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Assessing bidding zone configurations: evidence from the Nord Pool market

Luisa Loiacono*

July 29, 2022

Abstract

As the share of renewable energy sources in the electricity market increases, bidding zones are fundamental to give accurate market signals while maintaining security of supply. Smaller bidding zones (and nodal pricing) are claimed to facilitate congestion management thanks to prices better reflecting market signals. Nevertheless, the ongoing debate on bidding zones configuration is based on theoretical models. In this work I give evidence of the effectiveness of the bidding zones re-configuration that took place in Sweden on November 2011. First, using a difference-in-differences approach, I find that after the re-configuration prices in Sweden increased by 0.1% - 4% of the average price. Secondly, with a regression discontinuity in time I find an increase in cross-country opportunities: the net flow from Sweden to Finland increased by 5% - 14% of the average flow.

Keywords: electricity market, market segmentation, bidding zone, spot price

JEL Classification: O13, Q41, L52, D47

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1 Introduction

Configurations of bidding zones in electricity markets are fundamental to give accurate signals while maintaining security of supply, especially given the increasing share of renewable energy sources (RES) in the market. Different configurations do not modify the actual network transmission capacity, but they affect price formation mechanisms and import/export flows.

The debate on the optimal bidding zone configuration is polarized; on one hand, the nodal market and smaller bidding zones are claimed to facilitate congestion management thanks to prices reflecting scarcity, on the other hand, larger zones should favour liquidity and avoid price spreads. Nevertheless, the ongoing debate on the configuration of the optimal bidding zones is mainly based on theoretical models. The goal of this work is to empirically assess the effects of the different bidding zones[1].

In particular, I focus on the market re-configuration in Sweden, where the Transmission System Operator (TSO) was accused to abuse its dominant position (Art. 102 Treaty on the Functioning of the European Union, from now on TFEU) by curtailing Available Transmission Capacity[2] (ATC) with the neighbouring countries. On April 2010, the European Commission announced that from November 2011, the single Swedish bidding zone would have been split into four smaller zones.

In fact, because of the Swedish network bottlenecks due to the localisation of inelastic demand in the South and cheap hydroelectric supply in the North, the Swedish TSO, was accused to curtail Available Transmission Capacity (ATC) with neighbouring countries in order to manage internal congestion. Although Art. 18 and 35 of TFEU expressly prohibit discrimination based on nationality and quantitative restrictions on exports. As a consequence, during congestion hours, the average prices in Sweden were claimed to be significantly low and the TSO accused to curtail the ATCs. The market split was introduced to have price signals to reflect actual internal bottlenecks. Using empirical

[1] I provide the definition of a bidding zone and I explain the difference between the nodal and the zonal market in Section A.1 in Appendix

[2] The Available Transmission Capacity is the maximum amount of electricity that can be traded in the day-ahead market through a specific inter-connector between two areas. National TSO determines ATCs hourly for each direction and each inter-connector.

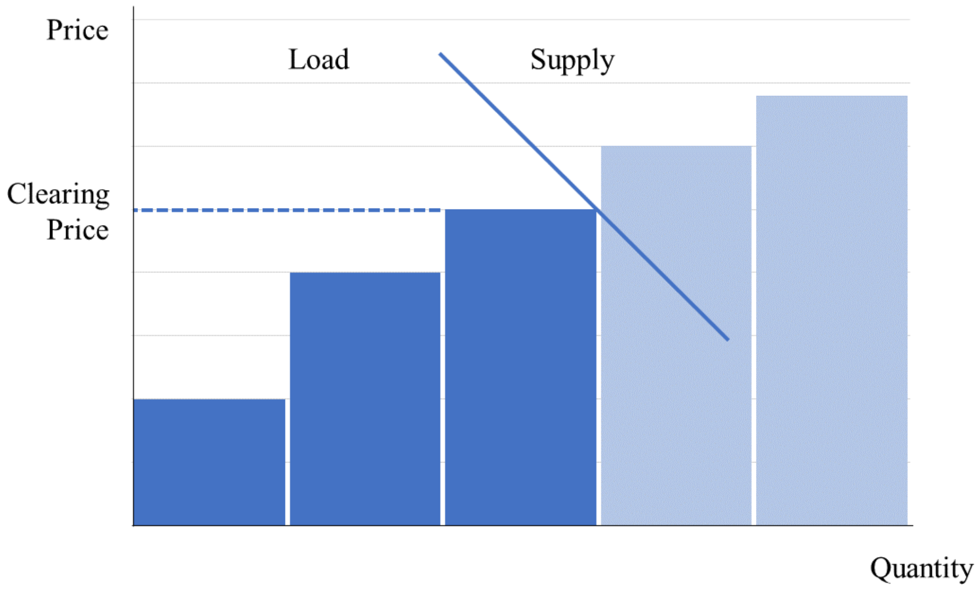
data, I consider that the re-configuration of the Swedish market should translate into changes in the average price in Sweden and to differences in cross-zonal and cross-country flows thanks to a more accurate use of the inter-connectors and congested lines.

In this work I perform both a difference-in-differences to estimate the impact of the policy intervention on prices and a regression discontinuity in time to estimate the impact on the policy on cross-zonal and cross-country flows.

The prices I analyse are spot prices, that are set in the electricity wholesale markets. In these markets, buyers and sellers simultaneously send their bids with the amount of energy they are willing to buy and sell and the relative price. Once that bids are set, they are aggregated by the power market using the merit-order criterion where bids are ranked in ascending order of price[3]. The market clearing price is then calculated at the point of intersection of buyers' and sellers' curves as in Figure 1. The difference between the price buyers were willing to pay and the clearing price is the consumer surplus, vice versa for the producer surplus. This mechanism is called "system marginal price" and it is the mechanism behind the formation of the electricity prices I use in this work. This mechanism takes place in each bidding zone and it is sensitive to the bidding zones configuration. In fact, as theoretically shown by Bjørndal and Jörnsten (2001) in case of a single nationwide zone, average prices in the day-ahead market will be lower compared to multiple smaller zones. In case of internal congestion, the multiple zonal prices will incorporate the congestions by taking them into account in the price formation. Conversely, the zonal pricing ignores internal congestions that are solved by the TSO either with costly remedial actions or by curtailing Available Transmission Capacities. I repeat this exercise by empirically showing how the average price in Sweden changed after the re-configuration. My empirical analysis can be considered as a comparison between the nodal (four bidding zones) and the zonal market configuration (one nationwide bidding zone). The existing literature has widely covered the comparison between the nodal and the zonal systems, however, it is mainly based on theoretical models that are sometimes combined with anecdotal evidence. My contribution confirms the theoretical results from Sarfati,

[3]Since RES are considered to have zero marginal cost, they enter at the bottom of the merit order. In fact, RES are characterized by very low operating costs but high capital expenditures.

Figure 1: Uniform auction under perfect competition.



Note: Authors' elaboration based on Cretì and Fontini (2019).

Hesamzadeh, & Holmberg (2019) that prove that the zonal market leads to distorted signals of transmission constraints. Indeed, I analyse to what extent the cross-zonal and cross-country flows changed thanks to non-distorted price signals that were better reflecting scarcity.

Throughout my empirical analysis I model electricity prices taking into account the regional seasonality. In particular, I use monthly and day of the week dummies, as in Hadsell, Shawky, and Marathe (2004) and Huisman & Kiliç (2013). Finally, as I use the temperature as an exogenous instrument for prices, I want to highlight that the strong relationship between prices and temperatures has already been observed by Huisman (2008). He uses average prices in peak hours (from 8 am to 8 pm) from the Dutch APX market, from January 2003 throughout February 2008, to show that temperatures are a key predictor for prices.

The different designs upon which my econometric analysis rely on show that the market efficiency improved after the market re-configuration. My measure of market efficiency relies on accurate price signals and the exploitation of cross-country available transmission capacities. As theoretically shown by Sarfati, Hesamzadeh, & Holmberg (2019), I confirm that the zonal market gives distorted price signals on transmission constraints. Firstly, with my diff-in-diff analysis I find that prices in Sweden increased, the estimated magnitude of the effect varies from 0.1% to 4% of the average price. Secondly, with my regression discontinuity in time I find that cross-zonal flows from the Northern to the Southern part of Sweden decreased by approximately 11%. The better use of cross-country inter-connectors increased the export of the electricity produced in the North while the price differences resulting from the splitting pushed producers in the South to enter the market. Thirdly, I find that cross-country opportunities increased, namely, the net flow from Sweden to Finland increased from 5 to 14 percent of the average flow.

1.1 Description of the Swedish market

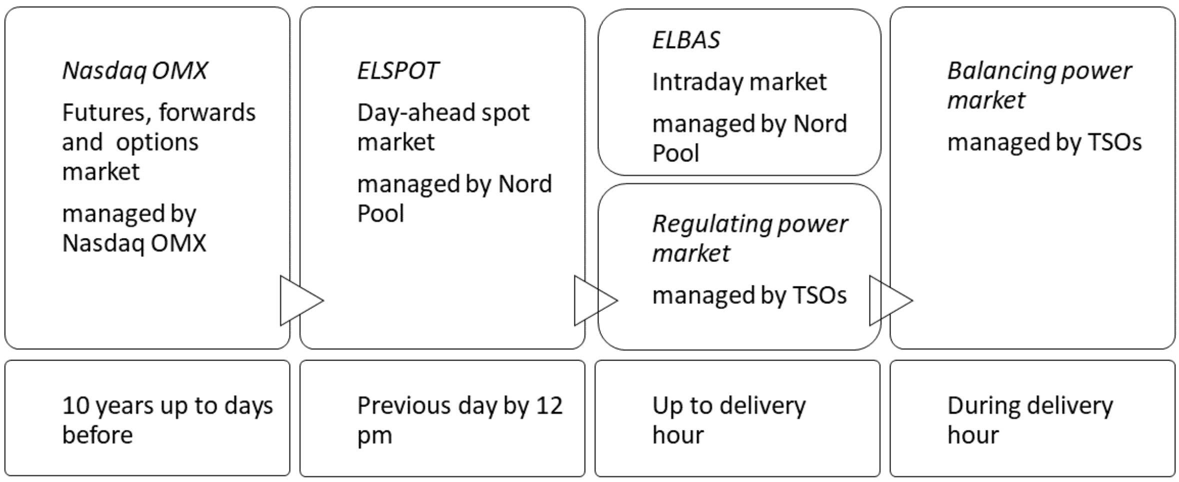
The Swedish market is an integrated part of the Nordic electricity market. The Nordic market is divided into bidding zones, and in each zone demand and supply curves meet to form the zonal price. When transmission capacities between bidding areas are not sufficient, congestion will lead to price divergence between areas; while when transmission capacities between bidding areas are within the capacity limits set by the national TSOs, congestion will lead to price convergence between areas. The zones configuration should be created to handle congestions in the grid.

Both Norway and Sweden underwent bidding zones re-configurations over the years 2008-2011. Norway's adjustment was driven by physical bottlenecks and the change was gradually implemented by the Norwegian TSO, Statnett, without a decision of the European Commission. The Swedish case, however, resulted from the Commission assessment that the national TSO, Svenska Kraftnät, might have abused of its dominant position (Art. 102 TFEU) by discriminating between domestic and foreign (namely, Danish) network users. The splitting in multiple bidding zones was announced on April 2010 and implemented on November 2011, in between the TSO had to avoid further curtailments on the Danish border. The market re-configuration is my treatment variable and it can be considered as an exogenous variation as it was imposed by the European Commission.

The Nordic electricity market consists of four markets (Figure 2). Firstly, the OMX

Nordic Exchange is an equities and derivatives market where Nordic power products such as futures and options are traded from 10 years up to days before deliver. Secondly, the ELSPOT market (which is my main focus) is a day-ahead hourly two-sided auction market managed by the common power exchange Nord Pool where the wholesale electricity trading takes place. Participants can place offers for each hour of the next day until gate closure, 12 hours before the market opens (12pm), meaning that hourly bids for the following day generate in parallel. Thirdly, the ELBAS continuous market operates after the day-ahead market with products that can be traded up to the delivery hour. The ELBAS market, also managed by Nord Pool, works simultaneously with the Regulating Power Market, it counteracts imbalances related to the planned day-ahead market and is managed by the Transmission System Operators (TSOs). Lastly, the balancing market, also managed by the TSOs, takes place during the delivery hour. Either the generators or the buyers can increase/decreases their output/consumption, if needed for system balance.

Figure 2: Market Design in the Nordic Area.

