost savings in the case of more wind energy in a European energy system with nodal pricing.

By introducing multiple bidding zones, a country can move closer to this first best option. An investigation of these welfare effects of zonal pricing is provided by Grimm et al. (2016). The authors model an electricity market with three nodes in order to simulate different scenarios of moving from a single to multiple bidding zones. They can show that multiple price zones lead to inefficient investment decisions if there are binding transmission constraints within zones. However, they also find that it is welfare enhancing to have multiple bidding zones if their borders coincide with network constraints. Thereby, their findings highlight the importance of a thoughtful policy implementation for welfare maximization.

This finding is backed by the earlier work of Bjørndal and Jørnsten (2001) who show that the task of designing an optimal zonal market is difficult due to the trade-off between market efficiency and physical feasibility. Meanwhile, Holmberg et al. (2015) employ a game theoretical approach to show that it is difficult to find support for a zonal pricing approach. They find the same welfare outcomes for zonal and nodal pricing in a competitive market with many producers, yet higher payoffs for producers in a zonal regime. Additionally, they show that the higher liquidity under zonal pricing incentivizes producers to bid their marginal costs. Hence, this paper also underscores the importance of liquidity for the efficiency of electricity markets.

Employing a large-scale simulation model for the German market, Trepper et al. (2015) show that market splitting decreases congestion related costs. If bidding zones get too small however, illiquidity and inefficiency of markets will ensue, which again highlights the important task of policy makers. Similarly, Egerer et al. (2016) find that dividing Germany into two bidding zones is beneficial with regard to congestion related costs. They further argue that multiple bidding zones would induce efficient investment in transmission capacity expansion. Bjørndal et al. (2014) conduct a similar study for the Nordics. They simulate the entire market to investigate the effects of introducing a nodal pricing approach and find positive effects of additional price zones for the TSO, which could handle capacity limitations more easily and in a more transparent way.

The specific issue of the Swedish bidding zone reconfiguration has received limited academic attention so far, with only a few papers that empirically analyze the efficiency of the post-reform market design. Figueiredo et al. (2016) construct an index that captures the price

convergence between the Swedish bidding areas, providing an assessment of the efficiency of the current bidding area configuration. They show the prices regularly converge, indicating an appropriate design of the zones. On the issue of market power as an indicator for efficiency in Nordpool, Lundin and Tangerås (2017) use a Cournot model of competition to analyze the behavior of Nordpool market participants. They find evidence for market power in Sweden with a 7 to 12% mark-up on marginal cost. The authors then investigate whether the Swedish market splitting led to increased market power in the entire Nordpool market. They find some support for the hypothesis that the reform led to anti-competitive behavior. Similarly, Mauritzen and Tangerås (2014) look at market power on the intraday and the day-ahead market in Nordpool by using price developments as a proxy. They find that both ELBAS and ELSPOT did not show consistently competitive prices during the observation period.

4.2. *Liquidity in Electricity Markets*

Prior to the liberalization of power markets, liquidity on these markets did not receive much academic attention. However, in recent years the body of literature on liquidity in electricity markets has grown, as liquidity is essential for the efficiency of a liberalized electricity market. Low liquidity can lead to welfare losses due to increased transaction costs and inefficient investment decisions due to less reliable market price forecasts (Frontier Economics and Consentec, 2013). This view is shared by the European Commission which lists market liquidity as one of the elements of market efficiency (European Commission, 2015). Moreover, the ENTSO-E highlights liquidity as an important factor of market efficiency because liquid markets show reduced transaction costs, risk premiums and induce efficient investment decisions. Additionally, they argue that a liquid market is more attractive to other traders and thereby leads to a self-enforcing mechanism of increasing liquidity (ENTSO-E, 2018).

Similarly, Freire et al. (2012) argue that illiquid markets are connected to market failures such as price spikes and information asymmetry. Using descriptive statistics to assess the liquidity of the Brazilian electricity market, the authors show that illiquidity is characterized by insufficiently many active participants, low available trade volumes and high transaction costs. As this thesis focuses on intraday market, it relates to Neuhoff et al. (2013) who investigate the effects of different market systems on intraday market's performance and liquidity. Specifically, the authors look at how the introduction of auction-based rather than continuous trading affected the German intraday market, based on an investigation of the intraday market mechanism and descriptive statistics. With regard to liquidity, the authors find that both market depth and trade volume would increase steeply after the implementation of auctions.

For the drivers of liquidity on intraday markets, Hagemann and Weber (2013) provide, to our knowledge, the most granular analysis. The researchers analyze the German intraday

electricity market to find its drivers of liquidity. They develop and present two alternative models explaining liquidity on intraday markets: the trading model and the fundamental model of liquidity. In their assessment of which model explains liquidity best for Germany, they test a set of opposing hypotheses using time series trading data from two years. They find that the trading model of intraday liquidity best describes the German market. According to this explanation, the electricity market is imperfectly competitive on the generation side. While all market participants on the intraday market try to maximize profits, they face transaction costs and imperfect information. Furthermore, participants are either patient or impatient. The patient traders can offer their flexible capacities to the market above marginal costs due to imperfect competition in generation. Meanwhile, the impatient traders are those with imbalances to settle, e.g. due to forecast errors. They have to settle them eventually, but can choose the time of trade that maximizes their profits. Thus, there is a strategic element behind providing liquidity to the intraday market, which highly depends on the incentives faced by all traders. In Section 5.1 we will rely on this model to describe the mechanisms of the Swedish intraday market.

4.3. *Intraday Markets for Electricity*

Finally, our paper adds to the growing body of empirical literature that analyzes intraday electricity markets. In this, it relates to Hagemann and Weber (2015), who investigate the impact of competitiveness on the liquidity on electricity intraday markets in Europe. By simulating the Danish market, they find that a higher market concentration leads to less trading by small firms on the intraday market. This can be seen as evidence that smaller markets with higher market concentration entail less liquidity.

In another study on drivers of intraday market trading, Kiesel and Paraschiv (2017) use a time series model to explain the price differences between the German day-ahead and intraday market. They show that the amount of total demand covered by the day-ahead market can act as a signal for liquidity on the intraday market. This is because any deviation from the covered demand has to be balanced on the intraday or balancing markets. Moreover, this deviation, together with the production forecast errors for intermittent energy sources, has a significant effect on the price difference between the intraday and the day-ahead market. The most detailed analysis of trading behavior on the Nordic intraday market Elbas is provided by Scharff and Amelin (2016). Using bid-level data, they analyze how intraday trading behavior affects profitability. They show that bidding behavior differs heavily between bidding areas, and that there is a strong time dependency of trades, as most trades are executed shortly before gate closure. The authors briefly discuss market liquidity and show that the trade volume depends on the amount of intermittent generation, the transmission capacity between the countries and the prices on the balancing market.

The economic mechanisms of the Nordic balancing market and especially its relationship to the intraday market have so far only received limited attention in the literature. To our knowledge, Ilieva and Bolkesjø (2014) provide the only empirical study on its dynamics. The authors estimate the effect of spot market prices and regulating volume on the balancing price for each Nordic bidding area. Using time series data, they find that the down-regulating price is more sensitive to changes in spot market prices and volumes than the up-regulating price. To better understand the relationship between the balancing and intraday markets from a theoretical standpoint, Skajaa et al. (2015) study the decision of a wind producer to participate on Elbas. By modeling a single agent's decision they find that wind farms can increase their profits by trading excess energy on Elbas. However, this benefit is highly sensitive to the size of the wind farm due to diseconomies of scale. Similarly, Soysal et al. (2017) analyze price premiums for the Elbas market. The premium is the difference between the price on Elbas and the day-ahead price, which is used to analyze the optimal bidding strategy for a wind producer who only considers these two markets. They find that wind producers and consumers do not drive the prices on the intraday market. However, they argue that further research is needed to fully understand the mechanisms of the Nordic intraday market.

Another important strand of literature on intraday markets studies the strategic decision to trade on such a market. Mauritzen (2015) analyzes the strategic decision faced by a wind power producer in case of an imbalance. She can either settle this imbalance internally by reducing the production of another generation facility in the portfolio, she can trade on Elbas or she can settle her imbalance on the balancing market. Testing the effect of forecast errors on the probability of Danish wind producers to trade on Elbas, the author finds that negative forecast errors lead to a higher probability of intraday market trading, while surplus production reduces the probability of trading. The author argues that this can be explained by traders settling imbalances internally, the structure of the balancing market and badly designed subsidies.[3]

5. Mechanisms and Hypotheses

In the previous sections, we introduced the problem of congestion, discussed how zonal pricing can be a solution to it, and presented the theoretical and empirical evidence that exist on the topic. In the following section, we combine this evidence in order to develop testable hypotheses about the effect of the Swedish bidding area reform on Elbas' liquidity.

[3]Please note, that the finding of imperfectly designed subsidies does not apply to Sweden. This is because Sweden does not have a power purchase obligation for renewable energy sources, which is the subsidy that caused the disturbances in Denmark.

5.1. *Mechanisms*

Based on the literature, and especially the papers by Hagemann and Weber (2013), Mauritzen (2015) and Skajaa et al. (2015), the decision to trade on Elbas can be understood as a strategic decision for both impatient and patient traders. We define an impatient trader as a producer who has an imbalance due to generating more or less electricity than scheduled. For example, an impatient trader may be a wind producer who is able to produce more electricity because the wind is stronger than forecasted, or it may be an owner of a conventional power plant who faces an unscheduled outage of her plant. When an impatient trader faces an imbalance, she has three options. First, she can trade the imbalance on the intraday market at a known price. Second, she can defer the trade to the balancing market, in which case the TSO takes over and settles the imbalance at a previously unknown price.[4] Additionally, traders with multiple generation units have the option to settle imbalances internally by altering generation in another facility.

Meanwhile, the patient traders on Elbas consist of power plants that can provide the demanded flexibility by either reducing or ramping up their production, i.e. hydro power and combined heat and power plants. Patient traders only offer to increase their generation if the price they receive is higher than their marginal costs of generation consisting of fuel, capital and potential start-up costs.[5] Likewise, the generators only offer to reduce their scheduled generation if the price they are paid on the intraday market exceeds the price they would be paid for generating electricity. Thus, both types of players only trade on the intraday market if their expected payoff from trading on Elbas is higher than the payoff of their alternatives.

The reorganization of the Swedish market into four bidding areas may affect Elbas' liquidity through its effect on this strategic interaction. Mauritzen (2015) describes the payoff of trading on Elbas' as the received price minus transaction costs. Thus, holding all alternatives constant, the bidding area reform may change the attractiveness of trading on Elbas by changing either of these factors. Specifically, it could impact the decision through its effect on uncertainty, transaction costs and strategic behavior that in turn affected the decision to trade or not to trade on Elbas.

First, the reform led to higher uncertainty for market participants. Prior to the reform, intraday market participants did not have to consider intra-Swedish congestion when trading on Elbas. After the reform, trades between the bidding zones might not be possible at all

[4]The price on the balancing market is uncertain not only because it is determined after the trader has made her decision to settle imbalances there. It also depends on whether or not the system as a whole has a positive or negative imbalance. Depending on this the day ahead, up- or down-regulating price is applied (Mauritzen, 2015).

[5]See The Division of Energy Market Oversight (2017) for a discussion of the generation costs of different generation types.

times due to congested transmission lines. Thus, impatient traders might become more risk averse and reduce their trading as they cannot be sure to find a trading partner on Elbas. As a consequence, this would lead to a lower expected payoff from trading on Elbas, and it might become more attractive for traders to settle their imbalances on the balancing market instead. The lower number of trading partners further decreases the expected payoff by increasing the transaction costs, because the search cost of finding a trading partner increases.

