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Title: Distributed Energy Generation Techniques and the Competitive Fringe Effect in Electricity Markets<sup>§</sup>

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**Highlights for “Distributed Energy Generation Techniques and the Competitive Fringe Effect in Electricity Markets”**

- We estimate a Cournot model with long-term contracts, international trade and fringe suppliers.
- Fringe suppliers increase competition and lead to a smaller spot market price.
- The pattern of the competitive fringe effect depends on the generation technology.
- Intermittent wind energy generation has a stronger effect than the CHP technology.

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# Distributed Energy Generation Techniques and the Competitive Fringe Effect in Electricity Markets<sup>§</sup>

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## Abstract

We analyse the impact of two different generation techniques used by fringe suppliers on the intensity of competition in the electricity wholesale market. For that purpose we derive a Cournot model of this market taking into account long-term contracts, international trade and fringe suppliers using different energy generating technologies. We apply this model to the Dutch market and estimate the impact of fringe supply on the Lerner index. We find that the fringe supply coming from both intermittent wind generation and combined heat and power (CHP) plants operated by horticultural farmers increases competition, which leads to lower prices in the electricity market. However, this impact is relatively small. The effect per unit of intermittent wind electricity generation on competition and, therefore, prices is stronger than that of the CHP technology.

**Keywords:** Green technology, Quantity competition, Fringe effect, CHP, Wind energy

**JEL Classification:** D24, D61, L13, Q27, Q41, Q57

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## 1. Introduction

Electricity markets in many European countries are subject to rapid changes due to government measures to promote the supply from renewable energy sources. In particular in Germany the share of wind and solar electricity in the total supply has reached historically unprecedented levels. During off-peak hours, this share is often more than 50% (Fraunhofer Institut, 2014). This strong increase in the supply from the intermittent generation sources with very low marginal costs reduces electricity prices, which is good news for electricity consumers. However, it also depresses incentives for investments in conventional power plants which may still be needed in case of insufficient supply from the renewable sources.

Another potential effect of the growing supply from renewable energy sources is that it raises the intensity of competition in the electricity wholesale markets. Since the start of the liberalisation of these markets, concerns existed about the lack of competition. The electricity wholesale markets are widely viewed to be vulnerable to competition problems because of the highly inelastic and volatile demand and the impossibility to store electricity while demand needs to be permanently equal to supply (Holmberg and Newbery, 2010). Indications of abuse of market power in electricity wholesale markets are detected by, amongst others, Borenstein et al. (2002), Joskow and Kahn (2002), Van Damme (2005), Bushnell (2007), Bushnell et al. (2008), and Fowlie (2009). In order to improve the functioning of the wholesale markets, a number of regulatory measures have been taken. These measures included a restructuring process which encompassed both vertical and horizontal unbundling although the extent of vertical unbundling varied among the EU member-states (Newbery, 2002; Jamasb and Pollitt, 2005). The separated transmission and distribution systems became subject to regulatory supervision, while the generation entities became commercial parties operating on wholesale markets. These measures have contributed to a more efficient allocation in the electricity wholesale markets (see e.g.

Amundsen and Bergman, 2006; Green, 2011; Mulder, 2015). At the same time, awareness of climate change challenges grew while new technologies to cope with these challenges spread out in society (Grimaud et al., 2011). Especially (distributed) generation of renewable energy took off (Lior, 2012). These changes may also have an impact on the intensity of competition. This is the topic of our paper.

We focus on the impact of the supply from two different distributed techniques on competition. We measure this impact through the effect of changes in the residual supply on the Lerner index. The residual demand captures both the total demand and the responses by fringe suppliers, i.e. agents whose supply is fully determined by their marginal costs in relation to the actual market price. Hence, the supply function of the fringe suppliers can be seen as negative demand from the perspective of the incumbents. The aim of our study is to estimate the impact of this fringe supply on competition and to analyse the differences in the way different techniques might have such an impact. We find that wind supply as an intermittent price-insensitive technique has a different effect on the market than the supply from horticultural farmers using Combined Heat and Power (CHP) plants combined with heat-storing facilities enabling them to be price sensitive.

Our analysis is directed at the Dutch wholesale electricity market during the period 2007-2011. A number of years ago, serious concerns were raised about the limited liquidity of this market and the ability of the incumbents to exert market power during peak hours (see Van Damme, 2005). Since then, the Dutch market has become more integrated with the neighbouring countries through both physical and virtual extensions of cross-border capacity (Mulder and Schoonbeek, 2013). Within the Dutch electricity market, the share of distributed generation has grown strongly to about 40%, according to Statistics Netherlands (CBS;

<http://statline.cbs.nl/StatWeb/default.aspx>). The majority of this distributed capacity is installed for own use by firms in a wide variety of industries. Only a small part of this capacity is used to supply electricity to the wholesale market. In particular, the generation capacity owned by horticultural farmers is increasingly used to act as a fringe supply (Velden and Smit, 2011). In this respect, the supply from their CHP plants is related to the outside temperature as it is mainly a by-product of the production of heat and CO<sub>2</sub>, which is an input in the horticultural industry. The horticultural farmers can fine-tune the timing of the supply to the market because of their ability to store the heat, enabling them to produce electricity during peak hours and to use the heat during night. In addition, and for comparison reasons, we also study the supply from distributed wind mills, which also can be regarded as fringe supply, as the electricity that is generated is directly supplied to the grid. In contrast to the horticultural farmers, producers of wind energy are almost completely unable to fine tune their supply of electricity as it is predominantly weather conditions that drive the (changes in) their electricity production while storage options are not available.

In this paper, we estimate a structural market model of the Dutch electricity market and, by using counterfactual simulations, evaluate the effect of the competitive fringe on competition in the market. The price sensitive competitive fringe supply is about 0.5 per cent of total electricity production in the Netherlands. Therefore, although we find that the Lerner index during peak hours would be higher if there was no competitive fringe in the market, the effect is very small. Hence, we conclude that the fringe supply so far only has a minor impact on competition in the Dutch electricity market. We also conclude that the different technologies for distributed generation have a quite different impact on competition. Horticultural farmers using CHP plants in particular affect competition during winter days when temperatures are low,

whereas the impact of wind supply on competition depends on the actual wind speed. We find a more pronounced impact on competition and prices of electricity from wind energy than from CHP plants (see also Meibom et al., 2009; Ketterer, 2012). This different effect can be due to differences in the elasticity of residual demand when these technologies operate or to the different levels of intermittency.

The remainder of the paper is organized as follows. Section 2 gives the theoretical background of our model which is presented in Section 3. Section 4 introduces the data used for the estimations of our model, while Section 5 presents the results. We conclude in section 6.