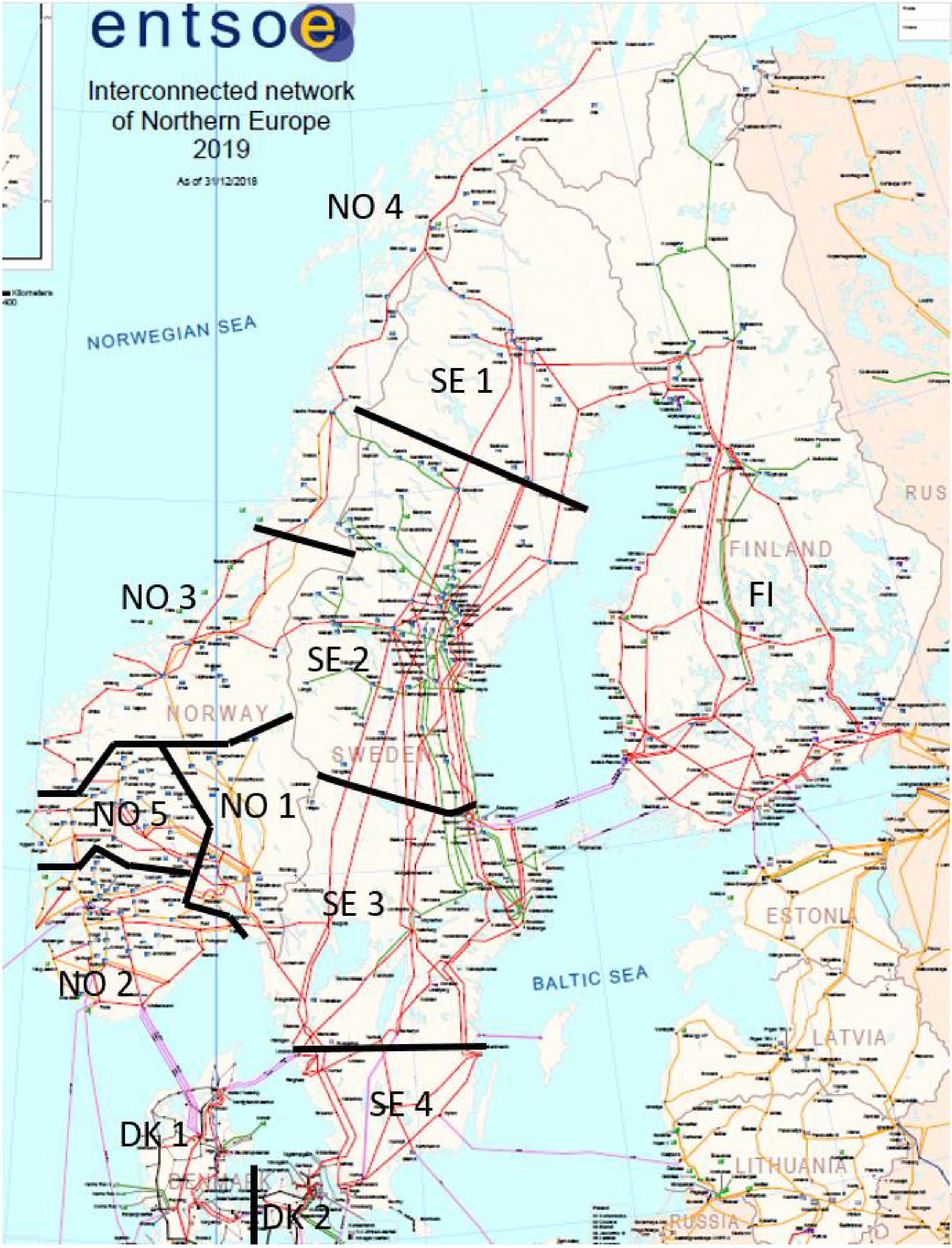


Note: Authors' elaboration based on TemaNord 2016:540, Nordic Council of Ministers.

The Nord Pool power market calculates one aggregate price based on four countries (Denmark, Finland, Norway, and Sweden) and twelve corresponding bidding zones[4](Figure

[4]On November 2011, after the re-configuration, the twelve zones are divided as follows: two zones for Denmark, one for Finland, five for Norway and four for Sweden. In these twelve zones, hydro-power contributes to about 50% of the total power generation, although countries have different generation mixes. Denmark takes its capacity evenly from thermal generation and wind power; Finland is based on

Figure 3: Bidding zone configuration as of Nov. 1, 2011.



Source: Nord Pool AS

3). This price, called the System price assumes away transmission constraints (capacities are set to infinity) and is determined as the unconstrained market clearing price of the above mentioned countries. Due to its calculation, the prices arising in each bidding zone differ from the system price because of congestions that are either country- or bidding zone- specific.

1.2 Data

I mainly collect data from the Nord Pool's Power Market Data and from the Svenska kraftnät[5] system data. I use data on electricity prices, consumption, production, import, export, temperatures and carbon dioxide prices. I focus on Sweden and its bidding zones. My dataset includes hourly observations for 14 years, from 2005 to 2019. Data on prices, production and consumption is collected from the ELSPOT day-ahead market: it includes hourly prices and traded buy and sell volumes [6]. I integrate the ELSPOT dataset with data from Svenska kraftnät where consumption and production per bidding zone is recorded also before the market splitting[7]. I collect data on import and export with neighbouring countries from a dedicated section in the Nord Pool's Power Market Data. By combining production and consumption with import and export, I can calculate data on the flows between Swedish bidding zones. I build the daily price variable by averaging 24-hour prices and by summing up the hourly volumes per day. The country-level price in the post-treatment period is obtained as an average weighted by buy volume per bidding zone, as in (as in Equation A1 in Appendix A.2[8]).

In my analysis, I use two empirical applications that I apply at different levels: firstly, I use a diff-in-diff approach to compare the Swedish price to the system price; secondly, I use a regression discontinuity in time (RDiT) to measure the effects on the flows within the Swedish bidding zones and between each zone and its neighbouring countries. Hence, I

conventional sources such as thermal and nuclear generation; Sweden is fuelled by hydro-power in the North and nuclear and thermal production in the South, even if it has been going through a process of nuclear decommissioning in the last decade; finally, Norway is almost entirely based on hydro-power, allowing for flexible and cheap energy.

[5]The Swedish Transmission System Operator

[6]Buy volumes are different from sell volumes because of trade between zones.

[7]The ELSPOT dataset only includes data on existing bidding zones.

[8]I use buy volumes as I take a consumer's perspective.

work on two different dimensions: national level prices (diff-in-diff approach) and bidding zones level production and consumption volumes (RDiT approach).

1.2.1 Price

In Table 1 I report summary statistics before and after the intervention for the relevant outcome variables of the diff-in-diff analysis. Over my period of interest, prices both from Sweden and from the System show a decreasing trend: in the post-intervention period prices were, on average, 20% lower. The standard deviation is also similar in terms of magnitude with slightly smaller values for the System price[9]. Figure 4 shows the

Table 1: Summary statistics of price by 12 months windows.

		Sweden		System	
Time window		Mean	Std. Dev.	Mean	Std. Dev.
2 windows before	357	47.91	11.43	46.99	8.48
1 window before	349	53.01	15.30	51.89	15.25
1 window after	353	33.21	10.89	31.58	9.99
2 windows after	365	40.08	7.12	38.78	6.19

Note: Summary statistics of average daily price by 12 months windows for System and Sweden prices. The windows start on November 1st and end on October 31st, e.g., "1 window after" the treatment is the average price from the first day after the intervention (November 1st, 2011) to 366 days afterwards (October 31st, 2012). Values in the top and in the bottom percentile are dropped.

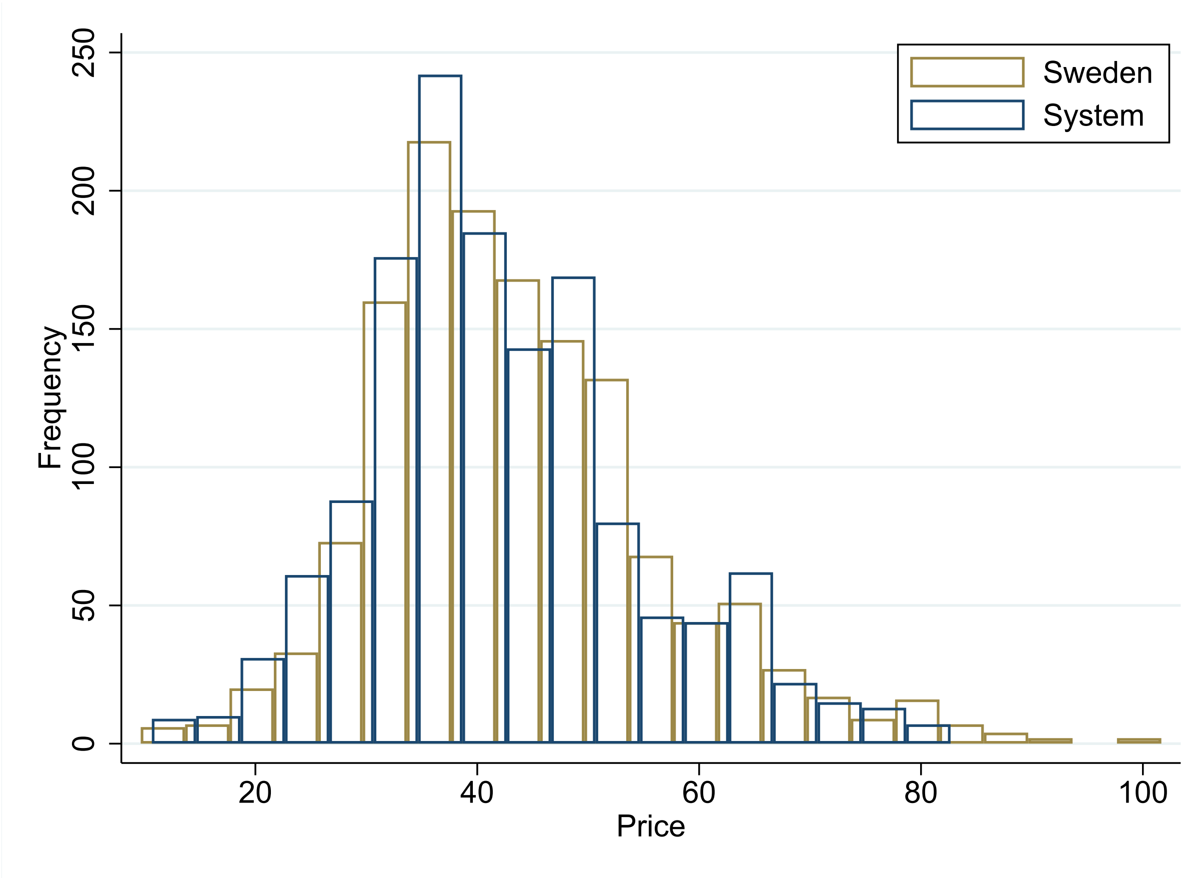
distribution of daily price in Sweden compared to the System values. The two sets of prices have a similar distribution, with the system price being slightly more right skewed.

Electricity prices and volumes have periodic fluctuations since they typically have hourly, weekly and yearly seasonality. Hourly seasonality is not considered here because I use average daily prices. In the RDiT I account for day of the week, monthly and yearly seasonality with seasonal dummies. I show the day of the week and monthly seasonality by including dummy variables in an OLS regression with robust standard errors. I estimate the following two equations:

$$Price_t = \alpha + \beta_1 Monday_t + \beta_2 Tuesday_t + ... + \beta_6 Saturday_t + u_t \quad (1)$$

[9]Summary statistics is replicated by including outliers, in Appendix A.3. Swedish higher values of the standard deviation are due to maintenance of nuclear power plants in 2010 that caused very high spikes in prices.

Figure 4: Distribution of Swedish and System price.



Note: This figure shows the distribution of price in Sweden compared to the System. Price values in the top and in the bottom percentile are dropped.

$$Price_t = \alpha + \beta_1 February_t + \beta_2 March_t + ... + \beta_{11} December_t + u_t \quad (2)$$

By estimating Equation 1 I find out that the day of the week seasonality has a clear and consistent pattern with higher prices during the week days that start decreasing on Fridays and reach their lowest point on Sundays. Table 2 shows the estimated coefficients: Sundays and Saturdays are not statistically different from each other and are, on average, much lower compared to the week days. Prices during the weekdays are at least 5€/MWh higher than the weekends' ones. By estimating Equation 2 I find that monthly seasonality shows a clear inverse relationship between cold temperatures and prices: the lower the average temperatures, the higher the prices [10]. Table 3 shows that estimated coefficients for each month: the highest prices are reached from December to March, while the summer months are characterized by lower prices with the lowest peak in July.

Table 2: Coefficients for day of the week dummies.

Monday	5.20*** (1.35)	Tuesday	5.79*** (1.33)
Wednesday	5.22*** (1.28)	Thursday	6.13*** (1.38)
Friday	5.17*** (1.43)	Saturday	1.57 (1.34)

Note: OLS with Swedish price as dependent variable. Number of observations:1,424. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

1.2.2 Swedish bidding zones

Table 4 describes the prices in the four bidding zones during the time period after the re-configuration. Zones 1 and 2 are almost identical for all the observed statistics, while they differ from Zones 3 and 4. In the observed time period, from November 2011 to November 2013, the prices among all the four zones converged for 466 days out of 731 (64%)[11] Zone characteristics help explain the prices and their relative difference. In the Northern parts of the country (SE1 and SE2) the power balance is significantly

[10] See Tables A2 in Appendix A.2

[11] SE1 and SE2 converged for 712 days (97%), SE2 and SE3 converged for 626 days (86%), SE3 and SE4 converged for 526 days (72%).

Table 3: Coefficients for monthly dummies.

February	4.17** (2.10)	March	-1.98 (1.93)	April	-7.53 (1.63)
May	-10.64*** (1.67)	June	-12.65*** (1.61)	July	-14.60 (1.69)
August	-12.77*** (1.64)	September	-11.11 (1.68)	October	-9396 (1.59)
November	-8.19*** (1.67)	December	-3.03 (2.26)		

Note: OLS with Swedish price as dependent variable. Number of observations:1,424. Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 4: Prices in the four bidding zones.