Second, the uncertainty and the decreasing number of possible trading partners due to congested transmission lines increases the risk of strategic behavior. As Mauritzen and Tangerås (2014) point out, Elbas was not a perfectly competitive market during the period investigated in this paper. Thus, large market players could try to increase their profits by strategically withholding capacities, thereby decreasing liquidity. This problem is exacerbated as more than 70% of Swedish electricity generation stems from three companies (Swedish Energy Markets Inspectorate, 2017).

Finally, all of the mentioned forces might reinforce each other in a self-reinforcing spiral of low liquidity, as described by Freire et al. (2012). If patient traders withdraw from the intraday market, the market becomes less attractive for impatient traders, and vice versa.

5.2. *Hypotheses*

Based on the above explanation of the mechanisms of impact, we develop three testable hypotheses in order to evaluate the effect of market splitting on intraday market liquidity. The Swedish reform in 2011 was a major policy change and has been successful in reducing congestion in the electricity system. Thereby, it set the stage for the further introduction of intermittent electricity into the generation mix. However, as long as forecasts remain imperfect and storage availability remains limited, intermittent producers depend on the intraday market to settle their imbalances.

As other countries look to expand their renewable and intermittent energy production, it becomes important to understand the effect of market splitting on the intraday market for electricity. Hence, we ask the question: Is there a trade-off between an effective congestion management and an efficient intraday market? In order to answer this question we investigate the following overarching hypothesis:

The Swedish reform in 2011 led to a decrease in Elbas*' liquidity.*

As discussed in Section 2.3, liquidity is a multidimensional concept that cannot be measured by a single indicator. Thus, it is crucial for an analysis of market liquidity to consider multiple indicators of liquidity. Due to the availability and structure of our data, we are able to test for three of the five dimensions of liquidity supported by most researchers. Hence,

we divide our overarching hypothesis into three separate null hypotheses with respective alternative hypotheses, for each dimension of liquidity. First, we are going to investigate the effect of the Swedish market splitting reform on *market breadth*, which can be captured by trade volume. Here, we hypothesize:

*H*1*: The Swedish reform in 2011 led to a decrease in* Elbas*' market breadth.*

In addition, we examine the effect of the Swedish market splitting on *market depth* which we measure by the number of trades per hour ("frequency"):

*H*2*: The Swedish reform in 2011 led to a decrease in* Elbas*' market depth.*

Finally, we look at the dimension of *resilience*, which we can measure with the hourly price variance:

*H*3*: The Swedish reform in 2011 led to a decrease in* Elbas*' resilience.*

Based on the assessment of these three separate hypotheses we are able to assess the overarching question of whether the bidding area reform had a negative effect on Elbas' liquidity.

6. Data

The empirical strategy in this paper is based on a fixed effects analysis as is explained in Section 8.1. The dataset we construct is of longitudinal form and contains observations on the distinct geographical areas of both the region where the policy change took place (Sweden) and a control group (Finland). Our dependent variables are the liquidity measures *Trade Volume*, *Frequency* and *Variance*, which we construct from raw trading data. A full overview of the structure of our dataset can be found in Table 4 of the appendix. For example, our dependent variable *Trade Volume* has the following specification:

$$\text{Tradevolume}_{it} \forall\ i \in \{\text{Sweden}, \text{Finland}\},\ t = \text{trading hour}$$

We use data from the Elbas intraday market to build the dataset for our analysis. The data is collected from three main sources. We collect most of the information from the Nordpool server database. This includes information such as forecast errors, trading data, price data and data on the quantity of electricity that is transmitted between the zones. The unit of observation for which the data is collected are the bidding zones within the Nordpool area [6].

However, the Nordpool server does not provide all necessary information to conduct our analysis. Most importantly, the database does not offer data on the production of different

[6] An overview of the dataset can be found at https://www.nordpoolgroup.com/globalassets/download-center/power-data-services/outline-nord-pool-ftp-server.pdf.

generation technologies for the observation period. Thus, hourly production data for every generation type is collected for each country separately from the Swedish TSO Svenska Kraftnät and the Finnish advocacy group Finnish Energy. An overview of the data sources is listed in Table 5 of the appendix.

We are interested in the effect of a change in regulation on the liquidity of the Swedish intraday electricity market. As previously discussed, liquidity is a multidimensional concept and can be measured by a variety of proxies. In our analysis we focus on three of them: trade volume, the number of trades and variance. We choose these measures over others such as tightness or immediacy, because these alternatives are not directly observable from the data. Similarly, the commonly used bid-ask-spread cannot be calculated directly from the trading data and its estimation via a so-called "tick test algorithm" is associated with significant drawbacks. In fact, the estimation of the bid-ask-spread from trading data has an error margin of up to 47.6% when classifying a trade as buy or sell. Furthermore, the test systematically underestimates the bid-ask-spread (Hagemann and Weber, 2013). Hence, we construct our analysis around the assumption that high volumes and frequencies of trade are proxies for the breadth and depth of the market, while volatility can be seen as a measure for resilience.

The Nordpool server provides the raw data of all trades that took place on Elbas since December 2009. For every trade the price, the volume traded, a time stamp and the zones between which the trade took place are indicated. Finally, the year, date and hour of delivery are specified for each observation. From this raw data we construct the liquidity measures for each trading hour and country separately. First, we classify each trade as belonging to Sweden, Finland or neither country based on the location of the trading parties. Second, we calculate the liquidity measures for each country and hour within our observation period. Third, we create a new dataset containing the liquidity measures and an identifier assigning each value to an hour and a country.

Additionally, we construct a dataset with our control variables. The variables *Forecast Error: Production* and *Forecast Error: Consumption* are measured in MWh. They are constructed from the data available on the server by calculating the absolute difference of actual and predicted values for each hour. We are interested in the absolute values as both negative and positive differences require producers and consumers to adjust their imbalances, and hence it is the magnitude of the error that has an effect on liquidity. The *Up-Regulation Price* and *Down-Regulation Price* of the balancing market are measured in EUR. A producer receives the up-regulation price for producing more than scheduled to help balance the system. Producers receive the down-regulating price for supplying less in order to mitigate a break-down of the system. Using these variables, we calculate the difference between balancing and Elbas market prices, by first calculating the average price for each hour on Elbas and then subtracting it from the corresponding balancing market price. This

yields the variable *Price Difference: Up-Regulation* and *Price Difference: Down-Regulation* which are likewise measured in EUR. The variables *Nuclear Generation*, *Wind Generation* and *Hydro Generation* are measured in MWh. After November 2011, we aggregate the information of the different Swedish bidding zones.

For both Sweden and Finland, we match our constructed liquidity measures with the relevant control variables, by using the previously constructed identifiers that mark every trading hour. Thereby, we construct a novel panel dataset describing how the trading activity on Elbas changed over time in Finland and Sweden. Next, we create dummy variables which provide time-related information for each observation: weekdays (*Weekend)* and peak hours (*Off-Peak 1 and 2* or *Peak*). We define the off-peak and peak periods according to the categories used by Nordpool. Thus, the time between 8am and 8pm is defined as peak, while the morning hours between midnight and 8am are Off-Peak 1 and the evening hours from 8pm to midnight are defined as Off-Peak 2. Finally, we create a discrete *Time* variable indicating in which hour each observation occurred.

The data is of hourly frequency, as trades on Elbas are reported on an hourly basis. The policy change that we are interested in took place in November 2011. Therefore, we look at data from January 2010 until the end of August 2013. This represents exactly 22 months before and after the policy change, which is the longest time frame that trading data is available prior to the policy change. However, data for the control variables balancing prices and forecast errors are only available from July 2010 onward. Thus, when these variables are included in the baseline regression we only consider the observations between July 2010 and August 2013. There are some data points missing from the Nordpool server on forecast errors, yet the omissions do not seem to be systematic.[7] Thus, we conclude that the missing data must be due to reporting errors and drop the observations for those hours from the sample. This results in a dataset with 27,659 observations per country, or 55,318 observations in total, for our baseline regression.

7. Descriptive Statistics

In our empirical analysis we are interested in the Swedish intraday market between January 2010 and August 2013. The respective summary statistics can be found in Table 1. Looking at the trading activity on Elbas in this period, we see that most trading took place in Sweden, followed by Finland and Germany. Apart from the multitude of other factors that could explain this ranking, one should note that Sweden and Finland were the original member countries when Elbas was created. Norway for example only joined in 2009, while Belgium and the Netherlands joined in 2011 (Nordpool, 2018*b*). We also observe that both

[7]Consumption forecast data is omitted for Swedish zones SE1 and SE2 on November 2^nd, 2011. For Finland, there is no forecasted consumption for February 26th 2010, May 18th 2010, May 29th 2010.

the average quantity and price per trade differ drastically between countries. However, the standard errors of both variables are very high for all countries, indicating that there is no statistically significant difference between them.

Table 1: Summary Statistics per Country

Elbas Countries	Number of Trades	Mean Quantity	Std. Dev. Quantity	Mean Price	Std. Dev. Price
Sweden	841,172	17.01	19.97	44.57	22.26
Finland	661,092	13.36	13.35	49.9	32.92
Germany	451,018	23.16	22.01	45.7	16.63
Denmark	287,556	18.75	25.96	37.01	12.03
Norway	86,128	22.24	32.86	40.7	18.07
Belgium	64,056	47.76	63.96	51.71	20.86
Netherlands	61,400	46.57	65.17	53.57	19.50
Estonia	44,347	14.832	12.94	46.15	14.28

As we investigate the effect of the policy change in Sweden on November 1^{st} 2011 we want to understand how the intraday market changed after this date. Table 2 shows that the average quantity per trade decreased in every country between the periods 2010 to 2011 and 2012 to 2013.

Table 2: Descriptive Statistics Before and After the Reform

Elbas Countries	Mean Quantity Before	Mean Quantity After	Mean Trade Vol. Before	Mean Trade Vol. After
Sweden	17.38	16.75	381.41	521.18
Finland	14.32	12.41	303.49	258.97
Germany	24.59	21.95	1022.76	1035.51
Denmark	17.22	18.76	513.57	515.89
Norway	27.15	19.81	331.50	270.11
Belgium	62.37	45.42	428.58	557.91
Netherlands	87.21	43.1	455.88	509.57
Estonia	15.06	14.8	218.01	263.62

The only exception to this trend is Denmark, which saw an increase in number of trades between the two periods. However, the average trade volume per hour increased in most countries during the same time, suggesting that there is an overall increase in number of trades per hour. Meanwhile, both the mean quantity per trade and the trade volume

decreased for Norway and Finland. Due to our special interest in Finland and Sweden, we notice that Finland saw a decrease in trade volume after the policy change while the mean trade volume per hour increased in Sweden over the same time period. However, this does not mean that the policy increased the liquidity of the intraday market. Instead, there is a variety of outside factors which could explain the increase in trading activity on ELBAS in Sweden, e.g. an increased amount of intermittent generation due to the increased construction of wind parks.

In this thesis, we focus on the Swedish and Finnish part of the ELBAS.[8] Thus, the remainder of this section investigates how liquidity developed in these countries over time. In the tables in Table 6 and Table 7 in the appendix it becomes apparent that the overall trend between January 2010 and August 2013 has been the same between the two countries. There was a drop in all three liquidity measures in 2011, which was followed by a steady increase over the following two years. Sweden's trade volume and frequency recovered more quickly than Finland's, where price variance approaches its pre-2011 level more slowly. The Swedish regulatory institution Energimarknadsinspektionen mentions that trading activity in the ELSPOT market decreased in 2011 due to lower consumption levels in the Nordics (Swedish Energy Markets Inspectorate, 2012). To our knowledge, the 2011 drop in liquidity on ELBAS is not explained in the existing literature or government reports published during that time. Hence, we cannot control for this drop and other unknown factors directly, but will instead employ a fixed effects regression, as presented in Section 8.1.