## 2. Modelling market power in the electricity market

There are two main strands of literature on electricity market modelling.<sup>1</sup> One group of papers, starting from Allaz and Vila (1993), is based on the assumption that electricity producers compete *a la* Cournot oligopolists (see also Borenstein et al. (1995), Arrellano (2003), Bushnell (2007), Bushnell et al. (2008), Fowle (2009), Lambertini and Tampieri (2012)). The main drawback of Cournot competition models is that they may systematically overestimate market power of firms. If sellers follow a slightly different pattern than the standard Cournot competition set-up and if it is assumed that the firms compete *a la* Cournot, then the estimated mark-ups can be much higher than the actual ones (Willems et al., 2009). If the oligopolists can sell their products prior to its production (i.e. forward trading), competition is set to intensify. In effect, the competition may intensify so far as to imply convergence to the Bertrand equilibrium, as shown in Allaz and Vila (1993).

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<sup>1</sup> We mention just a few of many papers that address electricity market models in this paper. Ventosa et al. (2005) and Willems et al. (2009) provide a detailed literature review on electricity market modelling.

As a result, a second strand of structural electricity market models has emerged, based on the seminal supply function equilibrium (SFE) model of Klemperer and Meyer (1989). According to this framework, firms face market uncertainty and choose their supply functions instead of only quantities. In most wholesale spot electricity markets, sellers submit their day-ahead supply schedules and buyers submit their day-ahead demand schedules, while an auctioneer sets a day-ahead equilibrium price and quantity by crossing these demand and supply schedules.<sup>2</sup> The advantage of this approach is that the supply function equilibrium allows more competitive behaviour of firms than the Cournot framework.

Willems et al. (2009) find that there is no significant difference among Cournot competition and SFE models in their analysis of the German electricity market if the existence of an electricity forward market is taken into account. The existence of such a forward electricity market puts additional competitive pressure on the firms and the equilibria in the Cournot and SFE frameworks become similar.<sup>3</sup> As a result, in this paper, we will apply a Cournot competition model which incorporates the forward electricity market. According to our results, the Cournot competition model quite well describes the Dutch electricity market during peak hours. However, the electricity producers' behaviour is more in line with the competitive SFE model during off-peak hours, which would result in an overestimation of market power under the Cournot competition model.

In this paper, we focus on the impact of the fringe supply on competition in the electricity market. In our set-up, we assume that the (few) large electricity producers behave *a la* Stackelberg leaders and face a competitive fringe in the Dutch electricity market. The idea to

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<sup>2</sup> For the examples of using SFE in the electricity market analysis see Green and Newbery (1992), Hortaçu and Puller (2008), Ciarreta and Espinosa (2010).

<sup>3</sup> The effect that a forward market makes a spot market more competitive has been observed by Holmberg (2011) and Newbery (1998) in SFE electricity market models and by Eijkel and Moraga-González (2010) in a Cournot competition model.

introduce a competitive fringe in the electricity market analysis is not completely new. The analysis usually starts with Allaz and Vila (1993) who introduce the possibility of forward trading. Bushnell (2007) extends their model to an environment with multiple firms and increasing marginal cost. He finds that when forward contracts are present, the importance of supplier concentration is greatly magnified relative to other determinants of unilateral market power such as demand elasticity. Puller (2007) applies Cournot competition model on the Californian electricity market by introducing a competitive fringe. Floro (2009) uses both Cournot and Stackelberg competition models in the analysis of the Italian electricity market. She finds that the model where the competitive fringe behaves *a la* Stackelberg follower fits better to explain the market equilibrium. However, in line with Puller (2007), she does not consider a forward market. Neuhoff et al. (2005) simulate the European electricity market for different competitive set-ups. They find that a competitive fringe has a negative effect on the market power of large electricity producers. However, their conclusions are drawn by using only the estimated electricity demand whereas we use a structural market model. Fowle (2009) uses a Cournot model to demonstrate the role of industry structure and firm conduct to determine the extent to which emission leakage occurs as well as the welfare effects of incomplete regulation.

Another extension of our research is that we look into different technologies regarding the fringe supply. We investigate the impact of the fringe supply of horticultural farmers who use combined heat and power (CHP) installations. Furthermore, we account for the provision of electricity with an intermittent source of energy, namely wind. The latter has been investigated by others before (Ambec and Crampes, 2012; Spiecker et al., 2013). However, these studies do not focus on the role of the fringe supply and do not model the market as a whole. Both our fringe suppliers are distributed generators of electricity. As far as we are aware of, the literature

so far does not investigate the role of different technologies in the fringe supply within the context of the Cournot and SFE model of the electricity market.

### 3. Model

In this section we provide the derivation of the electricity market model that we use in the empirical analysis. The market is characterized by a continuum of electricity consumers having different preferences, which results in an aggregated demand ( $Q^D$ ):

$$Q^D = \alpha + X\beta - \delta P + \varepsilon, \quad (1)$$

where  $P$  is the price,  $X$  is a vector of other factors that affect electricity demand,  $\alpha$ ,  $\beta$  and  $\delta$  are the parameters and  $\varepsilon$  is a random error term. The value of  $\varepsilon$  is observable in the spot market and firms know only the distribution of  $\varepsilon$  when they sign their forward contracts. The electricity market is open to both exports and imports. Electricity importing companies are price takers and behave as a Stackelberg follower. The supply of the importers is approximated by a linear supply function and is included in  $\delta P$ .

Next to the competitive import, electricity is sold by  $N$  large local electricity producers and a price sensitive local competitive fringe, which consists of horticultural energy suppliers. The supply function of this fringe is approximated by  $P = \frac{1}{\gamma} Q^{fringe}$ , where  $\gamma$  is a positive parameter. The wind energy suppliers are price insensitive and their supply is driven by wind speed only. We label the quantity supplied by these producers as  $Q^W$ . Consequently, the residual demand served by the large producers becomes

$$Q^R = \alpha + X\beta + \varepsilon - (\delta + \gamma)P - Q^W. \quad (2)$$

The large producers are active in both the spot and forward markets. Therefore, every firm solves a two stage optimization problem. In the first stage, a producer chooses an optimal forwardly traded quantity. The actual production level and, thus, the optimal quantity for the spot market, is chosen in the second stage (see Appendix A for the more detailed model derivations). After solving the first stage profit maximization problem, we obtain the optimal value for the forwardly traded quantity. We plug this quantity in the second stage first order condition which gives us the following equation

$$Q^R \frac{N+1}{N} = \frac{N(N+1)}{N^2+1} (\alpha - Q^W + \mathbf{X}\boldsymbol{\beta}) - \frac{N+1}{N^2+1} \mathbf{C}(\gamma + \delta) + \varepsilon, \quad (3)$$