Zone	Mean	Std. Dev.	Min.	Max.
SE1	35.67	10.24	7.38	99.61
SE2	35.70	10.23	7.38	99.61
SE3	36.15	10.79	7.38	101.26
SE4	37.49	10.98	7.38	101.26

Note: Prices in the four different zones in Sweden. Average of daily price over the post-treatment period from November 2011 to November 2013.

stronger than in the Southern zones, where 82% of the consumption takes place (Table 5). Moreover, while most of the consumption takes place in the Southern part (SE3 and SE4), the 81% of the electricity from hydroelectric is produced in the Northern part (SE1 and SE2)[12].

Table 5: Consumption and production by bidding zone.

Zone	Consumption	Production	Prod. Hydro
SE1	8.2	19.9	19.2 (96%)
SE2	15.2	39.5	37.4 (95%)
SE3	84.8	78.8	11.4 (14%)
SE4	23.7	6.3	1.7 (27%)
Total	131.9	144.5	69.7 (48%)

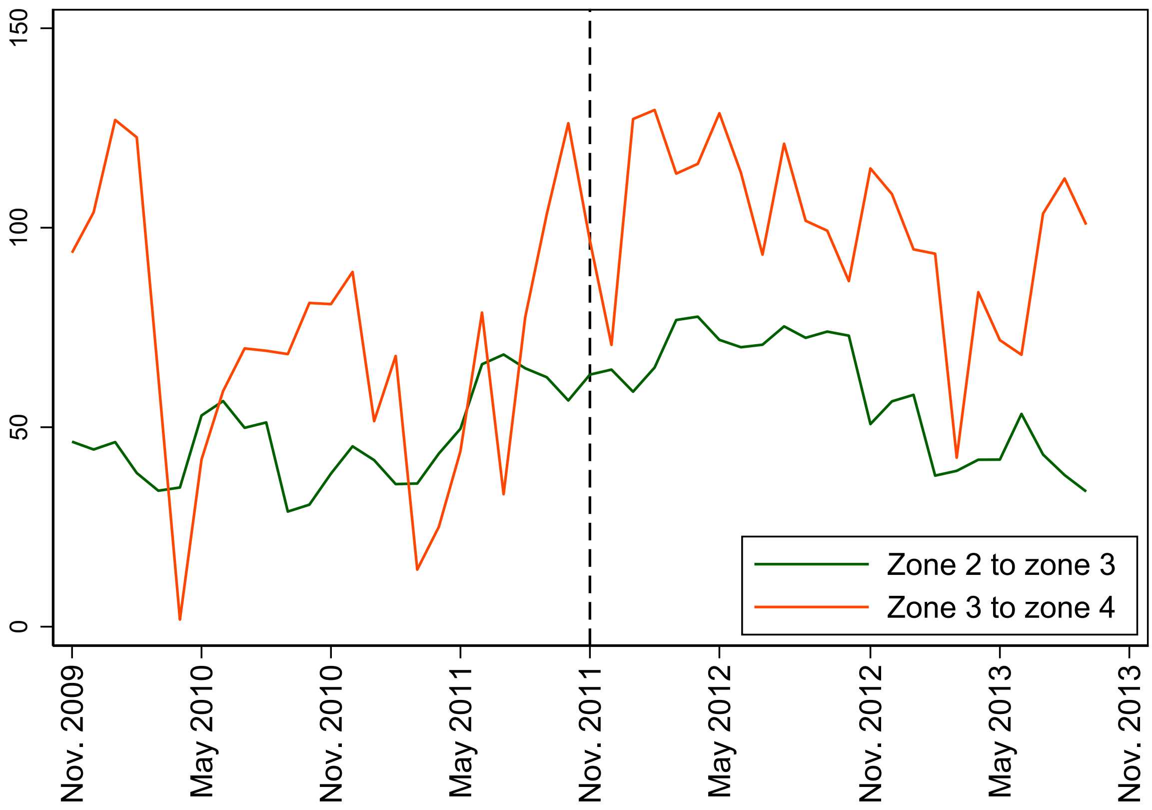
Note: Average yearly production and consumption from November 2009 to November 2013. Values are expressed in TWh.

A proper bidding zone configuration allows for a more efficient usage of the transmis-

[12]For yearly summary statistics see A2 in Appendix A.2.

sion grid and improved trading opportunities[13]. An inefficient use of the network that requires many remedial actions favours intra-zonal trading at the expense of the cross-zonal flows[14]. Therefore, the Nord Pool re-configuration is expected to increase flows with the neighbouring countries due to lower prices in the North and to diminish the internal flows towards the South because of the entrance of additional suppliers in zones 3 and 4, driven by higher prices. The flows between zones and with the neighbouring countries are respectively reported in Figures 5 and 6. In Figure 5 I include flows from zone 2 to 3 and from zone 3 to 4[15]. Graphical evidence (Figure 5) suggests that both zones 4 and 3 are net importers and that cross-zonal flows seem to increase over time. As for trading

Figure 5: Flows within zones.



Note: This figure shows the distribution of monthly net flows between zones in Sweden. Value are expressed in thousand MWh.

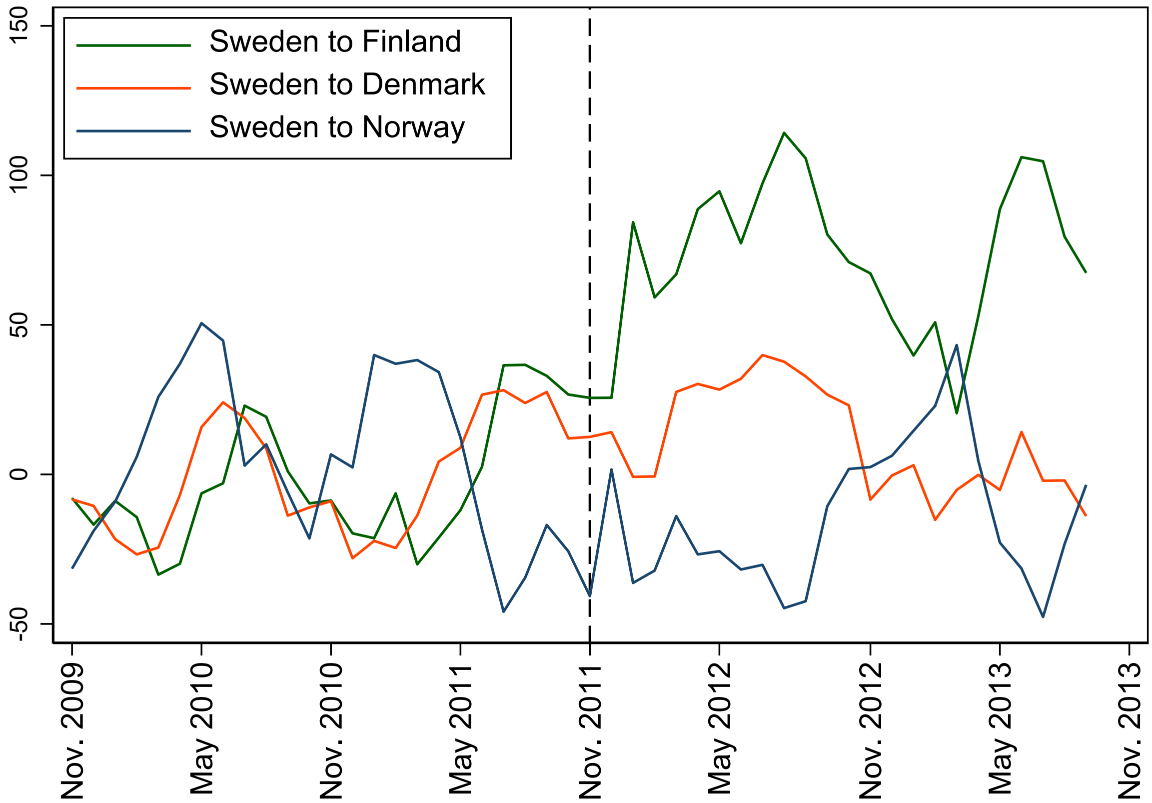
[13]Stakeholders argue that smaller bidding zones imply lower market liquidity and lower competition levels. This debate, although, is beyond the scope of this analysis

[14]Regulation (EU) 2019/943: *"the configuration of bidding zones in the Union shall be designed in such a way as to maximise economic efficiency and to maximise cross-zonal trading opportunities in accordance with Article 16, while maintaining security of supply."*

[15]For further details on the capacities between zones and countries, see Figure A4 in Appendix A.2

with neighbouring countries, Figure 6 shows no evidence of an increase for Denmark and Norway, while it seems that there is a net increase in export to Finland[16].

Figure 6: Flows with neighbouring countries.



Note: This figure shows the distribution of monthly net flows between Sweden and its neighbouring countries. Value are expressed in thousand MWh.

1.3 Methodology and Results

1.3.1 Difference-in-differences

I apply the diff-in-diff approach to estimate the impact of the re-configuration on national level prices, as described in Section 1.2.1 and I use the System price as comparison group. I estimate the following model:

$$Price_{it} = \alpha + \beta_0 Post_t + \beta_1 Treated_i + \beta_2 Treated_i * Post_t + f_i + f_t + u_{it} \quad (3)$$

[16]The observed increase in flows between Finland and Sweden does correspond to additional available transmission capacities as shown in Table A4 in Appendix A.2.

where i indicates either Sweden or the System and t is the day indicator. The key indicator variable in this specification is the interaction term between $Post_t$, a dummy variable equals to one after the policy intervention, $Treated_i$, a dummy variable equals to one for the treated group (Sweden). The coefficient of the interacted term $Treated_i * Post_t$ estimates the effect of the policy intervention for Sweden in the post treatment period. I add daily and area fixed effects. Errors are clustered at the area level to allow for dependence of observations within these groups. The key identifying assumption is that the System price is not affected by the policy intervention. This assumption is reasonable since the System price, by definition, is calculated for the Nordic area by setting internal transmission capacities between the bidding zones to infinity. The System price is a common benchmark for the Nordic Market that allows for more liquidity because, by assuming no bottlenecks, it limits the effect of temporary transmission constraints and reduces the risk of manipulation. I compare the untreated group, the system price, to the treated group, the Swedish price, and I assume that if no treatment had occurred the distance between the two groups would have stayed the same. Unfortunately, I can not add additional control as I do not have country specific characteristics for the system price (e.g. GDP, temperatures, population). For the parallel trends assumption to hold, I need to restrict my sample to 500 days before and after the policy intervention (roughly 3 semesters before and afterwards November 2011). Before running the full regression I do a back-of-the-envelope calculation, whose results are shown in Table 6. In Column 1 I report the means for price for Sweden, before and after the policy intervention, in Column 2 the price average values for the System, before and after, and in Column 3 the difference between Sweden and System average values, before and after. Price mean values are higher for Sweden both in the pre-treatment and in the post-treatment period. Taking the difference of the differences I get an increase in price equal to 0.2 euros.

Table 7 presents estimates from a linear regressions with time and group fixed effects, as in Equation 3. Each Column reports the estimates of the coefficient of interest, the interaction between $Treated_i$ and $Post_t$. The dependent variable is always the price level, for two price areas, Sweden and the System. In column 1a, I only include day and area fixed effects and I find that Swedish price increases by 0.21 euros significant at the 1 per-

Table 6: Back-of-the-envelope diff-in-diff.

	(1)	(2)	(3)
	Sweden	System	Difference
Before	51.43	50.42	1.01
After	35.12	33.91	1.21*
Diff-in-diff	16.31***	16.51***	0.20

Note: The number of observations before the market re-configuration is 968; the number of observation after the re-configuration is 976. Values in the top and bottom percentile are dropped. The significance is estimated with a t test.

cent level (approximately 0.5 percent of the average price) in the post-intervention period. In column 1b, I add to the model area specific trends, allowing for non-parallel trends. When the trend is included, the estimates remain positive and significant but gets smaller (coefficient equal to 0.06 euros significant at the 1 percent level, 0.1 percent of the average price). As a robustness check, I run the same regression on a reduced sample: I drop the 200 days in the window around the cutoff to check whether the estimated effect of the policy is due to an immediate reaction that does not last over time. In both the specifications I find that the result is stronger if I remove the window around the threshold, this implies that the result is stronger away from the threshold. In column 2a, with day and area fixed effects, I find that Swedish price increases by 0.50 euros significant at the 1 percent level (approximately 1 percent of the average price) in the post-intervention period. In column 2b, I add to the model area specific trends, I get a coefficient equal to 1.77 euros significant at the 1 percent level (approximately 4 percent of the average price)[17]. These results are not surprising since the re-configuration is expected to increase prices in the North and to decrease prices in the South, giving stronger price signals in the areas where supply is scarce. As theoretically proved by (Bjørndal & Jörnsten, 2001), I show that the average Swedish price increased after the re-configuration. This result also confirms that, as stated by the European Commission, prices in Sweden were low because the internal congestion was not reflected in the price formation mechanism. Before the market

[17] I repeat the main regressions keeping values in the top and bottom percentile. Results are shown in Table A5 in Appendix A.3. In December 2010 daily prices in Sweden were influenced by both an increase in demand for electric heating due to extremely cold weather conditions and reduced availability of the Ringhals-4 nuclear reactor. This capacity reduction resulted in a positive deviation of Swedish price compared to the System price (Directorate-General for Energy, 2011). Due to the presence of these exceptional high spikes, the estimated coefficients have opposite sign.

re-configuration, the internal congestion was more managed internally while keeping the day-ahead prices low. After the policy intervention, the internal congestion emerged because it was reflected into higher prices. Moreover, by curtailing ATCs, the Swedish TSO was also excluding the demand from the neighbouring countries by prioritizing internal flows.