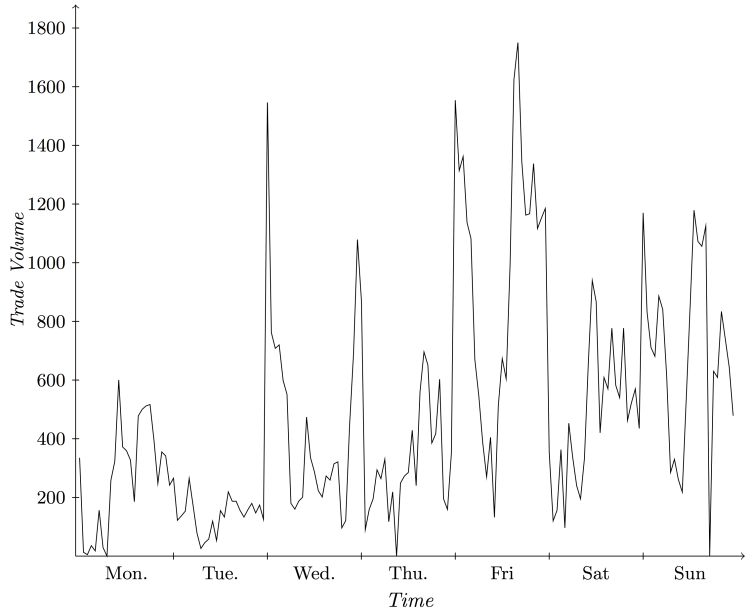


Figure 5: Trade Volume of a Representative Week

In order to better understand the drop in trading activity, we plot the monthly averages of

[8]The rationale on why we use the Finnish market as a counterfactual can be found in Section 8.2.

trade volume per hour for Sweden and Finland in Figure 6. There is a negative trend in trading activity starting in mid-2010, which persists until the end of 2011 and is a trend shared by both countries. The drop seems to be especially steep prior to the policy change in late 2011. However, after the Swedish policy change trade volume in Finland recovers more slowly than in Sweden. Again, we cannot infer from the graph whether or not this is caused by a policy change or, for example, by a change in intermittent generation.

We look at the development of trading volume over the course of a trading week in order to get an impression of the importance of time on the intraday market. We plot the trading for each hour of a random week in the beginning of October 2011 in Figure 5. From this we can infer that there is an uptick in trading activity towards the end of the working week, while less is traded on the weekend as well as in the beginning of the week.

Finally, we examine a trading day more closely. The related descriptive statistics can be found in Table 8 of the appendix. From this, we can infer that the number of trades and the trading volume is much lower during the off-peak 1 period than during peak times. The highest trade volume and number of trades, on average, happen during the last four hours of the day, during off-peak 2. However, price variance is highest during the early hours of the day, lowest during peak hours, and increases slightly in off-peak 2.

8. Estimation Strategy

In this paper we employ a fixed effects model to assess a policy change on the Swedish intraday market for electricity. In the following section, we present the estimation strategy and discuss the main assumptions that need to hold for our regressions to produce valid results. We base our approach on the work of Wooldridge (2013, p. 447–499) and Angrist and Pischke (2008, p. 221–246, 308–323). Second, we argue why Finland is a suitable counterfactual for the implementation of a fixed effect approach. Finally, we discuss our choice of control variables with regard to the existing literature.

8.1. *Fixed Effects Estimation*

As discussed above, in order to evaluate a change in regulation policy, we build a dataset which we use to exploit the differences between a control and a treatment group. We prefer this approach to a time series approach with the past time trend as a counterfactual, because the descriptive statistics indicate a sizable decrease in trading volume in 2010 and 2011. This decrease is, to our knowledge, not explained in the existing academix literature or government reports. Thus, if we were to use a time series approach, this decrease would be included in our counterfactual trend line and hence bias our results. However, by using a fixed effects estimation strategy we can exploit that we observe a similar time trend in

Finland, a country not affected by the policy change. Using a fixed effects model instead of relying exclusively on Sweden's historical data allows us to disentangle the effect of the policy change from other trends more clearly.

8.1.1. Econometric Approach

We employ a fixed effects model with both time and entity fixed effects. First, we assume that unobserved entity specific effects exist and capture those via country fixed effects. These effects are assumed to be fixed over time but to vary between countries and to have an effect on liquidity of the intraday market. An example for such an effect could be lower energy efficiency of buildings in one country, which leads to systematically higher power consumption over the entire observation period.

Second, we employ month fixed effects. With these we want to capture macro trends which vary over time but affect both observational units alike. We choose a monthly frequency to capture the overall change of liquidity between different months. Alternatives, such as daily or weekly fixed effects would capture the same trends but add substantial computational complexity to our regression model.

Third, we believe there is a variety of factors that affect liquidity differently both over time and between the countries. We include these variables in our estimation in order to control for their influence on liquidity. The choice of relevant control variables is discussed in Section 8.3.

Our analysis is based on the assumption that the policy change had no influence on the control group. Thus, the liquidity in the control group is described by country specific effects, time fixed effects and the vector of control variables. This assumption allows us to understand the effect of the policy change on Sweden's intraday market liquidity as the difference between Swedish and Finnish liquidity. If there had not been a policy change, the expected liquidity would have been determined by the same factors as in Finland. After the policy change though, Swedish liquidity is further explained by the effect of the reform on both level and trend of liquidity. We capture this effect in the coefficient ρ, which we estimate in two components following the argument presented by Angrist and Pischke (2008). In this, ρ_1 captures the immediate effect in the dummy variable *Policy* after the policy on the level of liquidity. Meanwhile, $I(t) = Policy * t$ is the *Interaction* term between the dummy variable and the time variable. Thus, the coefficient of the *Interaction* term ρ_2 measures the effect of the policy on the trend of liquidity on the Swedish part of Elbas.

8.1.2. General Specification

In summary, this yields the following specification of our estimation strategy:

$$Liquidity_{it} = \alpha_i + \lambda_t + \rho_1 Policy_{it} + \rho_2 * Policy_{it} * t + \mathbf{X_{it}}\boldsymbol{\gamma} + u_{it}, t = 1, ..., T \quad (1)$$

where α_i is the unit fixed effect, capturing unobserved time-invariant characteristics that differ between Sweden and Finland. The time fixed effect λ_t captures macro trends which vary over time, but not between units. The policy change dummy $Policy_{it}$ equals 1 when i = Sweden and $t >$ November $1^s t$, 2011, and 0 in any other instance. The estimator of $Policy_{it}$, written as ρ_1, captures the immediate break in level of Swedish market liquidity due to the change in regulation. As we expect the effect of the policy to also induce a change in trend for Swedish market liquidity, we are also interested in the coefficient of the *Interaction* term $T * Policy_{it}$, denoted by ρ_2, which captures this time trend. The variable $\mathbf{X_{it}}$ contains a matrix of controls which are based on our literature review. This control variable matrix includes a variety of factors influencing liquidity in both countries. The choice of control variables is explained in Section 8.3.

8.1.3. Important Assumptions

In the subsequent section we discuss the different assumptions that have to hold for the fixed effects regression to produce valid results. In addition, we present how we plan to mitigate the risk that the assumptions do not strictly hold.

a. Exogeneity

For both of our estimators ρ_1 and ρ_2 to be unbiased, the assumption of strict exogeneity has to hold. This means that the decision to implement the policy change was not influenced by liquidity. In our case this implies that $Cov(\rho_{it}|u_{it}) = 0$ where u_{it} is the idiosyncratic error of the composite error term $v_{it} = \alpha_i + u_{it}$. For the covariance to be zero, it demands that the policy decision was not influenced by quantity, price or anything else that influences trading volume, number of trades or price variance on ELBAS before or after the policy change. We argue that this assumption holds because the decision to split Sweden into multiple bidding areas was not related to liquidity on the intraday market. Instead, it was caused by a court case related to anti-competitive behavior from the Swedish TSO. Thus, we assume that the exogeneity assumption holds and that a fixed effects estimation approach yields a consistent estimate of the policy reform's effect.

b. Immediate Effect

In order to produce valid results for the estimator ρ_1, it has to hold that the break in level occurred immediately. In other words, we assume that the policy change had an immediate

effect on the outcome variables. According to the existing literature and the channels of influence presented in Section 5 this is the case: Immediately after the borders of the Swedish market area changed on November 1^st, 2011, traders had to take transmission constraints within Sweden and between zones into account, which they did not have to do under the previous "copper plate" market regime. Hence, the adjustment immediately changed the market environment which is the effect we capture in our dummy for market splitting. This is a strong assumption, which is why we include the *Interaction* variable to detect not just the break in level, but also the break in trend as measured by ρ_2.

c. Autorcorrelation and Heteroskedasticity

We need to ensure that our coefficients are best linear unbiased estimators and efficient so that our regression produces economically and statistically significant results. For this to hold, the error terms of our regressions must fulfill the condition $V(u_i|X_i) = \sigma^2$. In other words, the variance of the unobserved error term has to be constant. In order to test for this, we conduct the Breusch-Pagan test for heteroskedasticity. The test results strongly reject the null hypothesis of constant variance in the error term at the 1%-level. Hence, we need to correct for heteroskedasticity in our analysis.

Furthermore, for unbiased estimates, the assumption of no autocorrelation in the error term has to hold. This means that the condition $Cov(u_{it}, u_{i\tau}) = 0$ needs to be true for all $t \neq \tau$. If this is not the case our dependent variable is correlated over time, our error terms are biased and the estimators are not efficient. Therefore, we test for serial correlation in the within-group error terms by conducting the Wooldridge test for autocorrelation. We find evidence for serial correlation in the error terms. For all liquidity indicators we reject the null hypothesis of no autocorrelation on the 5%-level. This could be explained by the fact that we work with trading data, where the volume, frequency and volatility of trades in one hour easily affect the same indicators in the next trading hour. The test statistics are presented in Section G.1 in the appendix.

In order to deal with the problem of inefficient estimators due to heteroscedasticity and serial correlation, we have to adjust our standard errors. As discussed in Bertrand et al. (2004), non-parametric solutions, such as adjustment of the variance-covariance matrix by clustering the error terms on the state-time level, performs best in large samples. This is further specified by Kézdi (2004), who shows that large samples with more than 50 clusters yield standard errors that allow for efficient estimators. In our case, we cluster the standard errors at the country-month level, resulting in 74 clusters. We use this method in all of our regressions to make sure that we have robust standard errors and efficient estimators.

d. Random vs. Fixed Effects

The model specified in Equation (1) could be used in both a fixed and a random effects model. We can test which model is appropriate by running the Hausman test on our panel dataset in order to test whether we should use random effects or fixed effects. The null hypothesis of the test is that the part of the error term that is unique to the units i in our dataset is not correlated with the regressors. If we cannot reject the null hypothesis we run a random effects model rather than a fixed effects one. We can reject the null hypothesis on the 1% level. Therefore, we specify our model as a fixed rather than a random effects model.

8.2. *Choice of Finland as Counterfactual*

In addition to the previously stated assumptions, our estimation strategy hinges on the existence of a control group that shows the same trend in liquidity as Sweden prior to the policy change. As seen in the descriptive statistics in Section 7, there is an upward trend in trading volume on the intraday market from 2011 onward in Sweden. Given the overall upward trend for all Elbas countries, we believe that we would have observed an upward trend in liquidity in the Swedish intraday market, irrespective of the policy change. With the help of a control group, we investigate if the trend was dampened or not affected at all by the market splitting regulation.