where  $\mathbf{C}$  is the sum of marginal costs of all  $N$  firms. For estimation purposes we multiply the values of quantities and marginal costs by appropriate expressions of  $N$  and replace matrix  $\mathbf{X}$  by the following variables affecting electricity demand: a *trend* variable, the length of daylight ( $DL$ ) and the set of hour and day dummies ( $D$ ). As such, we arrive at the following equation, for which we provide estimation results in Section 5:

$$\tilde{Q}^R + \tilde{Q}^W = \tilde{\alpha} + \tilde{\beta}_1 trend + \tilde{\beta}_2 DL + D\tilde{\beta}_3 + (\gamma + \delta)\tilde{C} + \varepsilon, \quad (4)$$

where,  $\tilde{\alpha} = \alpha \frac{N(N+1)}{N^2+1}$ ,  $\tilde{\boldsymbol{\beta}} = \boldsymbol{\beta} \frac{N(N+1)}{N^2+1}$ ,  $\tilde{C} = C \frac{N+1}{N^2+1}$ ,  $\tilde{Q}^R = Q^R \frac{N+1}{N}$  and  $\tilde{Q}^W = Q^W \frac{N(N+1)}{N^2+1}$ .

In the estimation process, we mostly focus on the identification of parameter  $\gamma$  which captures the slope of the fringe supply function. This is done by incorporating additional information on the electricity supply of the horticultural sector. Namely, we replace the element  $\gamma P$  in equation (2) by the observable quantity of the sector, which is denoted by  $Q^{hort}$  and arrive at equation (5)

$$\tilde{Q}^R + \tilde{Q}^W + \tilde{Q}^{hort} = \tilde{\alpha} + \tilde{\beta}_1 trend + \tilde{\beta}_2 DL + D\tilde{\beta}_3 + \delta\tilde{C} + \varepsilon \quad (5)$$

where  $Q^{hort} = Q^{hort} \frac{N(N+1)}{N^2+1}$ . By estimating equation (5) we obtain the value of  $\delta$ , which allows us to identify the value of  $\gamma$ .

## 4. Market and data description

### 4.1. Market description

In 2007-2011 the electricity demand in the Netherlands was met by six big electricity producers<sup>4</sup>, imported energy and decentralized generation. In 2007 the share of centralized production in total supply was 55%, but this decreased to 52% in 2011. The contribution of decentralized production increased from 27% in 2007 to 31% in 2011 and the share of import was about 17% in both years. The intensity of competition in the Dutch electricity market grew over time as a result of the increase in generation capacity, in particular decentralized and more cross-border capacity (Mulder and Schoonbeek, 2013; Mulder, 2015). During the off-peak hours (10PM – 9AM)<sup>5</sup> the imported energy takes care of about 27% of the total residual demand (excluding supply from decentralized production) and the six electricity producers account for 73%. Meanwhile, during the peak hours (10AM – 9PM) electricity import takes 19% of total domestic demand, the big producers supply about 81% of the total residual demand. Additionally there is a big difference in the market price during the peak and off-peak hours: the average peak period price in 2007-2011 is 62 Euro/MWh while average off-peak price is 39 Euro/MWh in this period. Furthermore, the off-peak price is often below the marginal production costs, whereas the

<sup>4</sup> During the analyzed period there was no entry and exit in the group of these firms.

<sup>5</sup> Usually, the hours between 8AM and 11PM are called as peak hours, and the hours between 10AM and 6PM are called as super-peak hours. We have noticed that the oligopolistic model with a competitive fringe provides the best fit for the hours between 10AM and 9PM. These are mainly super-peak hours and a high electricity consumption in the additional hours can be explained by intensive electricity consumption by households in the first quarter of the year.

peak price is always above marginal production costs.<sup>6</sup> Therefore, we conclude that the degree of competition during the peak hours is much smaller, and in our analysis, we treat the Dutch electricity market in this period as an oligopolistic market with a competitive fringe.

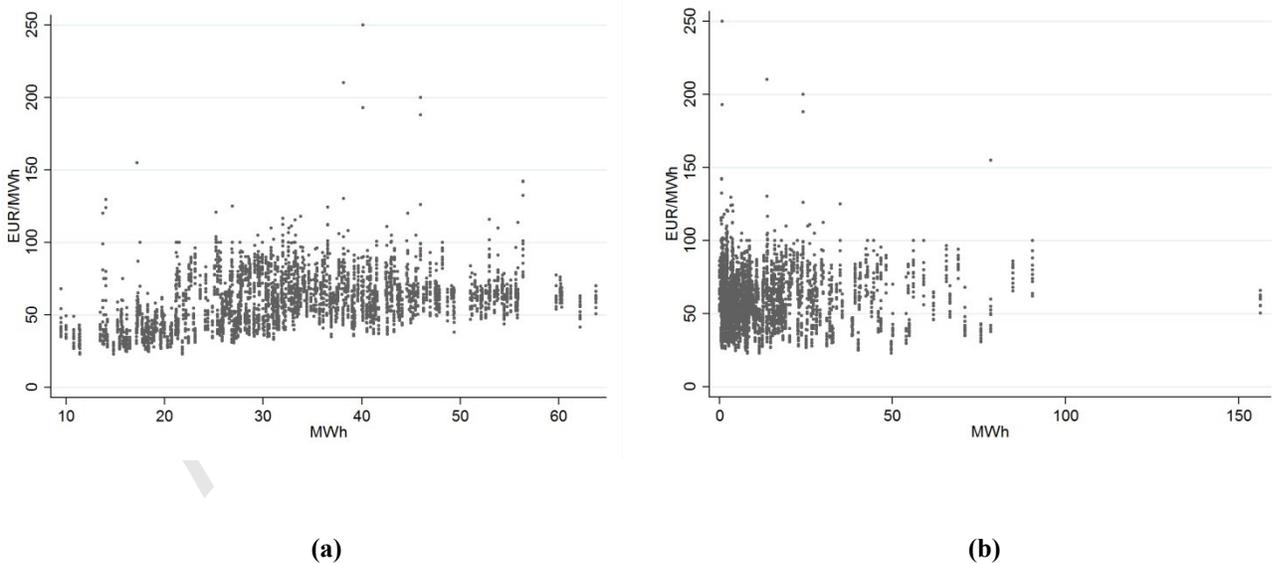
Of all the decentralized electricity production that takes place during the peak hours only a fraction of it is supplied to the market. The major part of the energy is produced by the chemical industry and other energy-intensive industries during production processes and is used for own needs. The later production is insensitive to the market price and has an effect on the intercept of the total linear demand function. In the estimation process we control for this by using hour specific dummies.