Table 7: Diff-in-diff estimation.

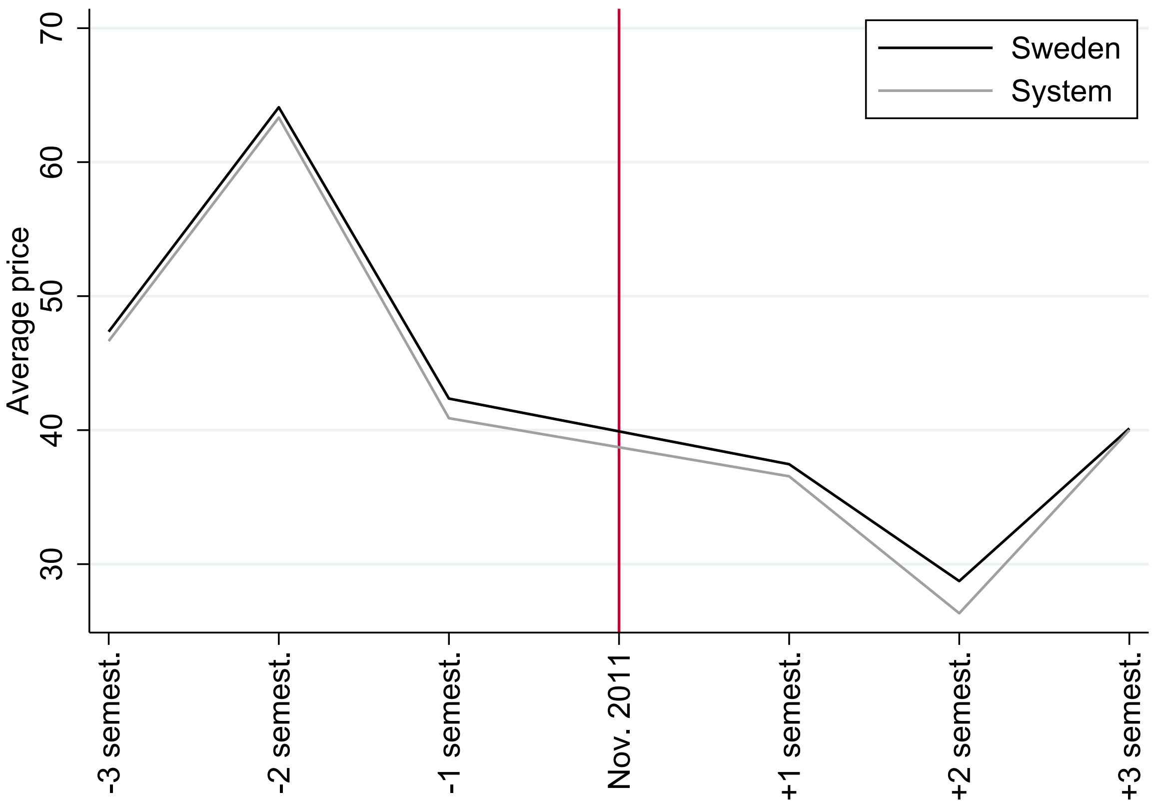
	Full sample		Reduced sample	
	(1a)	(1b)	(2a)	(2b)
$Treated_i \cdot Post_t$	0.21***	0.06***	0.50***	1.77***
	(0.00)	(0.00)	(0.00)	(0.00)
Mean Dep. Var.	42.69	42.69	43.86	43.86
Observations	1,944	1,944	1,556	1,556
R-squared	0.99	0.99	0.99	0.99
Trend	No	Yes	No	Yes
FE	area, day	area, day	area, day	area, day

Note: The table reports the coefficients and standard errors (in brackets) associated with $Treated_i * Post_t$ from the estimation of Equation 3. In the full sample, Columns 1a and 1b, variables are observed 500 days before and after the policy intervention. In the reduced sample, Columns 2a and 2b, variables are observed 400 days before and after a window of 100 days from the policy intervention (100 days before and 100 days afterwards). Values are expressed in euros. Values in the top and bottom percentile are dropped. Significance level: *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Figure 7 shows that the treated and the untreated groups were heading in the same direction in the pre-treatment period. The distance between the Swedish and the System price is constant in the lead-up to treatment. Prices are averaged by six months intervals for simplicity. In the pre-intervention period trends are parallel, with a slight divergence in the last semester. In the post-intervention period prices keep following a parallel trend for the first semester, however, as captured by the diff-in-diff, the Swedish price decrease less than the system price and their trend starts diverging. I further verify that the parallel trends assumption holds, by performing a falsification test to see if the trends are different. I run the following regression:

$$Price_{it} = \alpha + \beta_0 Trend_t + \beta_1 Trend_t * Treated_i + u_{it} \tag{4}$$

Figure 7: Parallel trends.



As a robustness check, I run Equation 4 using only data from before the treatment period where the $Trend_t * Treated_i$ coefficient allows for trends to be different for the two groups (results shown in Table A6 in Appendix A.3). The coefficient of interest is -0.002 with standard errors of 0.003, meaning that there is no evidence of a different trend between the two groups. As this test shows that parallel trends assumption is likely to hold, I am more prone to rely on the coefficients in Columns 1a and 2a from Table 7.

1.3.2 Regression discontinuity in time

I apply the Regression Discontinuity in Time (RDiT) to estimate the impact of the re-configuration on cross-zonal and cross-country flows. In the RDiT , the running variable of the regression discontinuity is time and it defines the treatment eligibility: the treatment begins after a threshold in time is reached. This empirical analysis presents several differences with a typical regression discontinuity design, the most relevant ones are: there is no need for testing for bouncing around the threshold, because it is not possible; it does not rely on cross-sectional analysis, therefore the window defined by the running variable can not be properly shrunk; a time-series approach needs to be adopted[18]. These issues raise the need for additional controls to identify the model correctly. I include both the auto-regressive term of the dependent variable to account for the time series nature of the data, and additional control variables to adjust for unobservable factors correlated with time. As for the time window, I use four years (two years before and two after the treatment) needed to absorb the seasonality effect. The identifying assumption behind my discontinuity is that absent the bidding zone reconfiguration flows would have changed smoothly at the cutoff date. Therefore I assume that the flows on the days before the policy intervention work as a counterfactual for the days after the the intervention. Any difference that smoothly changes close to the cutoff is captured by the running variable.

My main specification uses local linear regressions within a given bandwidth of the treatment threshold of two years, and controls for the running variable (distance from the

[18]Among the papers using RDiT: Anderson, (2014); Auffhammer & Ryan Kellogg (2011); Chen & Whalley (2012); Davis & Kahn (2010).

cut-off day) on both sides of the threshold. Formally, I estimate the following model:

$$\begin{aligned} Flow_t = \alpha + \beta_0 Flow_{t-1} + \gamma_0 \cdot 1(Time_t \geq C) + \gamma_1(Time_t - C) + \\ \gamma_2 1 \cdot (Time_t \geq C) \cdot (Time_t - C) + \eta_0 X_t + \eta_1 P_t + \\ f_{dow} + f_{month} + f_{year} + u_t \end{aligned} \tag{5}$$

where C is the cutoff day, equal to November 1st, 2011. In Equation 5, the RDiT estimator, γ_0, calculates the local average treatment effect (LATE) of the market re-configuration. The outcome variable $Flow_t$ is either the cross-zonal or the cross-country flows and is measured at day t, and $Flow_{t-1}$ is its lagged value. $(Time_t - C)$ is the distance in days from the cutoff and C is the cutoff defining the treatment group, so that the dummy variable $1 \cdot (Time_t \geq C)$ defines treatment and control groups, that correspond to before/after the treatment: it takes the value of one after the policy intervention, and zero otherwise. In some specifications, I also add the squared terms of the running variable and its interaction with the post-treatment variable. I add control variables that improve the efficiency of the estimation. In the vector X_t I include monthly carbon prices[19], and, for the cross-country flows I also include instrumented electricity prices. The vector P_t includes a third-order polynomial time trend to control for time series variation. I include day of the week monthly and year fixed effects. u_i is the error term, since the observations are likely to be serial correlated I cluster the standard errors at monthly-level.

Changes in net flows within Sweden and between Sweden and its neighbouring countries are an indicator of the re-configuration's effectiveness. Within Sweden, the policy is expected to decrease the flows going from North to South because it encourages production in the South by setting different prices in case of congestion. Between Sweden and its neighbouring countries, flows are expected to change depending on the prices of the neighbouring countries. In fact, the national TSO was accused to curtail capacity with the neighbouring countries due to internal congestion. Absent internal congestion thanks to the four bidding zones, a decrease in net flows from North to South should be observed.

[19] Carbon prices are European Union Allowance prices from the European Union Emission Trading System.

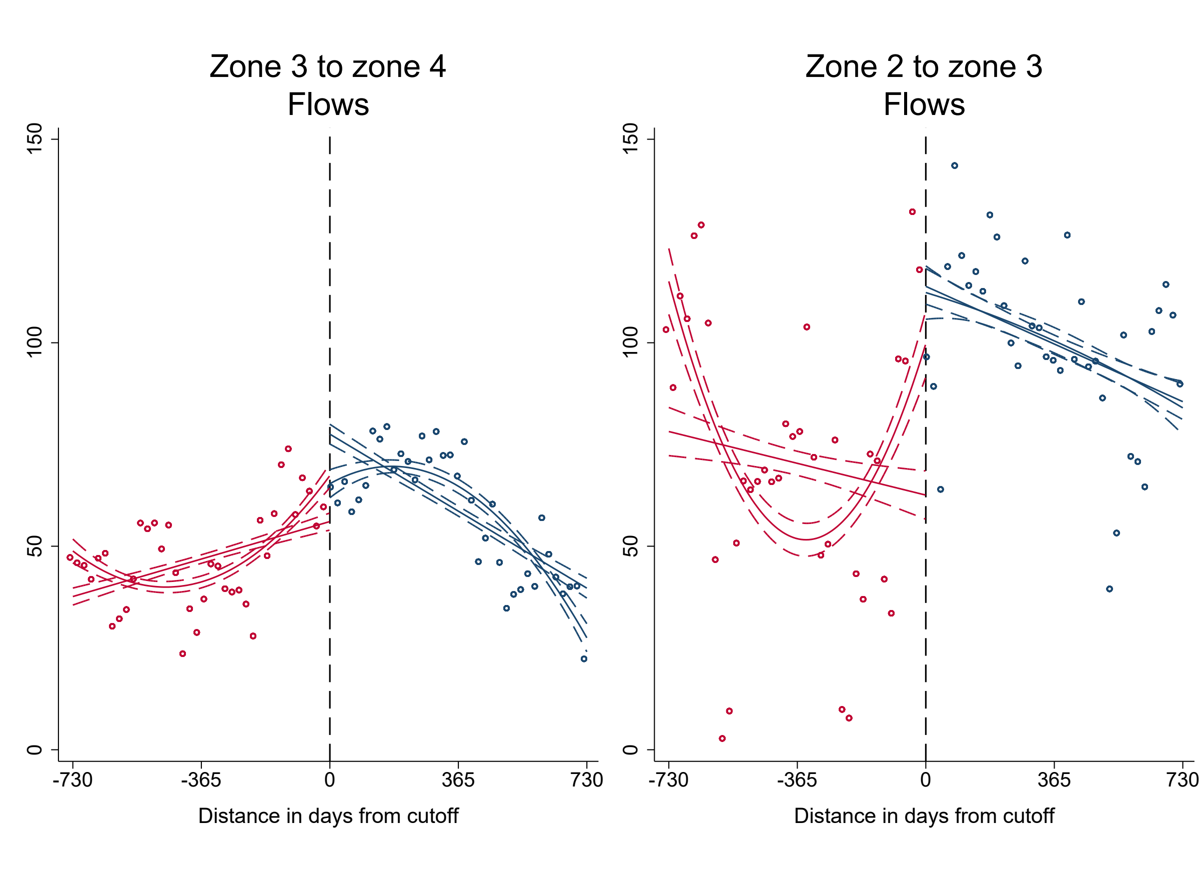
Cross-zonal flows. I estimate the cross-zonal flows with the regression described in Equation 5. I consider the flows between zones: from zone 3 to zone 4 and from zone 2 to zone 3. Both of the analysed net flows describe the flows going from North to South. I do expect a slight decrease in flows due to minor congestion. Given that the TSO stopped curtailing ATCs with other countries, Northern areas could export their electricity abroad (i.e. Finland). Moreover, higher prices in the South encouraged electricity producers to enter the market.

Before running my regressions, I show graphical evidence of the RDiT around the cutoff (Figure 8). I plot the means of the daily flows grouped in bins, then I add the linear and the quadratic fit for OLS on both sides of the cut-off. Given the shape of the data, my preferred specification is the quadratic fit, although the seasonality of the data makes it difficult to visually inspect the discontinuity. For the flows from zone 3 to zone 4 I do not notice any significant decrease either in the plotted bins or in the quadratic form, although I get a positive change in the linear fit. As for the net flows from zone 2 to zone 3 I notice an increase in net flows at the cutoff in both the linear and the quadratic form. In addition, if I look at the trend in the post-treatment period, I see a decreasing trend that suggests that over time the South reduced its reliance on the production in the North of the country.