We survey all possible intraday markets that could serve as a control group to Sweden. Out of all options, Finland is the market that is most suited as a counterfactual for a variety of reasons. First, Finland is better suited than any non-Nordpool market as it operates under the same regulatory framework than the Swedish market. Second, as mentioned before, Sweden and Finland are the two countries that have the most trading activity on Elbas. Therefore, Finland is better suited than a country such as Estonia which saw very little trading activity during the entire observation period. Third, Finland did not have a change in its bidding area configuration during the observation period. This stands in contrast to, for example, Norway, which saw multiple adjustment to its bidding area delineation.

Furthermore, Finnish and Swedish generation units that want to trade on the intraday market can only do so on Elbas. In contrast, German producers can choose between trading on the Elbas and the German intraday market offered by EPEX Spot. Thus, when analyzing Sweden and Finland we can disregard the interaction between multiple market platforms. Finally, the two countries have a fairly similar generation mix. In 2011, Sweden's generation mix was dominated by hydropower, which amounted to 45% of total production. This was followed by nuclear power that generated 39% (Swedish Energy Agency, 2018). In contrast, Finland produced 32% of its energy from nuclear power while Finnish hydro power plants generated only 17% of electricity. However, they produced another 36% of their electricity

from CHP technology (Finish Energy, 2018). CHP and hydropower palnts have very similar characteristics for trading on the intraday market as both can vary their production at low costs.[9] With more than 80% of electricity being produced by nuclear, hydro and CHP in both countries, we can consider the generation mix to be sufficiently similar for our analysis. Yet, Sweden had a stronger increase in wind power production over the observation period than Finland. In fact, yearly wind power production doubled between 2010 and 2013. Thus, we have to control for this factor in our regressions.

In addition to these regulatory and structural similarities, our estimation strategy depends on the two countries showing the same time trend in absence of the policy change. In order to confirm this, we generate trendlines using local linear regressions. These result in a smoothed trendline that we can visually inspect. The results for the variable *Trade Volume* are plotted in Figure 6. It is clear that both countries moved in tandem before the policy change, while clearly diverging after the change. The same can be seen for the local linear regressions if we change both the bandwidth of our regressions and the relevant liquidity indicator. The corresponding plots can be found in Figure 8–Figure 10 of the appendix.

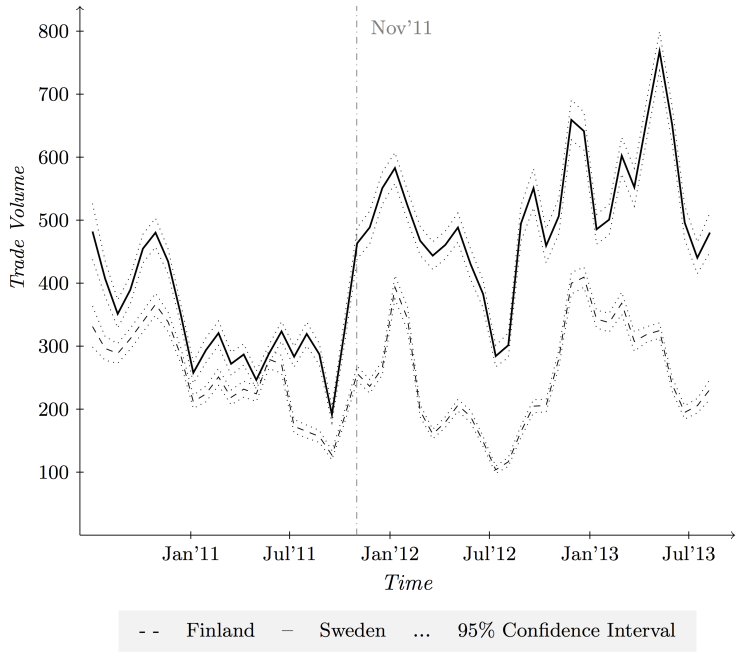


Figure 6: Trend of Tradevolume (1 Month Bandwidth)

Finally, we need to ensure that the control group was not affected by the policy change. This does in fact hold for Finland. The largest share of the Finnish intraday market activity consists of trades within Finland. These intra-zonal trades are not affected by the policy

[9]Hydropower plants can increase their production at costs close to zero by using water from their reservoirs. Similarly, they can defer production to a later period by redirecting the flow into their reservoirs. Meanwhile, many CHP plants schedule their production for heat rather than electricity production and can thus flexibly vary the production of their by-product electricity (Hagemann and Weber, 2013)

change. Meanwhile, cross-border trades might have been affected by the policy change. However, most cross-border trades between the two countries are conducted between Finland and the Swedish area SE3 (Scharff and Amelin, 2016). As can be seen in **??** in the appendix, the two areas are connected via a submarine cable. This means that the risk of congestion between the two areas existed both before and after the policy change. Thus, the behavior of agents should not have been affected by the reform as they already had to consider transmission constraints before the policy change. However, there remains the possibility that the change of Swedish trading behavior had an effect on the Finnish intraday markets' liquidity. This could lead to our estimators underestimating the effect of the policy change. Therefore, as part of our robustness checks we conduct a regression on a separate dataset that excludes all trades between Sweden and Finland.

8.3. *Choice of Control Variables*

While the choice of a fixed effects model with a suitable counterfactual is able to eliminate unobservable variation that affects both countries alike, we still need to control for factors that influence the liquidity of Sweden and Finland differently. Even though scientific evidence is scarce when it comes to understanding the drivers of intraday market liquidity, we can refer to our literature review (see Section 4), the strategic decision of trading on intraday markets (see Section 5) and our descriptive statistics (see Section 7) for reference towards which control variables we include in the analysis.

As shown in our descriptive statistics, trading on the intraday market varies over time in ways that are not controlled for by our monthly fixed effects. First, we control for the time of the day. This is because both electricity generation and trading vary throughout the day. On the one hand, electricity demand and supply are higher during the so-called peak hours. On the other hand, we would expect trading to be higher towards the end of the day, as forecasts of intermittent generation improve the closer we get to the delivery of electricity. Second, we control for the difference between weekdays and the weekend, as trading offices of the smaller market participants are probably unoccupied outside of the standard business hours (See Hagemann and Weber (2013)).

Forecast errors and intermittent generation have shown to be an important driver of intraday market trading as is shown by previous papers, e.g. Hagemann and Weber (2013), Mauritzen (2015) or Kiesel and Paraschiv (2017). For example, when the wind forecast was too high, wind farms will need to acquire the scheduled electricity short-notice on the intraday market. Thus, we control for forecast errors both in production and consumption. The forecast error in production controls for both the forecast error in intermittent generation and possible plant outages. Additionally, there might be a general effect of more wind production as wind producers are the key example of the impatient traders that we expect to drive liquidity on

the intraday market. This effect is measured by our *Wind Generation* variable. Given that both variables control for similar, but not the same effect we run our baseline regression twice - controlling either for *Forecast Error Production* or *Wind Generation*.

Additionally, we need to control for two remaining forces of the intraday market that vary in magnitude between Finland and Sweden: Balancing market prices and the generation of power plants that provide flexibility. An important aspect is the difference between balancing and intraday market prices as this influences the trader's strategic decision on whether to trade on the intraday market or not. This idea is discussed in Mauritzen (2015) and Scharff and Amelin (2016). Similar to the findings of Ilieva and Bolkesjø (2014), we only use the price difference between the down-regulation price on the balancing market and Elbas for our regression variable Δ *p* Elbas*/Bal.Market*. This further allows us to isolate more clearly the effect of a higher price on Elbas on a trader who has the choice to either create congestion or trade on the balancing market.

Hagemann and Weber (2013) use data on CHP generation sources as an explanatory variable, because they believe that these power sources can be used to offer electricity relatively flexibly on the intraday market. However, on the Swedish market hydropower and not CHP is providing such a flexible baseload generation. Thus, we use hydropower production as a control variable. Finally, we also control for the production by nuclear power plants. Nuclear power plants are very inflexible, so that a higher nuclear power generation should represent a reduction in flexibility.

9. Results

We run our baseline regression with entity, i.e. country, and time, i.e. month, fixed effects for all three liquidity indicators, each with two different control variable specifications. In the first specification we include production forecast errors, while in the second we substitute the variable with the wind generation measure. With this approach we separately test all three hypotheses stated in Section 5 to examine whether the Swedish market splitting led to a decrease in intraday market liquidity. The regression outputs can be found in Table 3.

For our first liquidity indicator, *Trade Volume*, we find a positive but insiginificant level effect, i.e. the coefficient of the variable *Policy*. However, there is a small but significant effect on the trend, as measured by the *Interaction* term between the policy and time: After the policy change there is an increase in trading volume of 4.75 MW per month. [10] Looking at the confidence intervals, we conclude that we can reject the null hypotheses of no effect of market splitting on the trend in tradevolume at a 99% confidence level. As the

[10] The regression indicates an increase of 0.006 MW per hour which translates into an increase of 4.75 MW in 30 days (720 hours).

direction of this highly significant effect is positive, we cannot confirm that Swedish market splitting led to a decrease in ELBAS' market breadth. In contrast, our regression analysis hints towards there being an increase in the trend of trade volume following the policy change.

For the second liquidity measure, *Frequency*, we find a large and positive break in level, which is significant at the 1%-level. This effect is equal to a 70% increase in trade frequency compared to the pre-reform mean in Sweden. Thus, we can again reject the null hypothesis and say that there has been a positive, instead of a negative policy effect on level at a 99% confidence level. Meanwhile, the sign of the *Interaction* term is negative but insignificant. Therefore, we cannot confirm that the policy change had a significantly negative effect on the market's liquidity. In fact, we observe a sharp increase in market depth in Sweden right after the market splitting was implemented.

Finally, the measures for a break in level and trend of our third liquidity indicator, *Variance*, are both insignificant. We can thus infer that there is no evidence for a decrease in intraday market resilience due to the 2011 policy change in Sweden. Therefore, we cannot confirm that the market splitting led to a decrease in the intraday market's resilience. We also note that the explanatory power of regressions (5) and (6) as measured by R^2 is substantially lower than of our other baseline regressions.

Overall, the baseline results do not offer support for the hypotheses formulated in Section 5.Our significant results strongly indicate that there was in fact a positive effect of the policy change on the trend in *Trade Volume* and level in *Frequency*. However, the effect cannot be shown for all liquidity indicators and is inconsistent across the different dimensions of liquidity. While regressions (1) and (2) indicate a trend of increasing liquidity after the policy change, the other baseline regressions do not show such an effect. The immediate, positive effect of market splitting on liquidity is only significant in regression (3) and (4). From our insignificant results however, we can only infer that we cannot reject the null hypothesis of no effect of the policy change on liquidity. Some indication of what this means for our interpretation can be derived from the standard deviations given by the results tables. For example, we can only reject the hypotheses of no direct effect on level of Trade Volume at a 76% confidence level. Thus, we cannot rule out that there has been a causal effect between market splitting and liquidity.

For the control variables, we find most of them are significant and show in the expected direction. However, we observe some deviations from our expectations. First, the *Forecast Error Consumption* and *Wind Generation* do not have a significant effect on liquidity in any specification. Second, the variable *Forecast Errors Generation* is only significant in our fist specification. In general, all other controls indicate a robust effect in the direction that we expect after examining the literature. A more detailed discussion of the baseline results and

controls can be found in Section 11.1.