The electricity that is supplied by the competitive fringe consists of wind energy and the electricity produced by horticultural firms. The production technology of both supplier types is very different which leads to different supply decisions. The wind energy generation features zero marginal production costs. Therefore, the main factor that determines whether the wind energy is supplied to the market is a sufficient wind speed. Furthermore, this supply is practically insensitive to the electricity market price: The correlation coefficient between wind power and the electricity price is no more than -0.02 (see also Figure 1b). As a result, in the derived model the supplied quantity enters the residual demand of big electricity producers by reducing the intercept. However, the supply of electricity from the horticultural sector is price sensitive. The electricity is a side product of the horticultural suppliers whose main objective is to produce heat for their greenhouses. According to their heat production technology, the horticultural suppliers can store the heat with some heat losses which happen due to the storage. The producers choose the time period of heat and electricity generation by comparing their production and storage costs

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<sup>6</sup>The fact that an off-peak price happens to be below the marginal production costs can be explained by high dynamic dispatch costs of the plants: for a relatively short period firms may decide to supply electricity when their marginal costs are above the market price, because not producing would result in higher costs.

with the price of electricity in the market. As soon as the electricity market price exceeds their marginal costs, the horticultural suppliers start supplying electricity to the market. The size of the heat-production facilities and the demand for heat vary among the horticultural farmers supplying electricity, which leads to a different number of the horticultural suppliers for every market price. While comparing the supplied electricity quantity with the wholesale market price we have observed that the horticultural supply function can be well approximated by the linear supply function (Figure 1a). Additionally, after estimating the linear relationship between the wholesale market price and the amount of the electricity that was produced by the horticultural sector, we find that the coefficient next to the supplied quantity by the horticultural firms equals 0.5965 and is significantly above zero. Meanwhile, after estimating the linear relationship between the wholesale market price and the amount of electricity produced by wind energy suppliers, we find that the coefficient is not statistically different from zero.

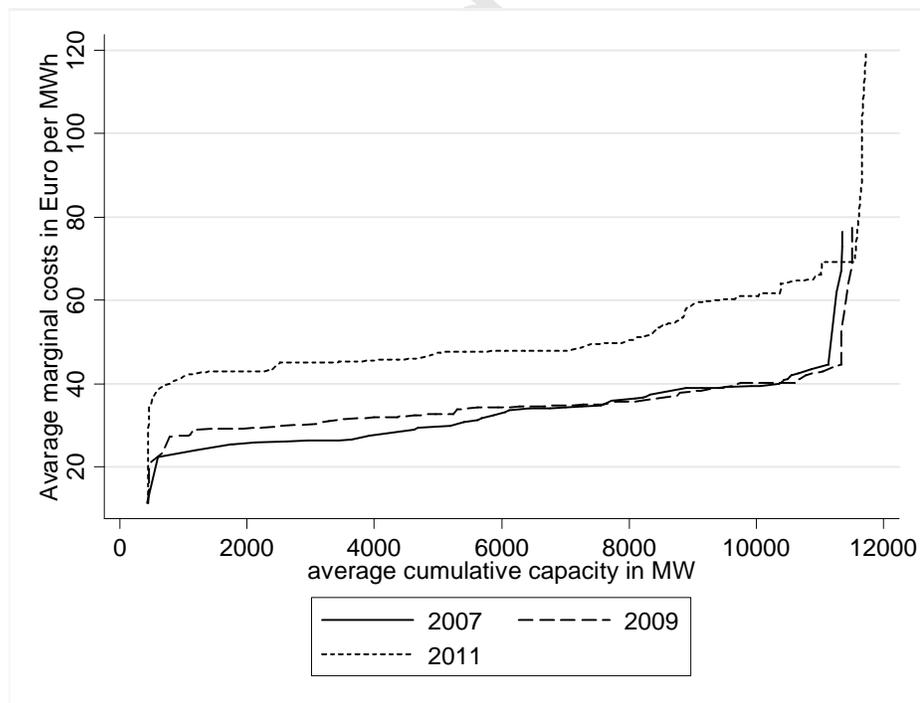


**Figure 1. The relationship between the produced electricity in a horticultural sector (a) and wind energy (b) and spotprices.**

The incumbent firms use different electricity generating technologies and their power

plants vary in their marginal costs. In the analysis, we assume that firms dispatch their power plants according to their merit order. Then by plotting the marginal cost curves of the producers we noticed that every firm produced in the range of relatively flat marginal costs (see Figure 2). Hence, in the subsequent derivations we assume that the sellers employ constant-returns-to-scale technology which results in constant marginal production costs.

The economic slowdown that took place in Europe starting from 2008 had an effect on electricity demand in the Netherlands. Additionally, because of the technological progress both firms and households needed less electricity to satisfy their needs (see Table 1 for the details). In order to capture this effect we introduce a linear yearly trend in the model.



**Figure 2 Marginal costs in the Dutch electricity market, on average per year in 2007, 2009 and 2011 (source: Mulder, 2015).**

**Table 1. The amount of electricity that was sold in NL during peak hours in 2007 (Q1)-2011 (Q1)**

	2007	2008	2009	2010	2011
Total residual demand, MWh <sup>a</sup>	12116	11474	10892	10818	9995
Change	-	-5.30%	-5.07%	-0.68%	-7.61%

<sup>a</sup> Total residual demand is computed by taking the total production of the incumbent firms, subtracting export and adding import and the supply of the fringe.

#### 4.2. Data

We use hourly data on the centralized production units in the Dutch market, obtained from the Netherlands Authority for Consumers and Markets. This database includes hourly data regarding the available generation capacity as well as the level of production for all centralized production units in the Dutch market over the period 2007-2011. In addition, the database contains information about the technical characteristics of each plant, such as generation technique, maximum technical capacity, fuel type and fuel efficiency. By combining these data with data on fuel prices, we are able to determine the hourly marginal costs of each plant. The marginal costs include fuel costs, operating and maintenance costs as well as start-and-stop costs. (see Mulder (2015) for the data description and the methodology how these costs are calculated).

From earlier studies, we know that electricity producing oligopolies do not always behave as Cournot competitors (Yao et al., 2004). In order to check this, we compute the Lerner index, labelled as  $L_{\text{actual}}$  in Table 4, which is based on the data about APX<sup>7</sup> spot prices and the actual marginal costs. We observe that for some hours this index becomes negative, which implies that a Cournot competition model cannot be applied for these hours. Hence, for the estimations, we

<sup>7</sup> APX is one of Europe's premier providers of power exchange and clearing services for the wholesale market, operating transparent platforms in the Netherlands, the United Kingdom and Belgium.

use the hours from 10AM to 9PM on working days (thus excluding public holidays and weekend days). In addition, we use the observations from a specific quarter (the 1<sup>st</sup>) in 2007-2011 in order to control for seasonal effects in demand. After this selection procedure, we end up with 3780 observations in total (about 750 observations per year). The summary statistics of the variables are presented in Table 2.