My main estimations for cross-zonal flows are presented in Table 9. In Columns 1 and 3 I run the linear RDiT, while in Columns 2 and 4 I run the RDiT in its quadratic form. I use both the full sample and a reduced sample, the donut hole where I drop observations in the 40 days around the cutoff date. For the net flows from zone 3 to zone 4 I do not find neither statistically significant or consistent results across all the specification. For the net flows from zone 2 to zone 3, contrary to graphical evidence, I notice a consistent negative sign that, however, is statistically significant only in the donut hole specification with the squared form. The coefficient of interest is equal to -9.63 with standard errors of 3.44 that correspond to decrease of 11% of the net flows.

To check how flows behave at varying bandwidths, I perform a bandwidth sensitivity test where I reduce the bandwidth from 730 (two years) to 330 days (less than one year) around the cutoff date. I run the RDiT as in Equation 5 using the quadratic form as in

Figure 8: Graphical evidence: cross-zonal flows.



Note: This figure shows the linear and quadratic fit for OLS on both sides of the cutoff. Values are expressed in thousand MWh.

Column 2 of Table 8. I show results in Figure A5 in Appendix A.3, and I notice that there seems to be a slight decrease in net flows from zone 2 to zone 3. The negative effect found in the donut hole, is validated by this robustness test where I find a significant decrease from 380 to 630 days. As for the flows from zone 3 to zone 4, it is not notably sensitive to the bandwidth choice.

Table 8: Regression discontinuity in Time estimation: cross-zonal flows.

	Full sample		Donut hole	
	(1)	(2)	(3)	(4)
	Panel A: Zone 3 to zone 4			
$1(Time_t \geq C)$	1.99	-5.41	3.17	-6.05
	(2.65)	(3.53)	(3.12)	(4.56)
Mean Dep. Var.	52.74	52.74	52.48	52.48
R-squared	0.75	0.76	0.76	0.76
	Panel B: Zone 2 to zone 3			
$1(Time_t \geq C)$	-2.38	-4.68	-4.59	-9.63**
	(2.67)	(2.81)	(4.08)	(3.44)
Mean Dep. Var.	85.05	85.05	84.48	84.48
R-squared	0.89	0.89	0.89	0.89
Observations	1,460	1,460	4,420	1,420
RD	linear	quadratic	linear	quadratic
Cubic Trend	Yes	Yes	Yes	Yes
FE	time	time	time	time

Note: The table reports the coefficients and standard errors (in brackets) associated with $1(Time_t \geq C)$ from the estimation of Equation 5. Variables are observed 2 years before and 2 years after the policy intervention. Values are expressed in thousand MWh. In all the regressions I include the lag of the dependent variable, daily temperatures and precipitations in Sweden, monthly carbon prices, a third-order polynomial trend and time fixed effects (day of the week, month and year). Columns 1 and 3 are based on linear RDiT, Column 2 and 4 on quadratic RDiT. In Column 1 and 2 I use the full sample. In Column 3 and 4 I use a donut hole and I drop observations in the 40 days around the threshold. Errors are clustered at monthly level. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Finally, as a robustness check, I run a falsification test where I drop the observations after the policy intervention and I introduce a fake treatment on November 1st, 2010. I repeat my RDiT as in Equation 5 using two years (from November 2009 to November 2011) with a fake treatment introduced halfway. I run the test using the full sample and the quadratic form. Across all the specifications, I do not find any effect of the fake treatment.

Cross-country flows. I analyse cross-country flows because after the re-configuration the likelihood that the national TSO could manipulate the Available Transmission Capacities strongly decreased. For this reason I expect to find an increase in the flows with neighbouring countries. In the new configuration, the national TSO did not have to intervene by curtailing ATCs because the new market mechanism with different prices in each zone already took into account the internal bottlenecks.

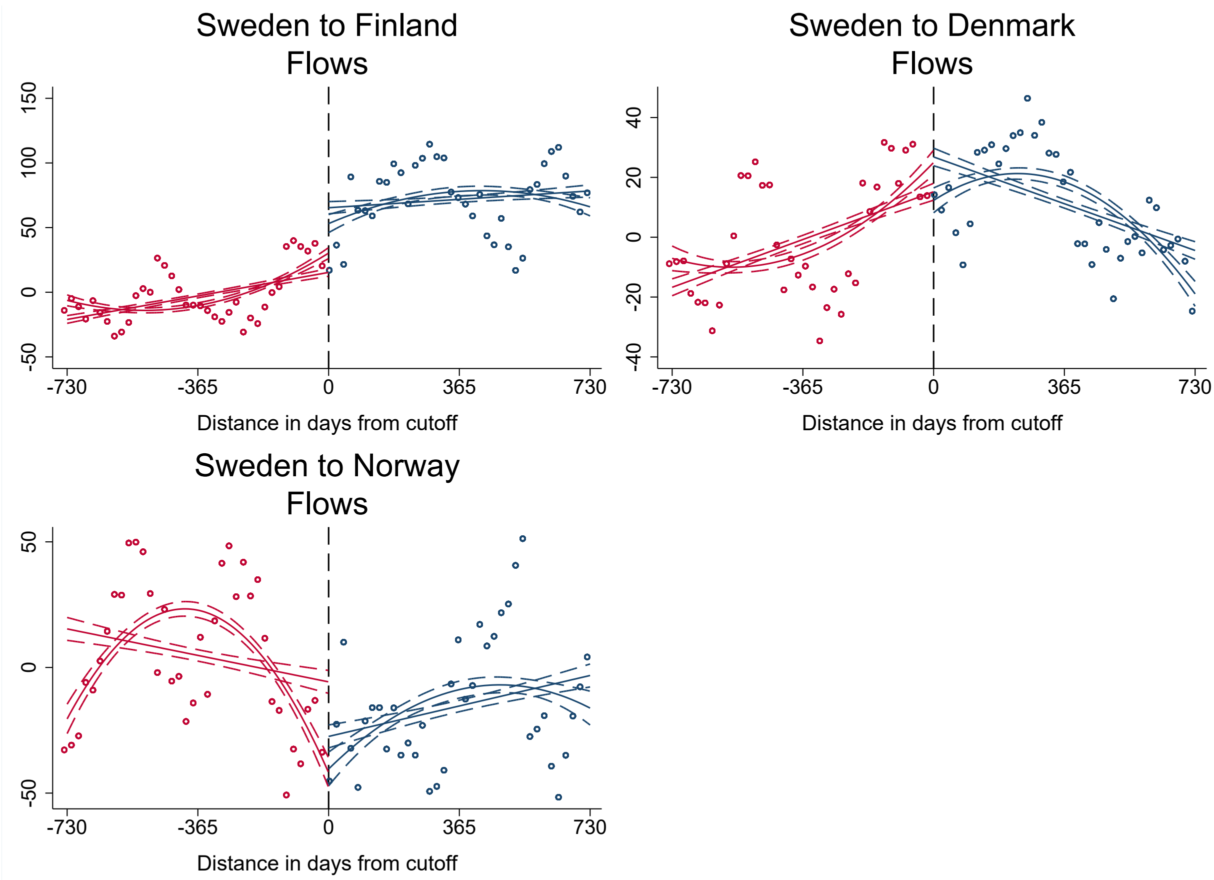
I estimate the cross-country flows with the regression described in Equation 5. In this model specification I also include the Swedish price since it influences the net export to neighbouring countries. However, as the Swedish price is endogenous to the model, I use a two-stage least-squares (2SLS) including average temperatures in Sweden as an instrumental variable.

Before running my regressions, I show graphical evidence of the effect of the market re-configuration (Figure 9). As for cross-zonal flows, I plot the means of the daily flows grouped in bins and I add the linear and the quadratic fits for OLS on both sides of the cut-off. Also in this case, given the shape of the data, my preferred specification is the quadratic fit. I consider the flows with countries in the Nord Pool area: Finland, Denmark and Norway. For the net flows from Sweden to Finland I notice that the fitted lines present a break at the discontinuity in both the linear and the quadratic form and the observed data show an increase in the the days after the cutoff. I do not notice any discontinuity for net flows from Sweden to Denmark, however I get opposite although small variations for the linear and quadratic fit, suggesting that modelling the time series properly is of pivotal importance in order to have accurate estimates. For the net flows from Sweden to Norway I do not see any discontinuity either in the plotted data, or in the quadratic fit. However, the linear form shows a decrease in net flows with a decreasing trend on the left side and an increasing trend on the right side.

As I want to estimate the net flows after the policy intervention, I need to account for factors that influence their pace. One of the main determinants that I want to include is the price in Sweden, which however is endogenous to the model. Therefore, I use a 2SLS where I use average daily temperatures in Sweden as an exogenous source instrument[20].

[20]The instrumental variable, temperatures, is the beginning of a casual chain that influences the

Figure 9: Graphical evidence: cross-country flows.



Note: This figure shows the linear and quadratic fit for OLS on both sides of the cutoff. Values are expressed in thousand MWh.

I use this instrument to account for exogenous variation in the Swedish price. Temperatures contribute significantly to the price formation since they are strongly related with consumption and production. On one side, the demand for electricity in winter sharply increases due to the widespread electric heating in the whole Nordic region[21]. On the other side, the cold temperatures and the ice create operational constraints in the system.

I examine the validity of the instrumental variable by showing results from the first stage and from the weak identification tests (Table A8 in Appendix A.3). In the first-stage the endogenous variable, price in Sweden, is regressed on the exogenous variables and the excluded instrument, average temperatures in Sweden. The estimated coefficients show that when temperatures in Sweden decrease the electricity price goes up by almost 2 euros. I find that this result is significant for all specifications at 1% level. The weak identification tests I use include the traditional F-statistics and the Montiel-Plueger (M-P) test[22]. I include the M-P test as it reports the effective statistics at 5% level and critical values in presence of heteroskedasticity. The reported F-statistics always satisfy the rule of thumb of a value at least equal to 10 (Staiger et al., 1997). The M-P test also suggests that the instrument is strong because the statistics are (almost) above the critical value of 23.11 that corresponds to a maximum bias of 10% [23]. From these tests and from the first stage I can conclude that average temperatures are a relevant instrument for the price in Sweden.

My main estimations for cross-country flows are presented in Table 9. In Columns 1 and 2 I run simple OLS regressions, respectively in their linear and in their quadratic form, that include the endogenous Swedish price. In Columns 3 and 4 I show the results from the 2SLS using the quadratic form, respectively using the full sample and the donut hole[24]. Across the four specifications net exports to Finland are significantly positive, ranging from 1.67 (5% of the net export) to 4.04 (12%), suggesting that the re-configuration

endogenous variable, price, that, in turn, affects the dependent variable, net flows (Angrist & Pischke, 2015).

[21] See the strong inverse relationship between temperatures and price in Figure A2 in Appendix A.2.

[22] In case of one instrument and one endogenous regressor the F test of excluded instrument and the M-P statistic coincide.

[23] The interpretation is that there is a 5% probability that the bias in the estimator is 10% of the worst possible case.

[24] In the donut hole I drop observations in the 40 days around the threshold.

Table 9: Regression discontinuity in Time estimation: cross-country flows.

	OLS		2SLS	
	(1)	(2)	(3)	(4)
	Panel A: Sweden to Finland			
$1(Time_t \geq C)$	1.67*	2.95*	4.04**	4.95*
	(0.88)	(1.48)	(1.65)	(2.83)
F-statistic	-	-	23.19	22.24
Mean Dep. Var.	34.52	34.52	34.52	34.97
R-squared	0.95	0.95	0.95	0.95
	Panel B: Sweden to Denmark			
$1(Time_t \geq C)$	4.17	-6.53	1.60	1.97
	(3.96)	(5.63)	(2.89)	(4.22)
F-statistic	-	-	22.86	21.96
Mean Dep. Var.	5.21	5.21	5.21	4.96
R-squared	0.80	0.81	0.78	0.78
	Panel C: Sweden to Norway			
$1(Time_t \geq C)$	0.24	-8.39	-0.88	0.14
	(2.41)	(3.66)	(3.01)	(3.99)
F-statistic	-	-	28.39	26.91
Mean Dep. Var.	-5.25	-5.25	-5.25	-4.31
R-squared	0.86	0.86	0.86	0.86
Observations	1,460	1,460	1,460	1,420
RD	linear	quadratic	quadratic	quadratic
Cubic Trend	Yes	Yes	Yes	Yes
FE	time	time	time	time

Note: The table reports the coefficients and standard errors (in brackets) associated with $1(Time_t \geq C)$ from the estimation of Equation 5. In Columns from 1 to 3 variables are observed 2 years before and 2 years after the policy intervention. In Column 4 I use a donut hole and I drop observations in the 40 days around the threshold. In all the regressions I include the lag of the dependent variable, daily temperatures and precipitations in Sweden, monthly carbon prices, a third-order polynomial trend and time fixed effects (day of the week, month and year). In Column 1 I only include the linear terms of the RDiT, in Columns from 2 to 4 I also include the quadratic terms of the RDiT. Columns 3 and 4 report the estimated local average treatment effect from a separate two-stage least squares regression. The reported F-statistic is the F-statistic for excluded instrument. Values are expressed in thousand MWh. Errors are clustered at monthly level. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

resulted in an increase in net export to Finland. From Table A4 in Appendix A.2 I get prima facie evidence that after the re-configuration there was an increase in Available Transmission Capacities that predicts the increase in net flows from Sweden to Finland that I find with my estimation.