Table 3: Baseline Regression with Time and Entity Fixed Effects

	(1)	(2)	(3)	(4)	(5)	(6)
	Trade Vol.	Trade Vol.	Frequency	Frequency	Variance	Variance
Policy	34.98	29.11	12.49***	12.20***	-11.37	-9.671
	(48.57)	(48.59)	(2.988)	(3.004)	(13.28)	(13.52)
Interaction	0.0066***	0.0066***	-0.0002	-0.0002	0.0009	0.0009
	(0.0022)	(0.0022)	(0.0001)	(0.0001)	(0.0006)	(0.0006)
Time	-0.0766	-0.0787	-0.0045	-0.0046	-0.0268*	-0.0265*
	(0.0740)	(0.0743)	(0.0043)	(0.0044)	(0.0154)	(0.0152)
Forecast Error Cons.	0.0056	0.0083	0.0004	0.0004	-0.0037	-0.0036
	(0.0068)	(0.0063)	(0.0003)	(0.0003)	(0.0036)	(0.0036)
Forecast Error Gen.	0.0361**		0.001		0.001	
	(0.0139)		(0.0007)		(0.0058)	
Wind Generation		0.0221		0.001		-0.0044
		(0.0181)		(0.0011)		(0.0051)
Hydro Generation	0.0082***	0.0086***	0.0004*	0.0004*	0.0067***	0.0066***
	(0.0025)	(0.0026)	(0.0002)	(0.0002)	(0.0023)	(0.0023)
Nuclear Generation	-0.0222*	-0.0237*	-0.0004	-0.0005	-0.0044	-0.0042
	(0.0115)	(0.0121)	(0.0006)	(0.0006)	(0.0037)	(0.0035)
Δp Elbas/Bal. Market	1.811***	1.835***	0.151***	0.152***	5.049***	5.050***
	(0.339)	(0.342)	(0.0130)	(0.0131)	(1.590)	(1.593)
Offpeak 1	-103.7***	-104.5***	-6.190***	-6.201***	-5.893*	-6.088*
	(11.15)	(10.70)	(0.544)	(0.522)	(3.133)	(3.110)
Offpeak 2	64.44***	63.80***	3.043***	3.025***	-12.97***	-12.99***
	(7.875)	(8.030)	(0.481)	(0.485)	(4.006)	(4.031)
Weekend	-20.66**	-20.86**	-1.170**	-1.169**	-3.764	-3.869
	(8.210)	(8.229)	(0.453)	(0.451)	(4.863)	(4.821)
Constant	836.8**	852.3**	42.61*	43.11*	241.5*	240.9*
	(383.2)	(386.7)	(22.16)	(22.30)	(120.5)	(121.3)
Observations	55,318	55,318	55,318	55,318	55,318	55,318
R^2	0.132	0.131	0.193	0.193	0.045	0.045
Country Fixed Effects	2	2	2	2	2	2
Time Fixed Effects	37	37	37	37	37	37
Robust Standard Errors	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

10. Robustness Checks

Our baseline results indicated that there was no negative effect of the policy reform on the liquidity of the intraday market. In contrast, the results hint at a positive effect of the market splitting on liquidity. In the following section we conduct a number of robustness checks to confirm the validity of our results.

When conducting robustness checks by altering the specification of our baseline regressions, we find that both the sign and significance level of our estimators of interest *Policy* and *Interaction* change. While some regressions again indicate a positive effect of market splitting on liquidity (see Section 10.1 and Section 10.3), other specifications indicate no or even opposite effects (see Section 10.2 or Section 10.4). Hence, we conclude that our analysis cannot provide robust and consistent evidence for a change in liquidity due to Swedish market splitting. Meanwhile, we do find confirming evidence for the underlying mechanism described in Section 5.1, as the relevant control variables keep their direction and remain significant in all specifications. This further validates our finding that there was no significant effect of the policy change on liquidity in Sweden, as the results are unlikely to be driven by a different mechanism behind Elbas.

In the following section we present the findings from our robustness checks in more detail. First, we exclude bilateral trades between Sweden and Finland. Second, we look at a more narrow time frame and only consider the six months before and after the policy change. Third, we reduce the granularity in the data by looking at liquidity on a daily instead of hourly level. Fourth, we use an alternative measure of resilience and substitute the price variance with a high-to-low measure of price fluctuations as suggested by the literature.

10.1. *No Bilateral Trades*

We want to ensure that the results are not biased by bilateral trades between the treatment and the control group. These bilateral trades amount to 27% of Swedish trades. For example, it could be the case that Finland's liquidity indicators are influenced by the policy change through bilateral trades, because the strategic decision of Finnish traders was altered by the lower attractiveness of trading with Sweden on Elbas. If this were the case, the coefficients of our baseline regression would underestimate the effect of the policy change. We thus create a new dataset that excludes all bilateral trades between the two countries and run our baseline regressions on this dataset. Overall, we can infer that bilateral trades between Finland and Sweden did only have a small effect on our estimates. The significant effects of market splitting on our liquidity indicators from the baseline regression stay the same with some minor changes in magnitude. Similarly, there are only a few changes in significance level for the control variables. These results indicate that using Finland as a control group is a valid choice.

As can be seen in Table 11 of the appendix, the coefficient for the break in level is again positive for both *Trade Volume* and *Frequency*, and again only significant for the *frequency* liquidity measure. As expected, the size of the effect is slightly larger than in the baseline regression. Apart from the size of the effects, the direction of the market splitting effect on variance changes to be positive, yet it remains insignificant. The coefficients of the *Interaction* term all point into the same direction as the baseline results, and indicate again a significant positive break in level for trade volume in the aftermath of the policy change. The control variables do not change direction, but we do see some change in significance level. The *Consumption Forecast Errors* for example are now significant at the 5%-level for both *Trade Volume* and *Frequency* in the second specification which includes wind generation.

10.2. *Reduced Time Frame*

In our baseline regression, we look at a relatively large time window. While we do account for more long-term factors with this approach, it could bear the risk of including more unobserved factors affecting our results. Hence, we focus on the six months before and after the policy change to see if we observe different effects. The results are depicted in Table 12 in the appendix.

We find that the effect on the level of liquidity becomes insignificant except for our volatility measure, which sees a positive significant break in level and a negative change in trend, This effect on the trend is only significant at the 10%-level though. For *Trade Volume* and *Frequency* however, the level effect stays positive but becomes insignificant. However, we now observe a significantly positive change in variance. We further note, that the standard errors on the coefficients of our *Policy* variable become very large in this specification. The change in trend is now insignificant for regression (1) through (4). The control variables however do again not change direction compared to the baseline results. In the shorter time frame *forecast errors of generation* become more significant and increase in size. Furthermore, the weekend dummy becomes insignificant, while the negative and significant effect of off-peak trading becomes smaller. Again, a higher price on Elbas compared to the balancing market increases *Trade Volume* and *Frequency*, while also inducing higher volatility on the intraday market.

In summary, the focus on a smaller time window captures more of the *Variance* in prices than changes in *Trade Volume* and *Frequency*. This could confirm our strategy to look at a larger time window, as it allows us to capture more of the long-term trends without the noise of short-term volatility. The observation is especially relevant for our purpose because we can see in the descriptive statistics in Table 12 of the appendix that liquidity during the year around the policy change showed large volatilities.

10.3. *Daily Data*

In our baseline results we use hourly data to capture the effect of the policy reform. Yet, hourly observations are of the highest possible frequency for the intraday market, which could lead to a lot of unexplained variation that distorts the results. Hence, we run the same set of regressions for the three liquidity indicators, but aggregate the data to the daily level. The results can be found in Table 13 of the appendix.

In general, the size of the effects increases, because we look at aggregated data which logically results in higher mean values. Most importantly, we see that the break in trend stays positive and is significant at the 5%-level for *Trade Volume*, while it remains insignificant for the frequency measure. The effect on the trend of *Variance* now becomes positive and slightly significant. Furthermore, the break in level for frequency is significant and positive, which is in line with the baseline results.

For the control variables, only the *Forecast Errors of Generation* change to be insignificant. Otherwise, the direction and significance levels largely stay the same. The negative effect of *Nuclear Generation* stays the same in size but becomes highly significant when looking at daily data. Also, the fit of our model gets better with a higher R^2 than in any other specification for all three liquidity indicators.

10.4. *Resilience*

In our baseline regression, we use price variance as the proxy for the liquidity measure of resilience. As explained in Section 2.3, resilience indicates the speed of convergence to its efficient value. Hence, a lower variance could indicate more liquidity in the market place. In our baseline regression we can see however that the fit of the model is relatively small with a R^2 of 0.045. Furthermore, throughout the robustness checks, the direction of the effect is the most inconsistent of all liquidity indicators. Thus, we want to exploit the fact that we have data for a similar measure of price variance, namely the high-to-low spread. We construct the variable by calculating the average difference between the maximum and the minimum price within one hour of trade. The higher the spread, the further away prices are from their efficient value, meaning that a higher high-to-low spread indicates less resilience. As can be seen in Table 14 in the appendix, the model has a much better fit for the high-to-low variable with a R^2 of 0.184 compared to a R^2 of 0.045 for variance. Furthermore, the break in level is significantly positive for the high-to-low spread, indicating an immediate decrease in liquidity according to this measure. The *Interaction* term also points in two different directions for both indicators.

Apart from this finding, the directions of all effects are the same, with similar significance

levels. The only difference can be found for the wind generation variable, which significantly reduces the high-to-low spread, even though the effect is very small: One MWh more wind production decreases the high-to-low spread by EUR 0.0015. This could hint at the fact that more wind generation increases liquidity on the intraday market.

11. Discussion

This paper examines the effect of the 2011 bidding area reform in Sweden on the liquidity of the Swedish intraday market Elbas. Thereby, we add to the discussion about the trade-off between reducing congestion costs and market efficiency, which is of interest to policy makers wanting to restructure a market's bidding areas. In Section 5 we identify uncertainty, higher transaction costs and strategic behavior as the main channels through which the Swedish market splitting could have had a negative effect on the liquidity of Elbas.

However, our baseline regressions do not offer support for the hypotheses of a negative effect of the reform on liquidity. Instead, the baseline results seem to suggest that the policy led to an increase in liquidity. This suggestion is not confirmed by subsequent robustness checks. The sign and significance on both our change in level (*Policy*) and the change in trend (*Interaction*) are changing between different regressions. As presented in Section 9, most of our estimators and respective confidence intervals indicate that we cannot reject the null hypothesis of no effect of market splitting on liquidity. Hence, we conclude that we cannot confirm that the Swedish bidding zone reconfiguration impacted liquidity on the Swedish intraday market.

In the following section we interpret these results, discuss how they relate to the literature, their external and internal validity as well as avenues for further research.

11.1. *Dynamics of Intraday Markets*

The result that the policy change did not lead to a significant decrease can thus be interpreted using this framework of a strategic trading decision. We assume that the attractiveness of the alternatives, i.e. settling imbalances internally or on the balancing market, did not change during the observed time frame. Therefore, finding no significant effect indicates that the intraday market did not lose attractiveness after the policy implementation. Furthermore, this lets us infer that the traders continued to trade on Elbas to the same extent as before, because the influence of uncertainty, strategic behavior and search costs did not change significantly after the policy change.

One reason for this absence of an effect of market splitting on liquidity could be that intra-Swedish congestion remains negligible after the reform (Figueiredo et al., 2016). Examining

data provided by Nordpool, we can identify that there was no congestion between January 2011 and December 2012 in approx. 80% of all hours.[11] The absence of regular congestion events might explain why traders on Elbas continued to consider the entire market in their trading decisions and did not change their behavior after the policy was implemented. This behavior is rational within our framework because the trader's experience tells them to expect no interference of congestion with their planned transactions. This robust behavior in the face of a policy change can further be interpreted as a testimony to Nordpool's successful market integration and the foresightful policy implementation by Sweden.