As data on fringe supply are not directly available, we compute these data using information on other variables. For the supply by the horticultural farmers, we are able to use the fact that they produce electricity as a side product of heat production through Combined Heat and Power (CHP) plants. The horticultural farmers can store the produced heat for a number of hours or days while the heat storage costs depend on the outdoor temperature. The lower the outdoor temperature the more heat is needed for greenhouses. Therefore, a horticultural supplier does not store its produced heat for a long time (days) if it is cold outside. On the other hand, if temperature is high, additional heat may be not be needed, which implies that the heat cannot be used at all. As a result, the heat storage loss, the costs of storage and, hence, the marginal costs of producing electricity by CHP plants are positively correlated with the outdoor temperature. This implies that electricity production costs are lower when the outside temperature is lower.

According to our modelling assumptions, every horticultural supplier has constant marginal electricity production costs, and the joint upward sloping marginal cost curve appears due to different options that producers have to utilise the heat and that depend on the type of their cultivation and the technical efficiency of the CHP plants.<sup>8</sup> When the outdoor temperature decreases, the marginal costs of all horticultural suppliers decreases. Therefore, for any market price the quantity that is supplied by the fringe suppliers is higher when the outside temperature

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<sup>8</sup> How the CHP plants differ in their technology and efficiency is very well described by the United States Environment Protection Agency "Efficiency Benefits", available at <http://www.epa.gov/chp/basic/efficiency.html> (accessed: 2014 Dec. 9).

decreases.<sup>9</sup> Thus, we use the outdoor temperature as an instrument, to compute the horticultural electricity supply.

We transform hourly temperature data from the Dutch Royal Meteorological Institute (KNMI; [www.knmi.nl/klimatologie](http://www.knmi.nl/klimatologie)) into the data on daily heating degree days (HDD), which is the general measure to measure energy demand related to heating.<sup>10</sup> Next, we use the daily values for HDD to allocate the aggregated annual supply over days, based on data from the Agricultural Economic Research Institute (Van der Velden and Smit, 2011), and by using hourly HDD data we compute hourly electricity supply of the horticultural sector.<sup>11</sup>

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<sup>9</sup> The decrease in the marginal costs of all horticultural suppliers shifts their joint supply curve vertically but does not affect the slope.

<sup>10</sup> HDD are defined as the number of degrees Celsius the average daily temperature is below the threshold of 18 degrees Celsius. Thus, if the outdoor temperature is lower, then HDD value is higher.

<sup>11</sup> The horticultural electricity supply is computed by using the following formula  $Q_y^{hort} = \frac{Q_y^{hort}}{HDD_y} * HDD$ , where  $Q_y^{hort}$  is the annual electricity supply of the horticultural sector and  $HDD_y$  is the sum of HDD over all days in a year.

**Table 2. Summary statistics of the variables, 1<sup>st</sup> quarter, 2007-2011***(MC: in euro/MWh; others in MWh/h average per day)*

Year (Q1)	Observations	Statistics	Production (centralized)	Export	Import	MC	Supply wind	Supply horticulture
2007	768	mean	9925.05	442.10	2599.20	136.81	14.44	19.72
		sd	833.09	349.56	379.07	25.50	17.24	5.68
		min	7398.78	0.00	1750.00	98.62	0.46	9.48
		max	11836.35	1504.00	3397.00	222.15	78.42	33.79
2008	744	mean	9814.93	453.65	2058.70	300.40	22.50	31.42
		sd	581.25	398.11	524.06	19.81	20.97	6.32
		min	7967.72	20.00	1124.00	266.01	0.29	21.20
		max	11221.29	1673.80	3437.00	379.52	90.49	48.18
2009	744	mean	9592.68	1251.17	2502.15	217.95	13.46	34.67
		sd	666.96	549.85	497.75	59.93	15.47	7.43
		min	7066.24	304.00	1188.00	144.27	0.00	24.12
		max	10741.76	3537.00	4012.00	462.38	75.60	56.37
2010	756	mean	11056.58	1536.72	1247.56	177.26	9.93	40.25
		sd	710.38	463.91	481.51	19.59	9.67	11.94
		min	8921.57	356.90	132.00	143.97	1.13	10.02
		max	12462.30	2917.10	2602.00	244.44	54.85	63.77
2011	768	mean	8643.56	878.48	2175.28	240.30	13.38	40.86
		sd	498.86	436.85	697.40	12.24	22.31	10.22
		min	6537.88	75.00	452.00	219.75	0.00	21.93
		max	9959.35	3064.40	3900.00	304.03	156.30	60.27

A similar approach has been applied with respect to computing wind energy supply. From the German market, we know that the level of production by wind mills is strongly related to the

wind speed when the latter is translated into wind power (Mulder and Scholtens, 2013).<sup>12</sup> Hence, for defining the relationship between the wind speed and generated wind energy, we use the data on the total annual electricity production by wind mills from Statistics Netherlands ([www.cbs.nl](http://www.cbs.nl)) and the data on the hourly wind speed from the Royal Dutch Meteorological Institute (source: [www.knmi.nl](http://www.knmi.nl)). Then, we use hourly data on wind speed to generate hourly wind energy supply.<sup>13</sup>

## 5. Results

We first estimate equation (5) by using Newey-West OLS estimators. None of the variables exhibit any significant stationarity-related problems (testing results are available upon request). The estimation results are presented in column Model A in Table 3. We find a negative effect of the marginal costs on the residual demand, as expected. Also daylight shows a negative coefficient, which partly follows from the fact that electricity is used for lighting. We also detect a negative trend, which can be explained by the fact that the demand for electricity has declined with the advent of the economic crisis (TenneT, 2012). Finally, we find that especially the super peak hours in the morning show a significantly higher electricity demand.

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<sup>12</sup> In the German market, daily data on both wind generation and wind speed is available. The correlation coefficient between wind generation and wind power appears to be about 0.85. Wind power is related to the cube of wind speed if wind speed is not lower than about 4 m/s or not above about 25 m/s (source: [www.pfr.co.uk/pfr](http://www.pfr.co.uk/pfr)).