In Column 1 the estimated increase in net flows is equal to 1.67 (standard errors of 0.88) while in Column 2 I get a coefficient of 2.95 (standard errors of 1.48) which corresponds to almost 9 % of the average flow. In Column 3the estimate coefficient is equal to 4.04 (standard errors of 1.65) which corresponds to an increase of 12% of the average flows. Finally, in the sample with the donut hole (Column 4) I find a slightly bigger effect of 4.95 (standard errors 2.83) which corresponds to an increase in net flows of 14%. This greater effect suggests that the effect is not guided by an immediate response. I do not find any significant effect for the other observed net flows (from Sweden to Denmark and from Sweden to Norway) with big standard errors of the estimated coefficients. These results are robust to both the linear and the quadratic form.

To check the robustness of these results, I perform a bandwidth sensitivity test where I reduce the bandwidth from 730 (two years) to 330 days (less than one year) around the cutoff date. I run the 2SLS as in Equation 5 using the quadratic form as in Column 3 of Table 9. Results, shown in Figure A6, are not notably sensitive to the bandwidth choice. The positive effect found for the net flows from Sweden to Finland holds for almost all the bandwidth choices, with smaller coefficients between 580 and 680 days. The coefficients of the net flows from Sweden to Denmark are approximately equal to zero and always statistically insignificant. Finally, the coefficient of the net flows from Sweden to Norway is statistically significant and negative between days 380 and 530, but firmly below zero and not statistically significant from 530 to 730 days.

As an additional robustness test, I run a falsification test as in Table A7 for cross-zonal flows. For the falsification test, I can not rely on the 2SLS as in Column 3 of Table 9 because in the shorter window adopted to run this test, the instrument chosen fails the weak identification tests. Therefore I use the OLS as in Column 2 of Table 9. The coefficients of the fake treatment, both in their linear and in their quadratic form show that there is no discontinuity at the fake cutoff date (see Table A9 in Appendix A.3).

1.4 Conclusions

My measure of market efficiency is based on accurate price signals and the full use of cross-country transmission capacities. This short term signals are necessary to attract investments in generation, load and grid where they are needed the most to realise long-term solutions.

In this empirical work, I analyse the impact of the market re-configuration on price, cross-zonal and cross-country flows.

My contribution to the literature is threefold. Firstly, I find evidence that in case of internal congestion, day-ahead prices slightly increase when smaller zones are adopted. The magnitude of the effect varies from 0.1 to 4 percent of the average price, depending on the preferred specification. As higher prices are set in zones where demand exceeds supply, this mechanism sends appropriate price signals for long-term investments, e.g., in additional power plants, in transmission lines. These results are robust to both the control for trend that allows for diverging trends in the pre-treatment period, and to the reduced sample where observations around the policy intervention are dropped. This result suggests that market efficiency improved as prices better reflected actual capacity constraints. Secondly, I find that the policy intervention increased the cross-country opportunities resulting in an increase in the net exports from Sweden to Finland. This increase was likely to be guided by the increase in Available Transmission Capacities between Sweden and its neighbouring countries. The size of the increase that I measure ranges from 5 to 14 percent. The RDiTs' results hold to varying bandwidths. I additionally run the falsification tests to exclude the hypothesis that the estimated effects are not driven by the policy intervention. These results suggest that inter-connectors between zones were fully used and this improved market efficiency.

I am aware that a full assessment of the bidding zones configuration also requires further analysis on liquidity and market structure. I hold space for future projects on these additional measures. Nevertheless, I want to stress out that my results prove compelling evidence that the market re-configuration was successful in giving more appropriate price signals and in eliminating congestion within the country.

References

(1) [dataset] EUA Emission Spot Primary Market Auction Report, available: eex.com/en/market-data/environmental-markets

(2) [dataset] National Oceanic and Atmosphere Administration, *Global Historical Climatology Network daily (GHCNd)*, available: https://www.ncei.noaa.gov/products/land-based-station

(3) Anderson, M. (2014). "Subways, Strikes, and Slowdowns: The Impacts of Public Transit on Traffic Congestion", *American Economic Review*, 2014, 104 (9), 2763–2796.

(4) Angrist, J. D., Pischke , J.-S. (2015). "Mastering 'Metrics: The Path from Cause to Effect", *Economics Books*, Princeton University Press, edition 1, number 10363.

(5) Auffhammer, M., Kellogg, R. (2011). "Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality", *American Economic Review*, 2011, 101 (6), 2687–2722.

(6) Bask, M., Lundgren, J., Rudholm, N. (2009). "Market power in the expanding Nordic power market", *Applied Economics*, 43(9), 1035-1043. doi: 10.1080/00036840802600269

(7) Bjørndal, E., Bjørndal, M., Cai, H., Panos, E. (2018). "Hybrid pricing in a coupled European power market with more wind power", *European Journal of Operational Research*, 264(3), 919–931. doi: 10.1016/j.ejor.2017.06.048

(8) Bjørndal, M., Jörnsten, K. (2001). "Zonal Pricing in a Deregulated Electricity Market", *The Energy Journal*, 22, 51–74. doi: 10.2307/41322907

(9) Chen, Y., Whalley A. (2012). "Green Infrastructure: The Effects of Urban Rail Transit on Air Quality", *American Economic Journal: Economic Policy*, 2012, 4 (1).

(10) Davis, L.W., Kahn, M.E. (2010). "International Trade in Used Vehicles: The Environmental Consequences of NAFTA", *American Economic Journal: Economic Policy*, 2010, 2 (4), 58–82.

(11) Dijk, J., Willems, B. (2011). "The effect of counter-trading on competition in electricity markets", *Energy Policy*, 39(3), 1764–1773.
doi: 10.1016/j.enpol.2011.01.008

(12) Directorate-General for Energy (2011). "Quarterly Report on European Electricity Markets".

(13) Egerer, J., Weibezahn, J., Hermann, H. (2015). "Two Price Zones for the German Electricity Market: Market Implications and Distributional Effects", *Energy Economics*, 59, 365–381. doi: 10.1016/j.eneco.2016.08.002

(14) European Union, "Regulation (EU) 2019/943 of the European Parliament and of the Council".

(15) Green, R. (2007). "Nodal pricing of electricity: how much does it cost to get it wrong?", *Journal of Regulatory Economics*, 31(2), 125–149. doi: 10.1007/s11149-006-9019-3

(16) Hadsell, L., Shawky, H. A., Marathe, A. (2004). "Estimating the Volatility of Wholesale Electricity Spot Prices in the US", *The Energy Journal*, Volume 25 (Number 4), 23–40. doi: 10.2307/4132335627

(17) Huisman, R. (2008). "The influence of temperature on spike probability in day-ahead power prices", *Energy Economics*, 30(5), 2697–2704.
doi: 10.1016/j.eneco.2008.05.007

(18) Huisman, R., Huurman, C., Mahieu, R. J. (2007). "Hourly electricity prices in day-ahead markets", *Energy Economics*, 29(2), 240–248.
doi: 10.2139/ssrn.918050

(19) Huisman, R., Kiliç, E. (2013). "A history of European electricity day-ahead prices", *Applied Economics*, 45(18), 2683–2693.
doi: 10.1080/00036846.2012.665601

(20) Karakatsani, N. V., Bunn, D. W. (2008). "Forecasting electricity prices: The impact of fundamentals and time-varying coefficients", *International Journal of Forecasting*, 24(4), 764–785. doi: 10.1016/j.ijforecast.2008.09.008

(21) Kristiansen, T. (2012). "Forecasting nord pool day-ahead prices with an autoregressive model", *Energy Policy*, 49, 328 - 332. (Special Section: Fuel Poverty Comes of Age: Commemorating 21 Years of Research and Policy)
doi: 10.1016/j.enpol.2012.06.028

(22) Mazengia, D. H., Le Anh Tuan. (2008). "Forecasting spot electricity market prices using time series models", In *2008 IEEE international conference on sustainable energy technologies*(p. 1256-1261).

(23) Neuhoff, K., Twomey, P. (2010). "Wind power and market power in competitive markets", *Energy Policy*, 38(7), 3198–3210. doi: 10.1016/j.enpol.2009.07.031

(24) Sarfati, M., Hesamzadeh, M. R., Holmberg, P. (2019). "Production efficiency of nodal and zonal pricing in imperfectly competitive electricity markets", *IFN Working Paper*, No. 1264, 2019. doi: 10.1016/j.esr.2019.02.004

(25) Staiger, D., Stock, J. H. (1997). "Instrumental Variables Regression with Weak Instruments", *Econometrica*, 65(3), 557–586. https://doi.org/10.2307/2171753

A Appendix

A.1 Bidding zone

In the electricity market, demand and supply must be balanced instantly, therefore when there is lack of capacity to transport the electricity from where it is produced to where it is demanded, the system incurs in congestion management issues. Congestion issues can be solved with market-based solutions that often take into consideration the market configuration, i.e. the bidding zones.

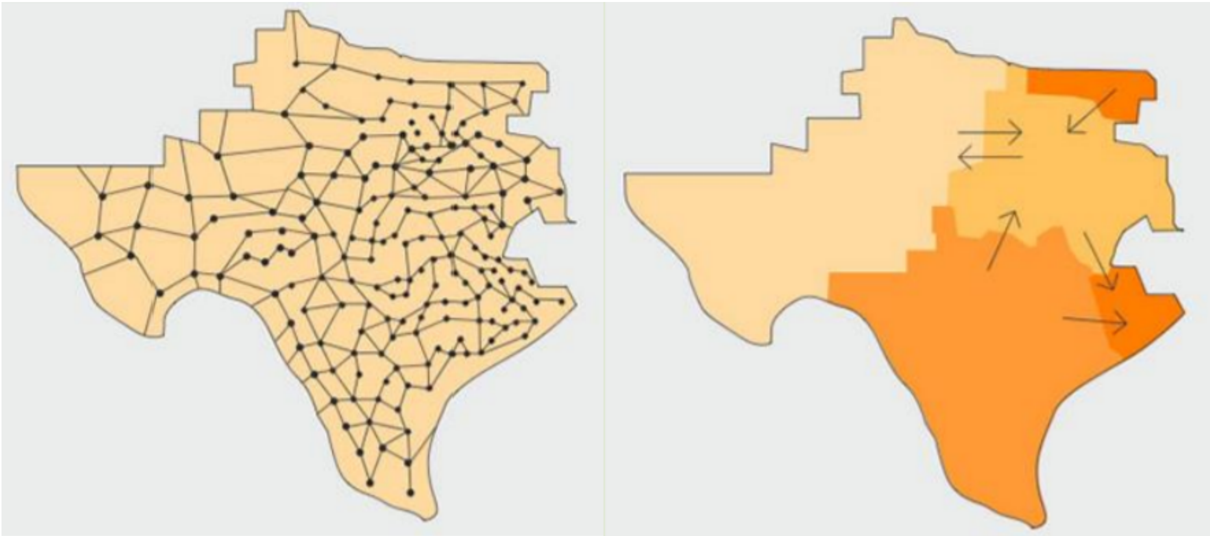
By definition, the bidding zone is the the largest geographical area within which market participants are able to exchange energy without capacity allocation (EU 543/2013).

In the zonal market, during the market clearing process that forms the price (as shown in Section 1) the transmission lines within a zone are set to infinity while the transmission lines between zones are taken into account. As the internal transmission constraints are ignored, the day-ahead dispatch may overload some transmission lines. For this reason, within a single bidding zone there should be no internal congestion. In fact, the internal congestion would affect both the internal market and the neighbouring zones. In case of internal congestion, as for the internal market, the Transmission System Operator (TSO) has to adopt costly remedial actions to remove congestion (e.g. re-dispatching, counter trading, Demand Side Response). As for the neighbouring zones, the TSO often reduce ex-ante the available transmission capacities because the operator wants to prioritize the internal flows. However, this response is not allowed as the Articles 18 and 35 of Treaty on the functioning of the European Union expressly prohibit discrimination based on nationality and quantitative restrictions on exports.

In a nodal market all the transmission constraints are considered in the day-ahead market and there are as many prices as nodes in the market. The market clearing mechanism itself eliminates congestion because the congestions are taken into account in the price formation. Zonal market can be interpreted as the aggregation of many nodal markets that converge in one single zone with uniform pricing.

In the European Union large bidding zones are widespread and in most cases they coincide with national borders. Nodal markets exist in the United States, Australia,

Figure A1: Nodal market (on the left) vs zonal market (on the right).



New Zealand. In Figure A1 I give graphical representation of the difference between the zonal and the nodal markets. On the left-hand side of the figure I show a nodal market where each dot corresponds to a node where the producer is paid with the local price. In this market configuration there are neither imports nor exports because the capacity constraints are already taken into account in the electricity dispatch. On the right-hand side of the figure I show a zonal market. The price is set within each of the colored areas and the arrows represent the inter-connectors that allow for flows between the zones. Throughout this work, I consider the re-configuration into four zones in Sweden as a proxy for the nodal market configuration because in extreme cases the small zones correspond to the nodes.