Meanwhile, the positive effect that we observe in the baseline regressions cannot be validated by the subsequent robustness checks. A positive change in liquidity would have been a surprising finding as it contradicts the existing literature as well as the intuition behind the policy debate about bidding zone reconfiguration. The contradictory findings on the different dimensions of liquidity, and especially the lack of an effect when reducing the time frame to one year, leads us to believe that the observation of a positive effect has to be caused by unobservable factors which we are not able to control for.

The results for our control variables support the mechanisms of intraday market liquidity as described in Section 5.1. For the generation technologies, the predictions that hydro generation has a positive effect on liquidity, while nuclear power has a negative effect, both hold. Hydro generation has a positive and significant effect on trade volume and frequency in our baseline results and most of the robustness checks. This is in line with our framework, because hydro generators are patient traders which will offer more flexibility if they produce more. In contrast, Nuclear power is less flexible as it is very expensive to change the scheduled electricity output for this technology. Hence, the more nuclear power is being produced, the more liquidity decreases in our results.

Similarly, the price difference between Elbas and the balancing market has a highly significant and positive effect on all measures of liquidity. Higher prices on Elbas encourage intraday trading for patient and impatient traders, which both face the same decision between trading on the balancing market, trading on Elbas or shuffling generation schedules within their portfolio. Hence, the higher the price on Elbas relative to the balancing market, the more trading will take place on Elbas.

Production forecast errors on the other hand only show a significantly positive effect on liquidity in some specifications. Wind generation only has a significant effect on the high-to-low spread, where it indicates a positive effect on liquidity, and consumption forecast errors do not show a significant effect in most specifications. Thus, the effect of intermittent

[11] We identify hours with congestion by identifying all hours in which prices on Elspot diverged between the zones.

generation and forecast errors is less strong than we expected. On the one hand, this finding could indicate a limited understanding of liquidity in the literature. On the other hand, if the trend in intermittent energy is similar for both Sweden and Finland, we might capture the effect in our time fixed effects.

With regard to the adequate liquidity measures for the analysis of intraday markets, we note that the fit of our regressions using *Variance* as a dependent variable is by far the lowest. Additionally, we find that some control variables do not show into the expected direction. Thus, we find resilience to be the last appropriate measure of liquidity.

In summary, our results do indicate that the framework behind our hypotheses is valid: Higher prices on Elbas relative to the balancing market, production forecast errors as well as flexibility do show a consistent effect on liquidity of the intraday market.

11.2. *Comparison to Prior Research*

Our results add important evidence to the literature by combining insights into both zonal pricing and the liquidity of intraday markets. Our study also is the first to empirically analyze the effect of a bidding area reconfiguration on intraday market's liquidity. Thereby, it adds to the understanding of the dynamics that govern trading behavior on intraday markets.

Our finding that the Swedish market splitting did not decrease the liquidity of Elbas contradicts the finding of Lundin and Tangerås (2017). In their paper, the authors find evidence for the bidding area reform increasing market power. Hence, it seems as if the reform had a negative effect on some aspects of market efficiency, while our results suggest that it did not affect other aspects, specifically intraday market liquidity. This dichotomy should be explored by future research in order to understand the effect of the Swedish reform thoroughly.

Meanwhile, the findings of this paper support arguments about the benefits of zonal pricing as made in theoretical papers, e.g. Bjørndal and Jørnsten (2001) or Grimm et al. (2016), by showing that a reform would not lower market liquidity as one aspect of efficiency. Finally, our regressions confirm the basic intuition provided by Hagemann and Weber (2013), Mauritzen (2015) and Skajaa et al. (2015) about the motivation of trading on intraday market. In fact, we find that forecast errors, balancing market prices and flexibility do indeed have an effect on liquidity in the case of Elbas. Of these mechanisms, our thesis confirms the importance of balancing market prices relative to intraday market prices most strongly though. This confirms that the decision making process of a trader as introduced by Mauritzen (2015) can be found in the data on the Nordics.

11.3. *Policy Implications*

Congestion related costs are one of the main barriers for realizing the vision for an integrated, decarbonized and liberalized European Electricity Market. In order to overcome this barrier, European policy makers are going to face the same options as Sweden did in 2011. They can change the market design, expand the grid or simply accept high congestion costs in the face of increasing amounts of intermittent energy sources. Our paper provides evidence that a change in market design is not necessarily related to negative effects on the electricity market's liquidity, and is therefore relevant for the decision making process on a European level.

Our results stand in contrast to the intuition provided by the literature and recent publications of policy groups, e.g. Frontier Economics and Consentec (2013), Consentec (2015), ENTSO-E (2018). These groups express concern over the negative effects of market splitting on the liquidity of electricity markets. However, their concerns are not supported by econometric analysis, but instead rely on argumentation and descriptive statistics. This thesis however expands the notion made in the academic literature of the positive effects of smaller bidding zones on welfare. Hence, our empirical findings provide encouraging evidence for the benefits of market splitting as a congestion management tool, by showing that there was no trade-off between less congestion related costs and liquidity due to the Swedish market splitting reform. Thereby, it supports the case of policy initiatives trying to introduce smaller bidding areas to the European market.

In conclusion, as the literature has shown multiple bidding zones lowering congestion costs and increasing allocative efficiency, such reconfiguration reforms could not only lead to a more efficient electricity market design. They could also promote the introduction of renewable energy sources and thereby reduce the harmful effects of climate change. Therefore, our result encourages the implementation of bidding area reconfigurations .

11.4. *Limitations and Further Research*

The estimation strategy employed in this paper accounts for a variety of factors such as autocorrelation, heteroskedasticity and unobserved time- as well as country specific effects. Thus, we are confident that our results are sufficiently unbiased and that further research on the topic will confirm that there was no effect of the reform on Swedish intraday market liquidity. Nevertheless, some limitations prevail that future studies should address.

To begin with, liquidity on electricity markets in general, and intraday markets in particular, remains an understudied field, possibly limiting the internal validity of our thesis. Our results are sensitive to unobserved factors which we cannot control for due to lack of information

on the drivers of intraday market liquidity. Indeed, the relatively low R^2 and the positive estimates of our *Policy* and *Interaction* variables in some regressions, suggest that the model of a strategic decision, as well as forecast errors guiding the trading decision on intraday markets, needs to be revised and improved. Additionally, our results might have been biased by the drop in liquidity that happened during the months before the reform was implemented. Furthermore, we only studied the intraday market Elbas, which may have limited external validity for similar markets in other regions. These limitations highlight and open up multiple interesting directions for further research though, especially with regard to the application of our findings to the European policy making process.

Finally, some limitations arise from the type of data we use. First, when investigating liquidity, the bid-ask-spread of trading data would be a prudent measure for transaction costs. However, Nordpool does not provide this data, and the statistical tools to create a proxy for this measure are not sufficiently potent. Second, it would be interesting to have micro-level data on the trading behavior of agents, which would allow us to better understand the decision making rationale of market participants.

The empirical approach to analyzing market splitting that has been used in this thesis opens up a variety of fields for further research. First, our findings can be tested by applying them to different settings. Other countries, such as Italy, have seen similar reforms which decreased bidding area size. Confirming that these had no effect on liquidity would increase the external validity of our results. Second, further behavioral and microeconomic research on the trading dynamics of intraday markets would improve any empirical analysis of such markets. Intraday markets will increase in their importance due to the rise of intermittent energy production. Thus, it is crucial for researchers to understand the mechanisms of the market and the decisions of market participants in order to help implement meaningful changes to the market design. Third, the dataset created for this thesis describes the Elbas market over the span of four years and could be used for a variety of further research projects, such as a general analysis of driving factors behind liquidity on Elbas. Such factors are the relationship of day-ahead, balancing and intraday market and the impact of forecast errors on trading decisions. Finally, there are a variety of other events on Nordpool that require further analysis in the context of intraday market liquidity. For example, Norway has a unique approach of dynamically dividing its bidding areas based on the needs of the market. Analyzing these market splits would deepen our understanding of such reforms.

12. Conclusion

The purpose of this paper is to empirically answer whether the Swedish bidding area reform in 2011 lead to a decrease in the liquidity of the Swedish intraday market. Thereby, the paper

contributes to the debate about the efficiency of zonal pricing approaches as a congestion management tool. In order to answer this question we build a novel dataset by aggregating raw trading data and constructing liquidity measures and control variables from different sources. We then use a fixed effects estimation strategy with both entity and time fixed effects to empirically assess the effect of the reform on ELBAS' liquidity as well as to conduct a variety of robustness checks. Overall, we cannot find a clear and robust effect of the Swedish market splitting on the intraday market's liquidity.

Thus, the paper suggests that the European Union's efforts to introduce a zonal market design with smaller bidding areas within Europe should be expanded. Zonal pricing has already proven to be an effective measure to combat congestion related welfare costs, thus facilitating the expansion of variable and renewable energy sources. In addition to that, our paper suggests that it does not have a detrimental impact on intraday markets, which we expect to increase in importance as intermittent generation gains market share. Therefore, a more granular zonal pricing approach can not only help to reduce inefficiencies in current-day electricity markets: It also offers a chance to support the integration of carbon free generation sites and thereby to reduce the effects of man-made climate change in the future.

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Appendices

A. Swedish Generation Mix

This graph shows the changes in the share of total Swedish generation for the main generation technologies: Hydro, Nuclear, Wind and Thermal.

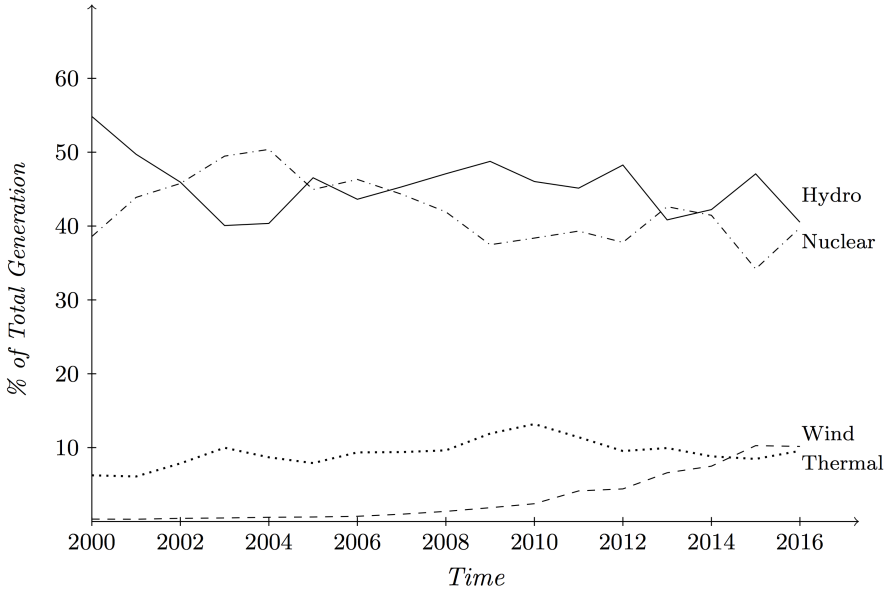


Figure 7: Development of Generation Mix
Source: Swedish Energy Agency (2018)

B. Structure of the Dataset

The table gives an overview of the structure of our panel dataset.

Table 4: Representation of Dataset Structure

Country	Time	...	Tradevolume	...	Production: Hydro Power	Consumption: Forecast Error	...	Weekend	Peak	..
1	4441	...	800	...	5704.49	203	...	0	0	...
1	4442	...	240	...	5630.67	141	...	0	0	...
...	...	...	...	...	...	...	...	...	...	...
2	4441	...	720	...	1151.31	194	...	0	0	...
2	4442	...	312	...	912.59	356	...	0	0	...
...	...	...	...	...	...	...	...	...	...	...