<sup>13</sup> The supply of wind energy producers is computed by using the following formula:  $Q^w = \frac{Q_y^w}{S_y^3} \times s^3$  where  $Q_y^w$  is an annual wind energy supply,  $s^3$  is the cubic speed of wind and  $S_y^3$  is the sum of cubic wind speed over the year. We also account for the cases when the wind is too strong or too weak. In these cases wind turbines are turned off.

**Table 3. Estimation results**

Variable	Model A	Model B
	Dependent variable: $\tilde{Q}^R + \tilde{Q}^W$	Dependent variable: $\tilde{Q}^R + \tilde{Q}^W + \tilde{Q}^{NORT}$
MC	-9.970** (3.109)	-9.764** (3.118)
Daylight	-3.871*** (0.494)	-3.911*** (0.496)
Year (trend)	-364.8*** (27.76)	-359.3*** (27.90)
Day_2	238.1* (111.9)	239.3* (112.3)
Day_3	187.6 (115.6)	189.8 (115.9)
Day_4	181.2 (107.4)	183.6 (107.7)
Day_5	232.8* (104.4)	232.8* (104.6)
Hour_10	799.3*** (44.45)	799.2*** (44.53)
Hour_11	789.4*** (49.71)	789.3*** (49.80)
Hour_12	772.4*** (49.96)	772.3*** (50.05)
Hour_13	608.3*** (48.57)	608.2*** (48.66)
Hour_14	628.2*** (47.30)	628.1*** (47.39)
Hour_15	532.4*** (45.98)	532.3*** (46.07)
Hour_16	415.1*** (45.30)	415.0*** (45.39)
Hour_17	341.0*** (43.59)	340.9*** (43.67)
Hour_18	390.2*** (45.61)	390.2*** (45.69)
Hour_19	383.9*** (44.07)	383.8*** (44.14)
Hour_20	413.0*** (30.96)	413.0*** (31.01)
Constant	13555.6*** (346.1)	13591.5*** (348.3)
<i>N</i>	3780	3780
<i>F</i>	50.39	49.75
<i>df<sub>m</sub></i>	18	18
<i>df<sub>r</sub></i>	3761	3761

Note: Standard errors in parentheses; \*  $p < 0.05$ . \*\*  $p < 0.01$ . \*\*\*  $p < 0.001$

For the identification of  $\delta$  we estimate equation (5) and the estimation results are in Table 3 (Model B). The coefficient for the marginal costs is the value of  $\delta$  and it is significantly negative. Furthermore, both the daily and hourly patterns are quite in line with the results for Model A.

After we estimate the values of  $\gamma + \delta$  and  $\delta$ , we can compute the value of  $\gamma$ . When this value is known, we set  $\gamma + \delta = \gamma$  in equation (5) and simulate the total produced quantity which would be supplied if there were no horticultural firms. Then we use this predicted quantity in equation (2) to compute the predicted market price  $P_{no\_hort}$ . By using the information on predicted price we compute the Lerner index  $L_{no\_hort}$ .

Similarly, by setting  $Q^W = 0$  in equation (5) we compute how much large electricity producers would produce if there were no wind energy suppliers. Then we use this predicted quantity to compute a new equilibrium market price and a new Lerner index. Both the price and the index have a subscript *no\_wind*. The simulation results for the electricity price and the Lerner index are given in Table 4. For the comparison reasons we add by the model estimated equilibrium price and the Lerner index denoted by  $P_{Est}$  and  $L_{Est}$  respectively.<sup>14</sup>

<sup>14</sup> Lerner index for a Cournot oligopoly model is computed by using formula  $L = \frac{P - C_i}{P}$  and  $|\epsilon|$  is computed by using the following algorithm. In a Cournot competition model  $\frac{P - C_i}{P} = \frac{q_i}{P} \frac{\partial P}{\partial q_i}$ . If we sum this equation across all the firms then we get  $\frac{NP - C}{P} = \frac{Q}{P} \frac{\partial P}{\partial Q} = \frac{1}{|\epsilon|}$ . Thus,  $|\epsilon| = P(NP - C)^{-1}$ .

**Table 4 . The electricity spot price and the Lerner index in different scenarios, 2007 (Q1)-2011 (Q1)**

	Mean	St.dev.	Min	Max
$P_{\text{actual}}$	59.754	18.426	22.95	250
$P_{\text{Est}}$	60.204	10.935	41.674	102.691
$P_{\text{no\_hort}}$	60.823	10.946	42.253	103.356
$P_{\text{no\_wind}}$	61.714	11.354	42.146	102.792
$L_{\text{actual}}$	0.4664	0.1372	-0.0253	1.0983
$L_{\text{Est}}$	0.5060	0.1188	0.2840	0.8160
$L_{\text{no\_hort}}$	0.5130	0.1191	0.2890	0.8239
$L_{\text{no\_wind}}$	0.5219	0.5219	0.2849	0.8307

Table 4 shows that the supply from wind and horticultural industry has a positive effect on competition. Without this supply both the electricity price and the Lerner index would be higher. Without the supply of wind the electricity price is about 1.51 euro/MWh higher, while the absence of the fringe supply from the horticultural farmers would result in 0.62 euro/MWh higher prices (see also Mulder and Scholtens, 2013). The Lerner index would be 0.016 higher in the first case and 0.007 in the second one.<sup>15</sup>

<sup>15</sup> While comparing the coefficients next to MC both in Model A and Model B in Table 3, we obtain that  $t$  statistics equals 2.8764, which allows rejecting the hypothesis that  $\alpha$  equals zero. However, the significance of the impact of fringe supply must be treated with caution due to additional error terms that appear due to the use of instruments to measure the supply of the fringe.

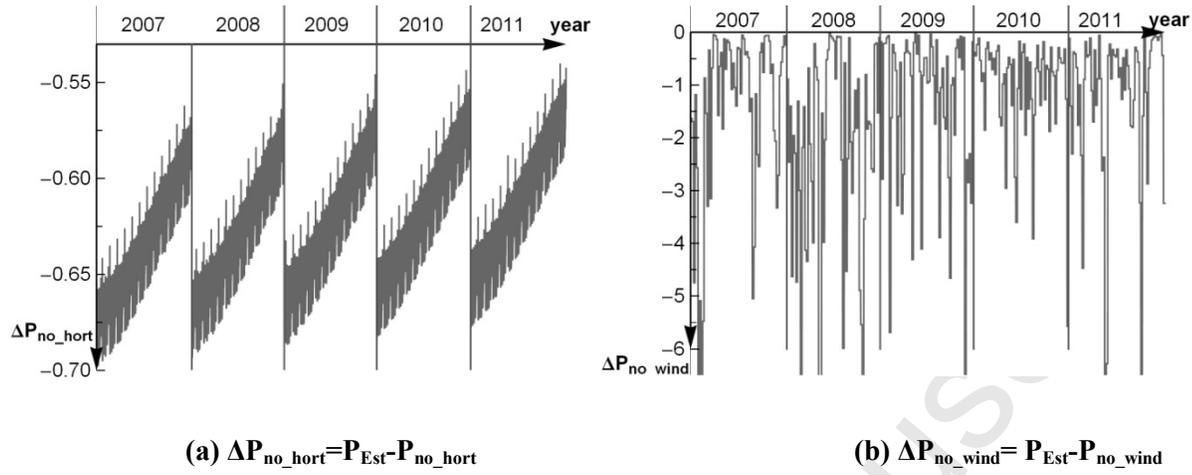


Figure 3. The effect of horticultural producers (a) and wind energy suppliers (b) on the spot market price of electricity