A.2 Data

$$Price\ Sweden = w_{1,t} * P_{1,t} + w_{2,t} * P_{2,t} + w_{3,t} * P_{3,t} + w_{4,t} * P_{4,t} \tag{A1}$$

Data on temperatures are retrieved from The Global History Climatology Network Daily, which is an integrated database of daily climate summaries from land surface stations in the world. It is a dataset from the National Oceanic and Atmosphere Administration from the United States of America. For each country, the database contains as many observations as the number of stations present in the country. Therefore, the country daily temperature is calculated by taking the averages of all the available stations.

Prices from the European Union Emission Trading Scheme are collected from the European Energy Exchange (EEX) where Emission Spot Primary Market takes place. These prices are conventionally called EUA. Data is collected at monthly level. Flows between zone 3 and 4 are calculated as follows:

$$Flows_{3\to4} = Production_4 - Consumption_4 - Export_4 + Import_4 \tag{A2}$$

When calculating the flows from zone 2 to 3 I also subtract the net flows from zone 3 to 4 estimated with Equation A2. Therefore, I estimate:

$$Flows_{2\to3} = Production_3 - Consumption_3 - Export_3 + Import_3 + Flows_{3\to4} \tag{A3}$$

I can not estimate flows from zone 2 to 1 because I can not disentangle the exchange of zones 1 and 2 with the Northern part of Norway (NO4). I verify my results by comparing the flows I estimate with the Nord Pool data on the internal flows after the reconfiguration: values are consistent with my estimation.

Table A1: Descriptive statistics from November 2009 to November 2013.

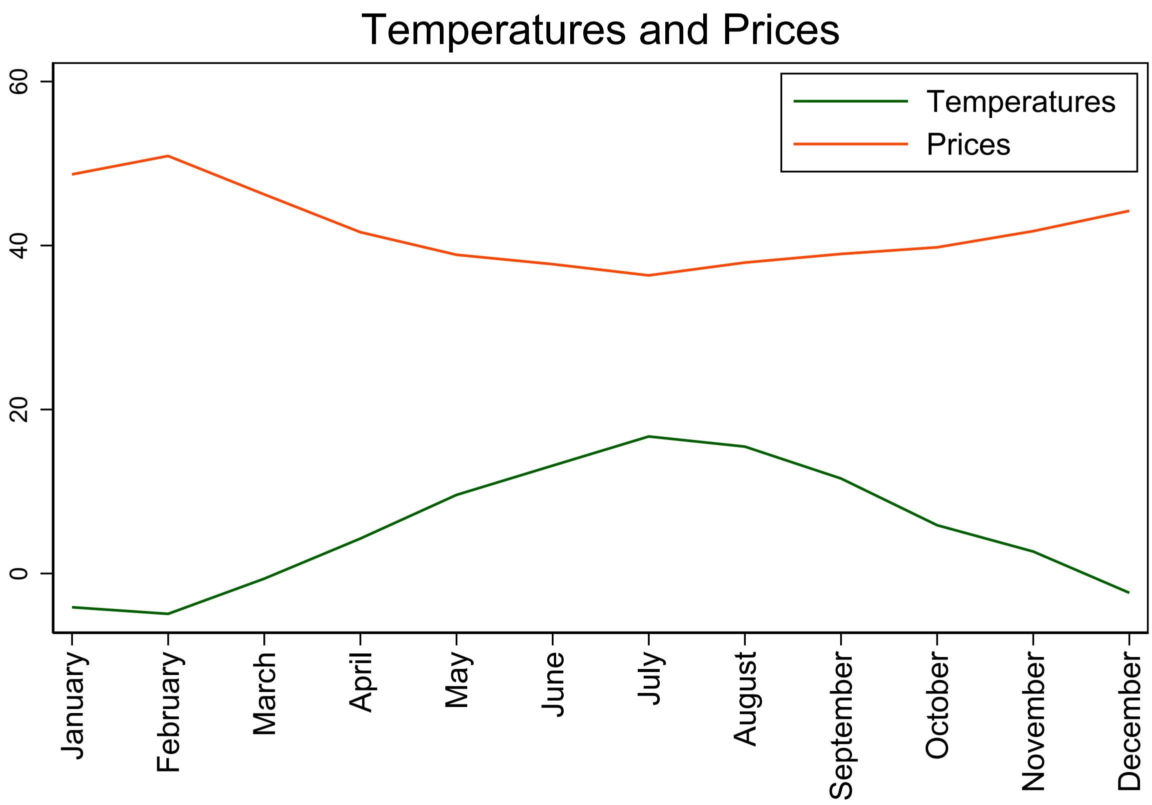
Variable	Mean	Std. Dev.	Min.	Max.
Price Sweden	44.495	21.883	7.377	505.681
Price System	42.490	14.623	5.790	134.804
CO_2 price	10.146	4.231	3.54	16.4
Flows from 2 to 3	85.053	39.265	-38.396	182.762
Flows from 3 to 4	52.743	187.827	-0.207	97.944
Flows from Sweden to Finland	34.525	46.939	-41.927	131.720
Flows from Sweden to Denmark	5.212	22.603	-44.986	47.52
Flows from Sweden to Norway	-5.250	33.606	-76.780	81.917
Temperatures Sweden	5.441	8.330	-16.725	21.25
N observations: 1,460				

Table A2: Consumption and production by bidding zone.

Zone	Consumption	Production	Prod. Hydro
	Nov 2009 - Nov 2010		
SE1	7.7	17.5	17.1 (97%)
SE2	15.2	38.2	36.7 (96%)
SE3	86.4	72.9	12.1 (17%)
SE4	23.9	6.8	1.7 (26%)
Total	133.2	135.4	67.6 (50%)
	Nov 2010 - Nov 2011		
SE1	7.8	17.5	16.8 (96%)
SE2	15.5	38.8	36.8 (95%)
SE3	85.8	79.2	10.8 (14%)
SE4	24.3	6.6	1.9 (29%)
Total	133.5	142.0	66.4 (47%)
	Nov 2011 - Nov 2012		
SE1	8.4	22.9	22.0 (96%)
SE2	15.1	45.0	42.9 (95%)
SE3	83.0	80.0	12.5 (16%)
SE4	23.2	5.8	1.8 (32%)
Total	129.7	153.7	79.2 (52%)
	Nov 2012 - Nov 2013		
SE1	8.7	21.8	20.7 (95%)
SE2	15.1	36.0	33.3 (93%)
SE3	83.9	83.1	10.0 (12%)
SE4	23.5	6.1	1.3 (21%)
Total	131.2	147.0	65.3 (44%))

Note: Average yearly production and consumption. Values are expressed in thousand MWh.

Figure A2: Temperatures and prices by month.



Note: Temperatures are expressed in degrees Celsius and prices in euros.

Table A3: Summary statistics of Swedish and System prices by 12 months windows.

Time window	Obs	Sweden		System.	
		Mean	Std. Dev.	Mean	Std. Dev.
2 windows before	365	51.50	32.66	47.98	11.07
1 window before	365	53.88	18.89	52.24	17.30
1 window after	366	32.55	12.07	30.99	11.18
2 windows after	365	40.08	7.12	38.78	6.19

Note: Summary statistics of average daily price by 12 months windows for System and Sweden prices. The windows start on November 1st and end on October 31st, e.g., "1 window after" the treatment is the average price from the first day after the intervention (November 1st, 2011) to 366 days afterwards (October 31st, 2012).

Figure A3: Cross-country flows between Sweden and Finland, import and export. Values expressed in thousand MWh and observed daily between November 2009 and November 2012.

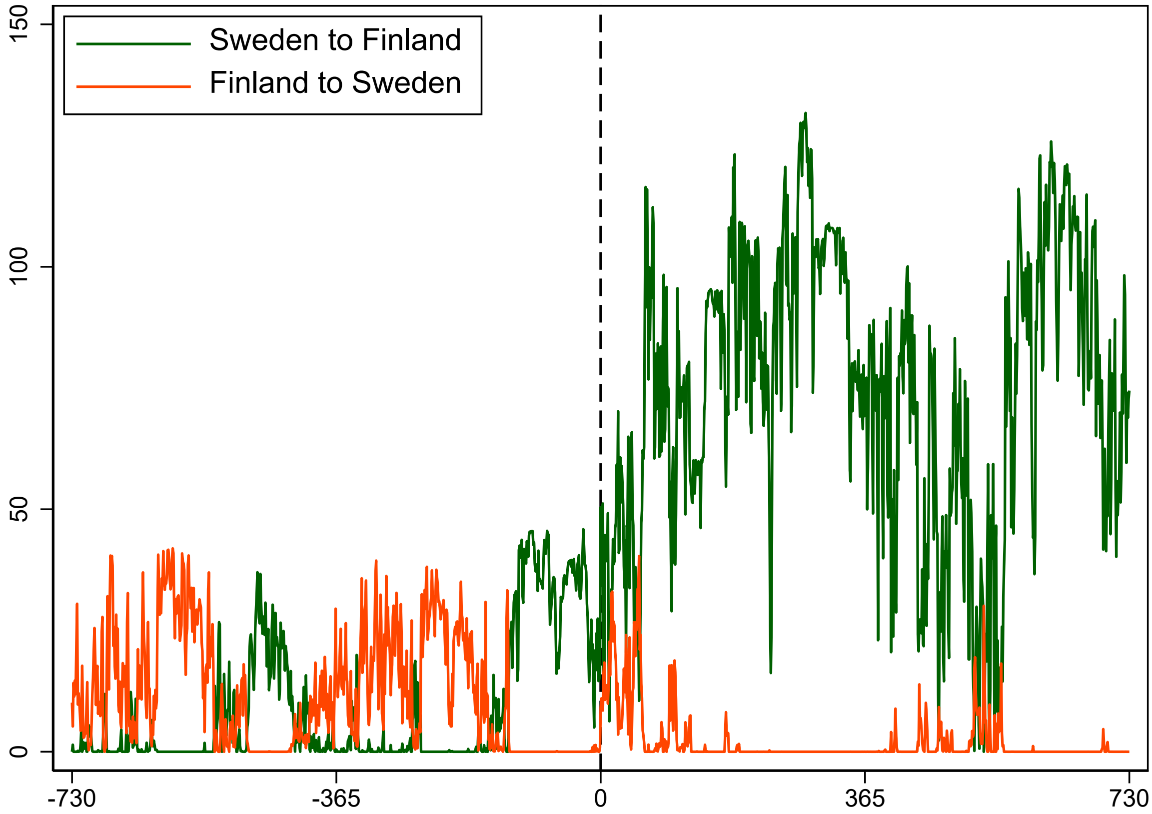
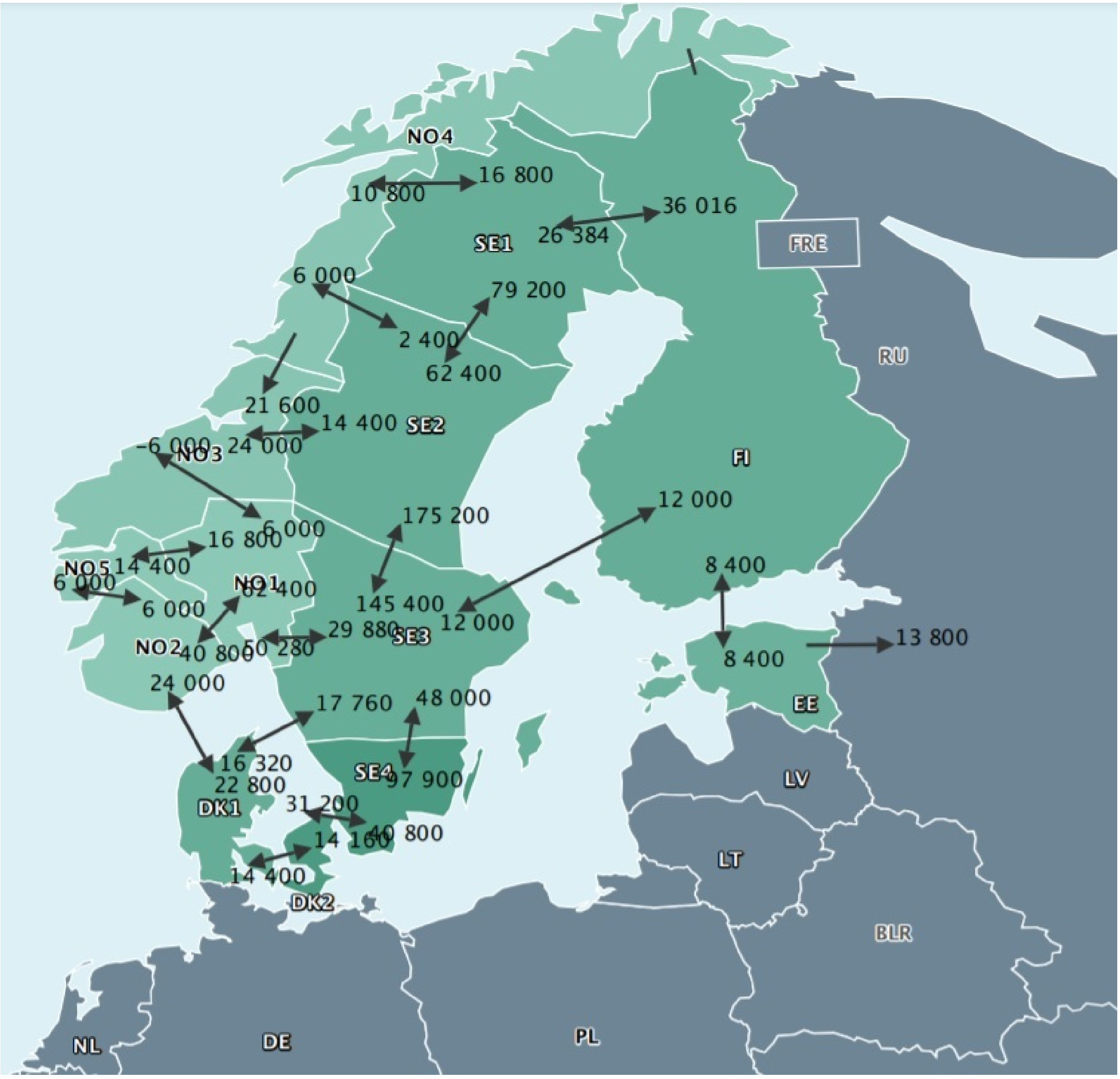


Table A4: Available Transmission Capacity (thousand MWh) between Sweden and Finland.