C. Swedish Transmission Network

This map shows the complete transmission network for the Nordpool countries Norway, Sweden, Finland, Denmark, Estonia, Latvia and Lithuania.



Figure 8: Structure of Swedish transmission network
Source: Svenska Kraftnät (2018*a*) - modified

D. Origin of Variables

The table is an overview of the data sources we use for each of our variables.

Table 5: Data Sources

Nordpool FTP Server (Nordpool, 2018*a*)	**Svenska Kraftnät** (Svenska Kraftnät, 2018)	**Finish Energy** (Finish Energy, 2018)	**Self-Constructed**
Tradevolume[1]	Production: Hydro	Production: Hydro	Time
Number of Trades[1]	Production: Wind	Production: Wind	Day of the Week
High-To-Low Ratio[1]	Production: Nuclear	Production: Nuclear	Off-Peak
Price Variance[1]	Total Production[1]	Total Production	On-Peak
Forecast Errors Consumption[1]			Summer
Forecast Errors Generation[1]			Winter
Up-Regulation-Price			Weekend
Down-Regulation-Price			
Price Difference[1]			

[1] Variable self-constructed based on information retrieved from the dataset.

E. Descriptive Statistics

E.1. *Descriptive Statistics per Year for Sweden*

The table shows the summary statistics per year for Sweden for our three liquidity indicators.

Table 6: Descriptive Statistics per Year for Sweden

Sweden						
Year	**Variables**	**Mean**	**Std. Dev.**	**P(25)**	**P(50)**	**P(75)**
2010	Tradevolume	458.9	449.0	160	332	616
	Number of Trades/Hr	25.68	19.14	12	20	36
	Price Variance	109.5	3,411	1.333	4.840	13.61
2011	Tradevolume	327.0	370.4	90	208	429
	Number of Trades/Hr	19.76	17.11	7	15	27
	Price Variance	19.66	49.78	1.971	6.030	16.33
2012	Tradevolume	483.8	481.5	170.2	337	630
	No. of Trades/Hr	29.49	22.31	12	24	41
	Price Variance	33.20	232.5	1.913	4.805	15.05
2013	Tradevolume	580.3	529.2	212.5	423	783
	No. of Trades/Hr	33.67	24.52	15	27	45
	Price Variance	14.75	36.21	2.506	5.596	13.32

E.2. *Descriptive Statistics per Year for Finland*

The table shows the summary statistics per year for Finland for our three liquidity indicators.

Table 7: Descriptive Statistics per Year for Finland

Finland						
Year	**Variables**	**Mean**	**Std. Dev.**	**P(25)**	**P(50)**	**P(75)**
2010	Tradevolume	375.5	352.5	138	276	500
	No. of Trades/Hr	25.44	18.05	12	20	36
	Price Variance	375.5	352.5	138	276	500
2011	Tradevolume	219.2	223.2	67	145	297
	No. of Trades/Hr	16.73	13.42	6	12	24
	Price Variance	219.2	223.2	67	145	297
2012	Tradevolume	231.1	246.3	72.95	153	300
	No. of Trades/Hr	18.69	15.65	7	15	27
	Price Variance	231.1	246.3	72.95	153	300
2013	Tradevolume	306.0	268.6	113	225.9	420
	No. of Trades/Hr	24.30	18.33	10	20	33
	Price Variance	316.4	282.3	115	231	435

E.3. *Descriptive Statistics per Time of the Day*

The table shows the summary statistics per time of a trading day for our three liquidity indicators *Trade Volume*, *Frequency* and *Variance* for Sweden.

Table 8: Descriptive Statistics per Time of the Day

Sweden					
Time	**Variables**	**Mean**	**Std. Dev.**	**Min**	**Max**
Off-peak 1	Tradevolume	325.4	338.8	0.300	3,528
	No. of Trades/Hr	20.87	16.72	1	150
	Price Variance	74.61	2,41	0	234,91
Peak	Tradevolume	486.3	487.0	0.100	4,710
	No. of Trades/Hr	28.04	22.10	1	210
	Price Variance	13.58	38.07	0	1,143
Off-peak 2	Tradevolume	559.8	519.0	2	4,809
	No. of Trades/Hr	31.76	23.02	1	147
	Price Variance	14.28	56.18	0	1,972

F. Local Linear Regressions

F.1. *Tradevolume (2 Months Bandwidth)*

The graph depicts the trends for the liquidity variable *Trade Volume* of Sweden and Finland.

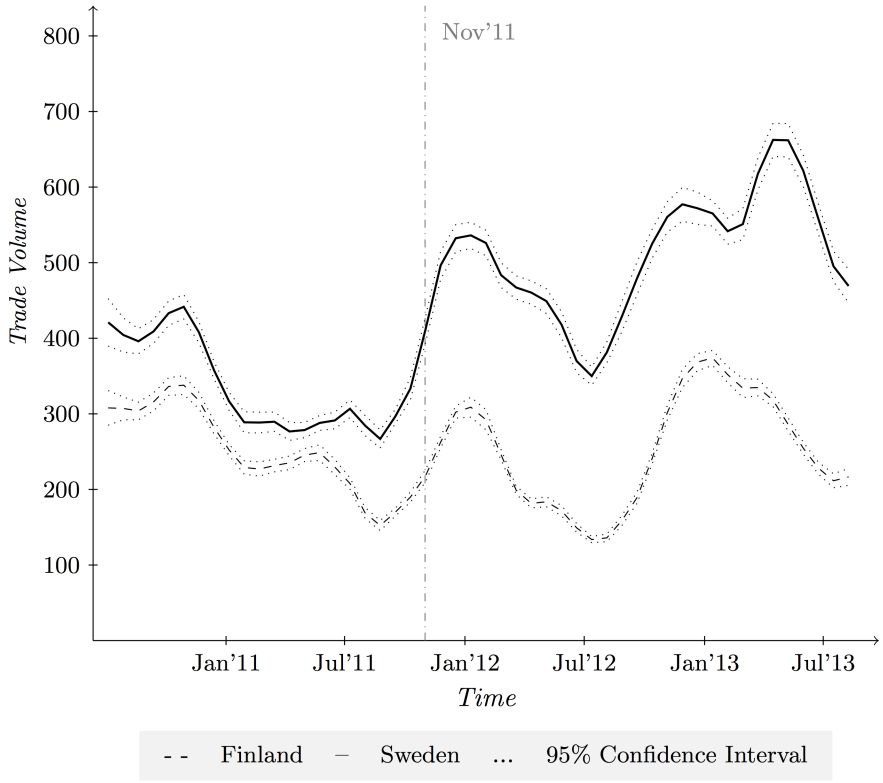


Figure 8: Time Trend Tradevolume

Source: Author's rendering of Nordpool FTP server data (2018).

F.2. *Frequency (2 Months Bandwidth)*

The graph depicts the trends for the liquidity variable *Frequency* of Sweden and Finland.

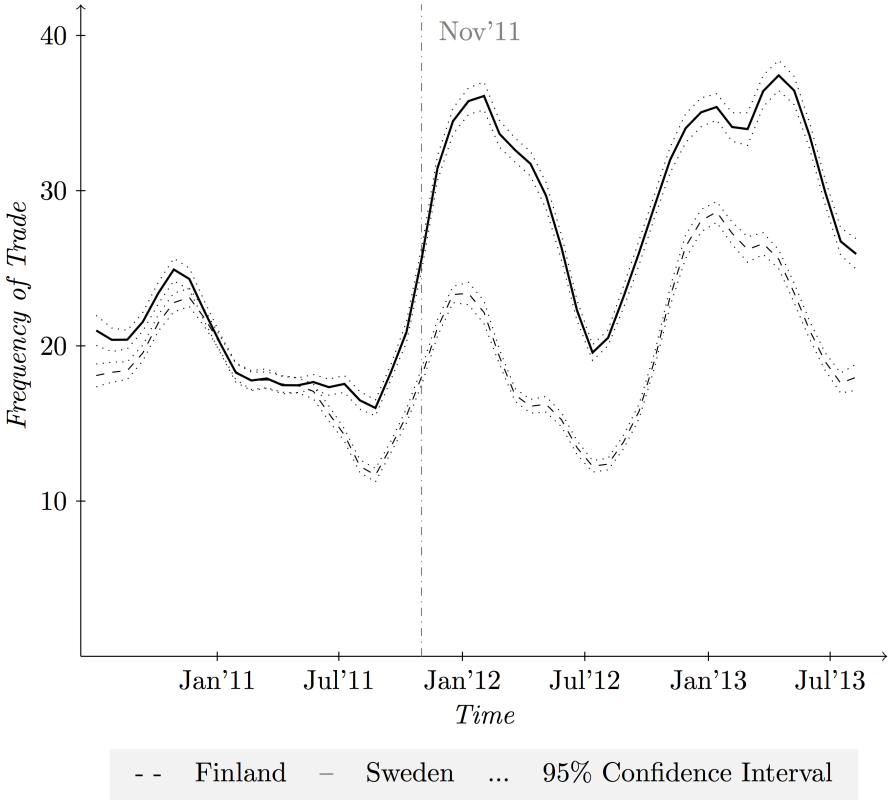


Figure 9: Time Trend Frequency

Source: Author's rendering of Nordpool FTP server data (2018).

F.3. *Variance (2 Months Bandwidth)*[1]

The graph depicts the trends for the liquidity variable *Variance* of Sweden and Finland.

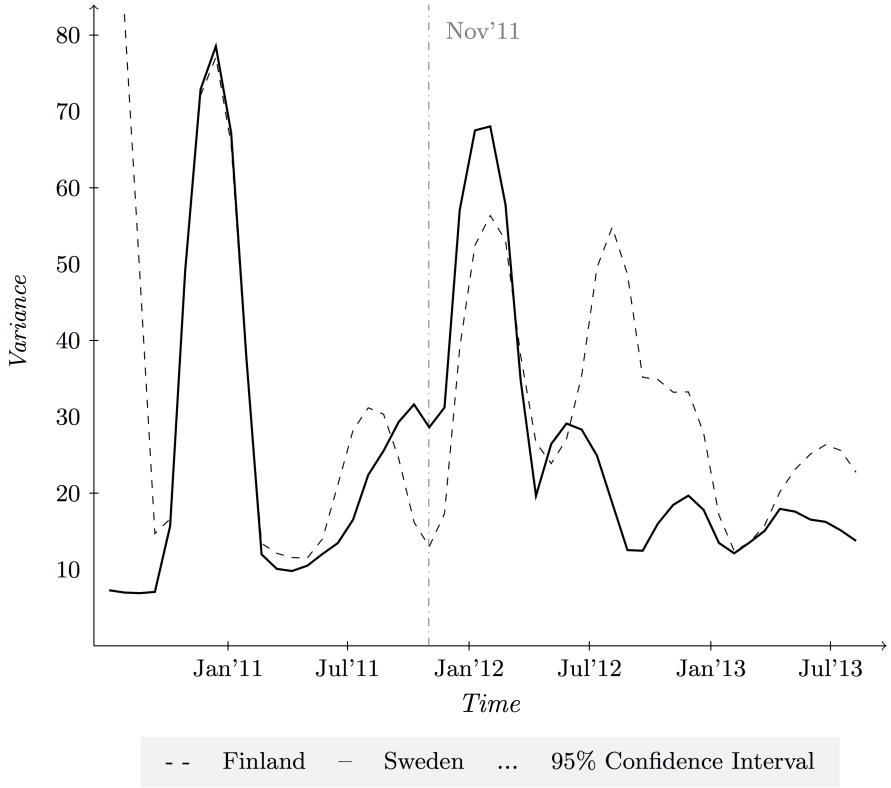


Figure 10: Time Trend Variancy

[1] Confidence Intervals omitted for better visibility

Source: Author's rendering of Nordpool FTP server data (2018).