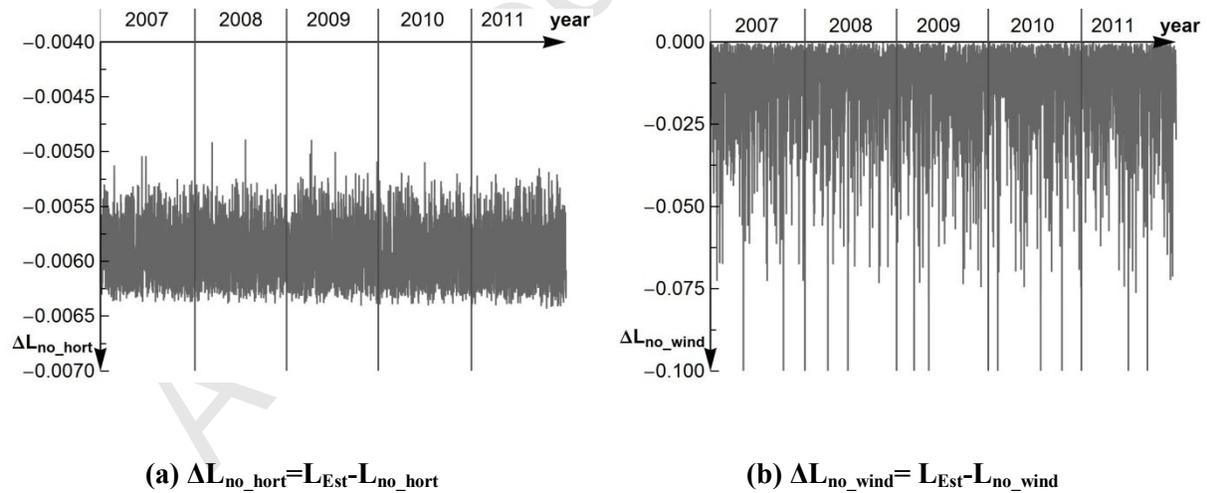


Figure 4. The effect of horticultural producers (a) and wind energy suppliers (b) on the Lerner index of the electricity market

In Figures 3 and 4, we plot the change in the spot price and the Lerner index respectively

if the horticultural electricity producers (a) or wind energy suppliers (b) were not in the market. As one can easily observe, the effect of the horticultural electricity producers on the equilibrium price shows a strong seasonal pattern. As the average temperature increases during the first quarter, the electricity supply by the horticultural sector decreases, which increases the residual demand for the large producers. This results in the fact that the horticultural producers play a smaller role in the spot market. In contrast, wind speed does not show a seasonal pattern over the first quarter of the calendar year and features intermittency. As a result, the effect of wind producers on the spot market price does not show a clear trend over time.

In Figure 5, we depict the effect of the average impact per unit of supply by the horticultural suppliers and the wind energy suppliers on the spot market price. Again because of a smaller effect on competition the average effect of the horticultural suppliers on the spot price is smaller than the one of the wind energy suppliers. The different patterns for the two technologies occur due to the different manner in which the two types of fringe suppliers enter the residual demand function. The wind energy producers are price insensitive and, thus, their fringe supply decreases the *intercept* of the linear residual demand function. Because of the assumptions about the linear marginal cost and the demand functions, the average effect of the wind energy producers on the spot market price is linear as well. However, the horticultural farmers affect the residual demand of the large electricity producers by altering the *slope* of the residual demand. Furthermore, due to the fluctuations in the residual demand – which happens due to the daylight, wind energy supply and other factors – the effect of the horticultural farmers on the electricity spot price is fluctuating.

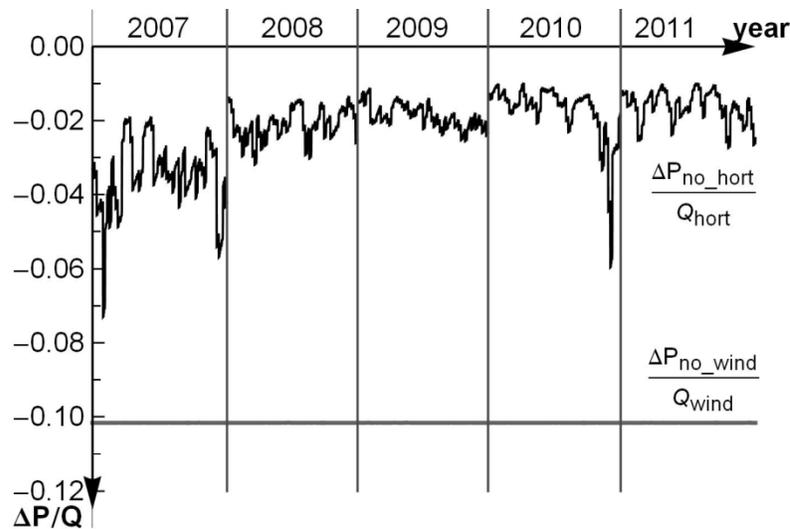


Figure 5. The impact of fringe supply of wind energy and CHP on electricity spot price changes

## 5. Conclusion

We investigate the competitive fringe effect in the Dutch electricity market, focussing on how two very different generation techniques (horticultural Combined Heat and Power generation and wind mills) interact with the conventional energy system. We account for spot and forward contracts as well as international electricity trade. The model is estimated on the basis of 3780 observations in the period 2007-2011. We observe that the fringe supply plays a minor role in the intensity of competition in the Dutch wholesale market for electricity. We find that without the supply of wind, the electricity prices would be about € 1.50 / MWh higher, and that without the fringe supply from the horticultural farmers, electricity prices would be about € 0.63 / MWh higher. The Lerner index would be 0.01 higher in the former case and 0.005 in the latter. As such, we conclude that the fringe supply from the price insensitive wind farmers has a much more pronounced impact on prices and competition than that of the horticultural farmers

with their CHP facilities(see also Meibom et al., 2009).