Date	SE → FI	FI → SE
2 windows before	43.492	38.848
1 window before	43.861	38.043
Date	SE → FI	FI → SE
1 window after	56.872	49.090
2 windows after	57.336	47.177

* *Note:* Summary statistics of average daily ATC. The windows start on November 1st and end on October 31st, e.g., "1 window after" the treatment is the average price from the first day after the intervention (November 1st, 2011) to 366 days afterwards (October 31st, 2012).

Figure A4: Capacities in the Nord Pool area as of November 1st, 2011.



A.3 Additional results

Table A5: Diff-in-diff estimation including outliers.

	Full sample		Reduced sample	
	(1a)	(1a)	(2a)	(2b)
$Treated_i \cdot Post_t$	-0.21***	-0.03***	-0.03***	1.45***
	(0.00)	(0.00)	(0.00)	(0.00)
Mean Dep. Var.	42.71	42.71	44.05	44.05
Observations	2,002	2,002	1,600	1,600
R-squared	0.99	0.99	0.99	0.99
Trend	No	Yes	No	Yes
FE	area, day	area, day	area, day	area, day

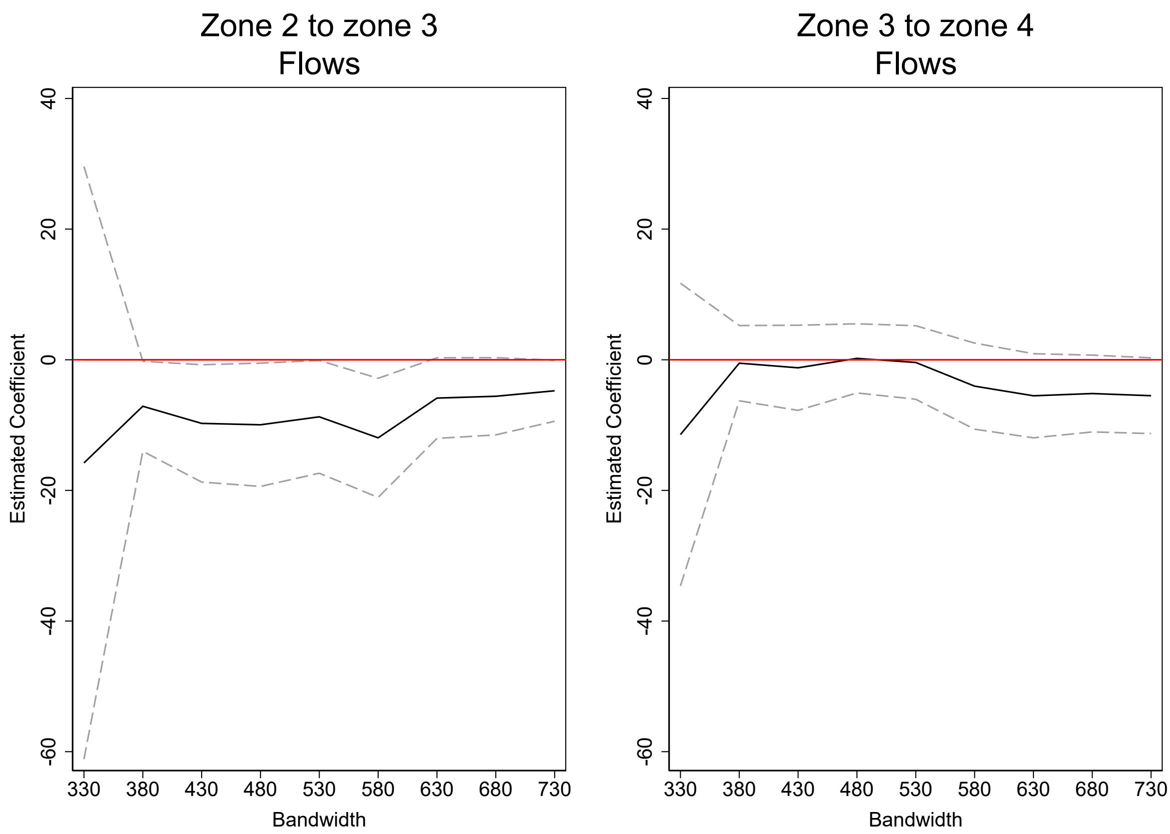
Note: The table reports the coefficients and standard errors (in brackets) associated with $Treated_i * Post_t$ from the estimation of Equation 3. In the full sample, Columns 1a and 1b, variables are observed 500 days before and after the policy intervention. In the reduced sample, Columns 2a and 2b, variables are observed 400 days before and after a window of 100 days from the policy intervention (100 days before and 100 days afterwards). Values are expressed in euros. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Table A6: Falsification test: price.

	Dep. Var.: Price
$Treated_i \cdot Trend_t$	-0.002
	(0.003)
$Trend_t$	0.005
	(0.004)
Mean Dep. Var.	50.93
Observations	968

Note: The table reports the coefficients and standard errors (in brackets) from the estimation of Equation 4. The sample is restricted to observations before the policy intervention. Values are expressed in euros. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Figure A5: Sensitivity of estimates to varying bandwidths.



Note: Coefficients and standard errors of the estimated coefficient $1(Time_t \geq C)$ from Equation 5 with the full sample and the quadratic RD as in Column 2 of Table 8. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Table A7: Falsification test: cross-zonal flows.

	Zone 3 to zone 4		Zone 2 to zone 3	
	(1)	(2)	(3)	(4)
$1(Time_t \geq F)$	34.65	-52.01	34.71	738.57
	(46.77)	(204.33)	(118.86)	(424.80)
Mean Dep. Var.	46.85	46.85	70.39	70.39
R-squared	0.78	0.78	0.92	0.92
Observations	729	729	729	729
RD	linear	quadratic	linear	quadratic
Cubic Trend	Yes	Yes	Yes	Yes
FE	time	time	time	time

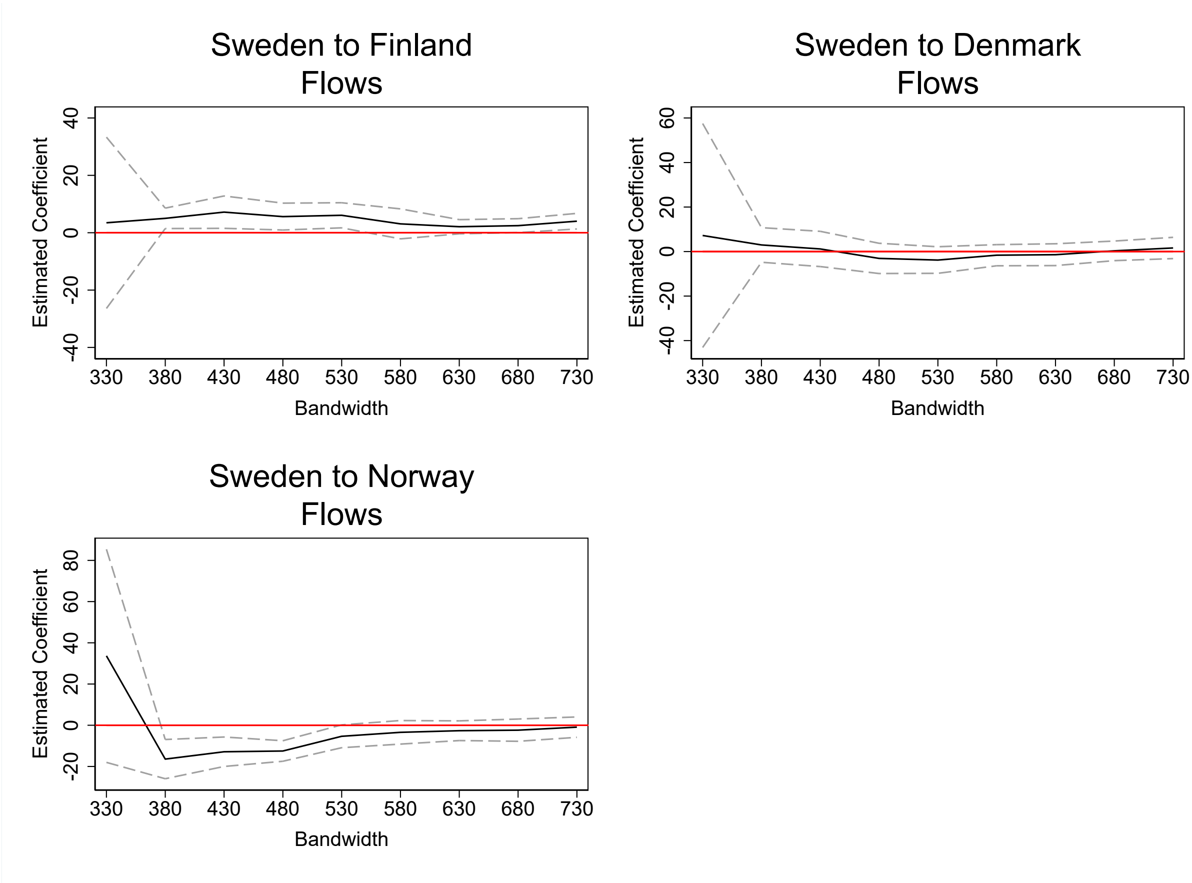
Note: The table reports the coefficients and standard errors (in brackets) associated with $1(Time_t \geq F)$ from the estimation of Equation 5. I replace the real cutoff date C with a fake treatment intervention F, one year before the actual treatment. F corresponds to November 1, 2010. Values after the real cutoff date are dropped, my sub-sample covers the period from November 2009 to November 2011. Values are expressed in thousand MWh. In all the regressions I include the lag of the dependent variable, daily temperatures and precipitations in Sweden, monthly carbon prices, a third-order polynomial trend and time fixed effects (day of the week, month and year). Columns 1 and 3 are based on linear RDiT, Column 2 and 4 on quadratic RDiT. Errors are clustered at monthly level. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Table A8: First stage regressions.

	Second stage DV: Price Sweden		
	(1)	(2)	(3)
From Sweden to	Finland	Denmark	Norway
Avg. Temper.	-1.88****	-1.85***	-1.78***
	(0.39)	(0.39)	(0.33)
F-statistic	23.19	22.86	28.39
M-P Critical Value	23.11	23.11	23.11

Note: The table reports first-stage coefficients from a separate two-stage least squares regression as in Column 3 of Table 9. The dependent variable is the daily price in Sweden and corresponds to the second stage dependent variable. The reported F-statistic is the F-statistic for excluded instrument. The M-P Critical Value refers to the Montiel-Pflueger robust weak instrument test for a maximum IV bias of 10% (I report this statistic because errors are clustered). Results differ because each regression has country specific controls. Variables are observed 2 years before and 2 years after the intervention. Errors are clustered at monthly level. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Figure A6: Sensitivity of estimates to varying bandwidths: cross-country flows.



Note: Coefficients and standard errors of the estimated coefficient $1(Time_t \geq C)$ from Equation 5 with the full sample and the quadratic RD as in Column 3 of Table 9. Significance level: *** p<0.01, ** p<0.05, * p<0.1.

Table A9: Falsification test: cross-country flows.

	Sweden to Finland		Sweden to Denmark		Sweden to Norway	
	(1)	(2)	(3)	(4)	(5)	(6)
$1(Time_t \geq F)$	-3.29	195.95	-33.24	200.81	-71.65**	12.90
	(23.41)	(125.62)	(22.77)	(210.51)	(28.42)	(159.74)
Mean Dep. Var.	-2.87	-2.87	-0.79	-0.79	4.83	4.83
R-squared	0.92	0.92	0.89	0.89	0.90	0.90
Observations	729	729	729	729	729	729
RD	linear	quadratic	linear	quadratic	linear	quadratic
Cubic Trend	Yes	Yes	Yes	Yes	Yes	Yes
FE	time	time	time	time	time	time

Note: The table reports the coefficients and standard errors (in brackets) associated with $1(Time_t \geq F)$ from the estimation of Equation 5. I replace the real cutoff date C with a fake treatment intervention F, one year before the actual treatment. F corresponds to November 1, 2010. Values after the real cutoff date are dropped, my sub-sample covers the period from November 2009 to November 2011. Values are expressed in thousand MWh. In all the regressions I include the lag of the dependent variable, daily temperatures and precipitations in Sweden, monthly carbon prices, a third-order polynomial trend and time fixed effects (day of the week, month and year). Columns 1 and 3 are based on linear RDiT, Column 2 and 4 on quadratic RDiT. Errors are clustered at monthly level. Significance level: *** p<0.01, ** p<0.05, * p<0.1.