G. Robustness Checks

G.1. *Robust Standard Errors Check*

The tables show the results of the test statistics. With the Breusch-Pagan Test we test for heteroskedasticity, while we test for serial autocorrelation with the Woolridge Test.

Table 9: Breusch-Pagan Test for Heteroskedasticity

Breusch-Pagan Test		
H0: Constant Variance		
Trade volume	Number	Variance
P-value = 0.0000	P-value = 0.0000	P-value = 0.0000

Table 10: Woolridge Test for Autocorrelation

Woolridge Test		
H0: No Autocorrelation		
Trade volume	Number	Variance
P-value = 0.0294	P-value = 0.0329	P-value = 0.0472

G.2. *Exclude Bilateral Trades*

Table 11 reports the regression results when bilateral trades between Finland and Sweden are excluded.

Table 11: Regression Output without Bilateral Trades

	(1)	(2)	(3)	(4)	(5)	(6)
	Trade Vol.	Trade Vol.	Frequency	Frequency	Variance	Variance
Policy	58.26	50.48	13.53***	13.08***	0.299	1.781
	(47.18)	(46.87)	(2.946)	(2.958)	(14.55)	(15.21)
Interaction	0.0057**	0.0058**	-0.0002	-0.0002	0.0003	0.0003
	(0.0022)	(0.0022)	(0.0001)	(0.0001)	(0.0006)	(0.0006)
Time	-0.0893*	-0.0913*	-0.0047	-0.0048*	-0.0231*	-0.0229*
	(0.0520)	(0.0522)	(0.0028)	(0.0028)	(0.0132)	(0.0130)
Forecast Error Cons.	0.0060	0.0077**	0.0004*	0.0005**	-0.0030	-0.0029
	(0.0040)	(0.0036)	(0.0002)	(0.0002)	(0.0029)	(0.0030)
Forecast Error Gen.	0.0228**		0.0007		0.0010	
	(0.0083)		(0.0004)		(0.0055)	
Wind Generation		0.0248		0.0013		-0.0038
		(0.0153)		(0.0009)		(0.0048)
Hydro Generation	0.0056**	0.0062**	0.0002	0.0002	0.0055***	0.0054***
	(0.0025)	(0.0026)	(0.0002)	(0.0002)	(0.0019)	(0.0019)
Nuclear Generation	-0.0191**	-0.0206**	-0.0004	-0.0005	-0.0042	-0.0040
	(0.0091)	(0.0096)	(0.0004)	(0.0004)	(0.0033)	(0.0032)
Δp Elbas/Bal. Market	1.396***	1.411***	0.107***	0.108***	5.235**	5.236**
	(0.206)	(0.207)	(0.0088)	(0.0088)	(2.017)	(2.020)
Offpeak 1	-84.80***	-84.92***	-4.857***	-4.839***	-4.142	-4.318
	(10.18)	(9.835)	(0.321)	(0.304)	(3.094)	(3.011)
Offpeak 2	29.79***	29.39***	0.956**	0.946**	-9.260***	-9.281***
	(7.267)	(7.359)	(0.409)	(0.413)	(2.719)	(2.712)
Weekend	-6.973	-6.880	-0.423	-0.408	-1.442	-1.535
	(6.165)	(6.214)	(0.370)	(0.376)	(3.065)	(2.999)
Constant	751.90**	764.00**	37.54**	38.01**	186.80**	186.30**
	(277.2)	(281.0)	(14.3)	(14.4)	(87.6)	(88.1)
Observations	55,318	55,318	55,318	55,318	55,318	55,318
R^2	0.121	0.121	0.175	0.175	0.051	0.051
Country Fixed Effects	2	2	2	2	2	2
Time Fixed Effects	37	37	37	37	37	37
Robust Standard Errors	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

G.3. *Reduced Time Frame*

Table 12 reports the regression results when we reduce the time frame to 1 year.

Table 12: Regression Output with Reduced Time Frame

	(1)	(2)	(3)	(4)	(5)	(6)
	Trade Vol.	Trade Vol.	Frequency	Frequency	Variance	Variance
Policy	423.2	468.0	2.026	4.174	160.2**	173.0**
	(270.9)	(278.7)	(15.23)	(15.74)	(75.65)	(80.78)
Interaction	-0.0147	-0.0170	0.0004	0.0002	-0.0081*	-0.0083*
	(0.0167)	(0.0170)	(0.0010)	(0.0010)	(0.0043)	(0.0044)
Time	-0.0635	-0.0602	-0.0028	-0.0026	-0.0468	-0.0444
	(0.0720)	(0.0728)	(0.0042)	(0.0043)	(0.0389)	(0.0368)
Forecast Error Cons.	0.0102	0.0203	0.0013	0.0018	-0.0102	-0.0084
	(0.0303)	(0.0303)	(0.0018)	(0.0017)	(0.0126)	(0.0130)
Forecast Error Gen.	0.0744***		0.0033**		0.0054	
	(0.0262)		(0.0014)		(0.0070)	
Wind Generation		-0.0166		-0.0010		-0.0204
		(0.0411)		(0.0023)		(0.0172)
Hydro Generation	0.0094	0.0088	0.0067*	0.0006*	0.0079	0.0073
	(0.0078)	(0.0077)	(0.0004)	(0.0003)	(0.0054)	(0.0051)
Nuclear Generation	0.0029	0.0041	0.0014	0.0015	-0.0139	-0.0143
	(0.0293)	(0.0293)	(0.0014)	(0.0014)	(0.0119)	(0.0117)
Δp Elbas/Bal. Market	1.157***	1.188***	0.0964***	0.0977***	2.737***	2.735***
	(0.3120)	(0.3260)	(0.0201)	(0.0209)	(0.6390)	(0.6370)
Offpeak 1	-42.37**	-46.27***	-3.059***	-3.245***	-10.08*	-11.11*
	(16.39)	(15.99)	(0.867)	(0.840)	(5.840)	(6.192)
Offpeak 2	45.62***	44.23***	2.573***	2.509***	-18.45**	-18.67**
	(14.04)	(14.14)	(0.751)	(0.758)	(7.710)	(7.914)
Weekend	-13.97	-16.40	-0.840	-0.953	8.994	8.542
	(18.83)	(18.72)	(1.117)	(1.110)	(7.864)	(7.488)
Constant	934.2	909.1	40.13	38.77	601.9	584.4
	(967.6)	(972.6)	(55.50)	(55.99)	(493.0)	(473.7)
Observations	17,546	17,546	17,546	17,546	17,546	17,546
R^2	0.115	0.113	0.191	0.189	0.062	0.063
Country Fixed Effects	2	2	2	2	2	2
Time Fixed Effects	12	12	12	12	12	12
Robust Standard Errors	Yes	Yes	Yes	Yes	Yes	Yes

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

G.4. *Daily Dataset*

Table 13 reports the regression results when we look at total daily trades.

Table 13: Regression Output with Daily Data

	(1)	(2)	(3)	(4)	(5)	(6)
	Trade Vol.	Trade Vol.	Frequency	Frequency	Variance	Variance
Policy	1,090	1,116	224.8***	227.8***	-15.65	-16.86
	(1,120)	(1,114)	(63.89)	(63.41)	(11.16)	(11.04)
Interaction	2.171***	2.165***	-0.0070	-0.0076	0.0162*	0.0164*
	(0.7340)	(0.7390)	(0.0399)	(0.0398)	(0.0081)	(0.0081)
Time	-23.19	-22.93	-1.371	-1.361	-0.306	-0.310
	(21.570)	(21.520)	(1.266)	(1.259)	(0.183)	(0.186)
Forecast Error Cons.	0.0093	0.0082	0.0004	0.0004	-0.0001	-0.0001
	(0.0073)	(0.0073)	(0.0004)	(0.0004)	(0.0001)	(0.0001)
Forecast Error Gen.		0.0213		0.0004		-0.0002
		(0.0135)		(0.0007)		(0.0002)
Wind Generation	0.0075		0.0004		-0.0002	
	(0.0193)		(0.0011)		(0.0003)	
Hydro Generation	0.0110**	0.0109**	0.0008**	0.0008**	0.0004**	0.0004**
	(0.0050)	(0.0048)	(0.0003)	(0.0003)	(0.0002)	(0.0001)
Nuclear Generation	-0.0220*	-0.0214*	-0.0003	-0.0003	-0.0001	-0.0001
	(0.0123)	(0.0120)	(0.0006)	(0.0006)	(0.0001)	(0.0002)
Δp ELBAS/Bal. Market	112.6***	112.0***	8.409***	8.385***	4.853***	4.862***
	(21.360)	(21.430)	(0.714)	(0.730)	(0.873)	(0.876)
Weekend	-386.2*	-381.2*	-18.90	-18.95	-4.163	-4.146
	(206.2)	(205.1)	(11.59)	(11.70)	(6.531)	(6.648)
Constant	11,357***	11,290***	467.1***	466.2***	108.5	109.0
	(1,595)	(1,586)	(89.78)	(90.17)	(77.04)	(76.32)
Observations	2,308	2,308	2,308	2,308	2,308	2,308
R^2	0.208	0.208	0.298	0.298	0.140	0.140
Number of country	2	2	2	2	2	2
Time Fixed Effects	37	37	37	37	37	37
Robust Standard Errors	Yes	Yes	Yes	Yes	Yes	Yes

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

G.5. *Volatility Robustness*

Table 14 reports the regression results when we use the high-to-low spread as a proxy for *Resilience*.

Table 14: Regression Output for Different Variance Measures

	(1)	(2)	(3)	(4)
	Variance	Variance	High-to-Low	High-to-Low
Policy	-11.37	-9.671	3.573**	4.128**
	(13.28)	(13.52)	(1.702)	(1.646)
Interaction	0.0010	0.0009	-6.09e-05	-6.75e-05
	(0.0006)	(0.0006)	(6.13e-05)	(5.95e-05)
Time	-0.0268*	-0.0265*	-0.0017	-0.0017
	(0.0154)	(0.0152)	(0.0014)	(0.0014)
Forecast Error Cons.	-0.0037	-0.0036	-1.95e-05	-7.19e-06
	(0.0036)	(0.0036)	(0.0003)	(0.0003)
Forecast Error Gen.	0.0010		0.0001	
	(0.0058)		(0.0003)	
Wind Generation		-0.0044		-0.0015**
		(0.0051)		(0.0005)
Water Generation	0.0067***	0.0066***	0.0008***	0.0007***
	(0.0023)	(0.0023)	(0.0002)	(0.0002)
Nuclear Generation	-0.0044	-0.0042	-0.0008**	-0.0007**
	(0.0037)	(0.0035)	(0.0003)	(0.0003)
Δp Elbas/Bal. Market	5.049***	5.050***	0.290***	0.290***
	(1.5900)	(1.5930)	(0.0368)	(0.0368)
Offpeak1	-5.893*	-6.088*	-1.989***	-2.046***
	(3.133)	(3.110)	(0.311)	(0.307)
Offpeak2	-12.97***	-12.99***	-1.415***	-1.418***
	(4.006)	(4.031)	(0.285)	(0.284)
Weekend	-3.764	-3.869	-0.652*	-0.683*
	(4.863)	(4.821)	(0.337)	(0.330)
Constant	241.5*	240.9*	17.73**	17.46**
	(120.5)	(121.3)	(7.226)	(7.181)
Observations	55,318	55,318	55,318	55,318
R^2	0.045	0.045	0.184	0.186
Country Fixed Effects	2	2	2	2
Time Fixed Effects	37	37	37	37
Robust Standard Errors	Yes	Yes	Yes	Yes

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1