Our model and results complement the existing literature in several respects. We have advanced Puller's (2007) Cournot competition model by accounting for electricity forward contracts. Our results are in line with those of Neuhoff et al. (2005), but ours are based on a structural market model. We include fringe supply from two alternative technologies which has not been studied before. The next challenge is to include additional technologies and to estimate the model within a market setting with substantially more renewable energy generation.

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## Appendix A. Derivation of the model

We assume that there are  $N$  oligopolists which produce electricity in the market and compete *a la* Cournot. The firms sell electricity either in the local market or abroad. There are  $M$  countries where the oligopolist may export electricity to. We label the export price (including transportation fees) in country  $l$  as  $P_l^E$ . The total export to country  $l$  is denoted by  $Q_l^E$ . The total export of firm  $i$  is labelled  $q_i^E$  and the export of firm  $i$  to country  $l$  is  $q_{il}^E$ . All the firms have constant marginal production costs and we denote the marginal costs of firm  $i$  by  $c_i$ . Next to exports, firm  $i$  sells electricity in both spot and forward markets. We label the forwardly traded quantity of firm  $i$  as  $q_i^f$  and the forward market equilibrium price is denoted by  $P^f$ . The total forwardly traded quantity is labelled as  $Q^f$ . Firms sign their forward contracts well before the spot market takes place. Hence, the profit maximization problem of a firm is in two stages.

In the first stage, the firm opens its forward position by maximizing its expected profit. In the second stage, the firm chooses its import, export and actual production quantities. As a result, we solve the profit maximization problem backwards. Firstly, we solve for the optimal import, export and actual production quantities as functions of  $Q^f$ . Afterwards, we solve the profit maximization problem with respect to forward quantities. Then, the profit maximization problem of firm  $i$  in the second stage is as follows

$$\max_{q_i, q_{il}^E} P(Q^R)(q_i - q_i^E) - c_i q_i + (P^f - P)q_i^f + \sum_{l=1}^M P_l^E q_{il}^E \quad (\text{A.1})$$

where the local residual demand is satisfied by locally produced minus exported electricity. i.e.

$$Q^R = \sum_{i=1}^N (q_i - q_i^E) \quad (\text{A.2})$$

The firm chooses its exports and produced quantities simultaneously. Thus, we get the following system of first order conditions for firm  $l$ .

$$P + \frac{\partial P}{\partial Q^R}(q_i - q_i^E - q_i^f) - c_i = 0 \quad (\text{A.3})$$

$$-P - \frac{\partial P}{\partial Q^R}(q_i - q_i^E - q_i^f) + P_i^E + q_{il}^E \frac{\partial P_i^E}{\partial q_{il}^E} = 0, \forall l = 1, \dots, M \quad (\text{A.4})$$

One can readily observe that the optimal export quantity does not depend on the production volumes as long as marginal costs are constant. From the first order conditions (A.3)-(A.4) we get

$$P_i^E + q_{il}^E \frac{\partial P_i^E}{\partial q_{il}^E} = c_i, \forall l = 1, \dots, M \quad (\text{A.5})$$

Hence, we can treat the exported quantities of a firm as constants in the subsequent derivations.

We plug in the value of  $P$  and its derivative with respect to  $q_i$  in equation (A.3) multiply it by  $\delta + \gamma$  and get equation (A.6), which is linear in  $q_i - q_i^E$ .

$$\xi - \sum_{j \neq i} (q_j - q_j^E) - 2(q_i - q_i^E) + q_i^f - (\delta + \gamma)c_i = 0 \quad (\text{A.6})$$

where  $\xi = \alpha - Q^W + X\beta + \varepsilon$ .

There are  $N$  firms in the market. Therefore we get the system of  $N$  first order conditions, which we can summarize by  $\mathbf{AX} = \mathbf{B}$  where

$$\mathbf{A} = \begin{bmatrix} 2 & 1 & \dots & 1 \\ 1 & 2 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \dots & 2 \end{bmatrix}, \quad \mathbf{B} = \begin{bmatrix} \xi - (\delta + \gamma)c_1 + q_1^f \\ \vdots \\ \xi - (\delta + \gamma)c_N + q_N^f \end{bmatrix} \text{ and } \mathbf{X} = \begin{bmatrix} q_1 - q_1^E \\ \vdots \\ q_N - q_N^E \end{bmatrix}$$

Then after applying Cramer's rule we get that

$$q_i - q_i^E = \frac{1}{N+1} (N\xi - Nc_i(\gamma + \delta) + Nq_i^f - \sum_{j \neq i} (\xi - c_j(\gamma + \delta) + q_j^f)) \quad (\text{A.7})$$

If we sum (A.7) over all the firms and multiply by  $N + 1$ , we get

$$Q^R(N + 1) = N\xi - C(\gamma + \delta) + Q^f \quad (\text{A.8})$$

where  $C = \sum_{j=1}^N c_j$ .

Now we move to the first stage optimization problem of a firm which can be written as follows

$$\max_{q_i^f} E[P(q_i - q_i^E) - c_i q_i + (P^f - P)q_i^f] \quad (\text{A.9})$$

We omit export income in this stage because the optimal export quantity does not depend on the forward position of the firm. Also note that  $E[(P^f - P)q_i^f]$  and  $E\left[\left(\frac{\partial P^f}{\partial q_i^f} - \frac{\partial P}{\partial q_i^f}\right)q_i^f\right]$  must equal zero in equilibrium because of a non-arbitrage condition. Therefore, the first order condition of firm  $i$  in the first stage is

$$E\left[P\frac{\partial(q_i - q_i^E)}{\partial q_i^f} + \frac{\partial P}{\partial Q^R}\frac{\partial Q^R}{\partial q_i^f}(q_i - q_i^E) - \frac{\partial c_i q_i}{\partial q_i^f}\right] = 0 \quad (\text{A.10})$$

We plug in the value of  $(q_i - q_i^E)$  from (A.7),  $Q^R$  from (A.8) and their derivatives to (A.10), multiply by  $(\gamma + \delta)(N + 1)^2$  and get equation (A.11).

$$E[(N - 1)\xi + (\gamma + \delta)C(N - 1) - (N - 1)Q^f - (N + 1)q_i^f - (N^2 - 1)(\gamma + \delta)c_i] = 0 \quad (\text{A.11})$$

After we sum (A.11) over all the firms we get

$$E[N(N - 1)\xi - (\gamma + \delta)C(N - 1) - (N^2 + 1)Q^f] = 0 \quad (\text{A.12})$$

which gives

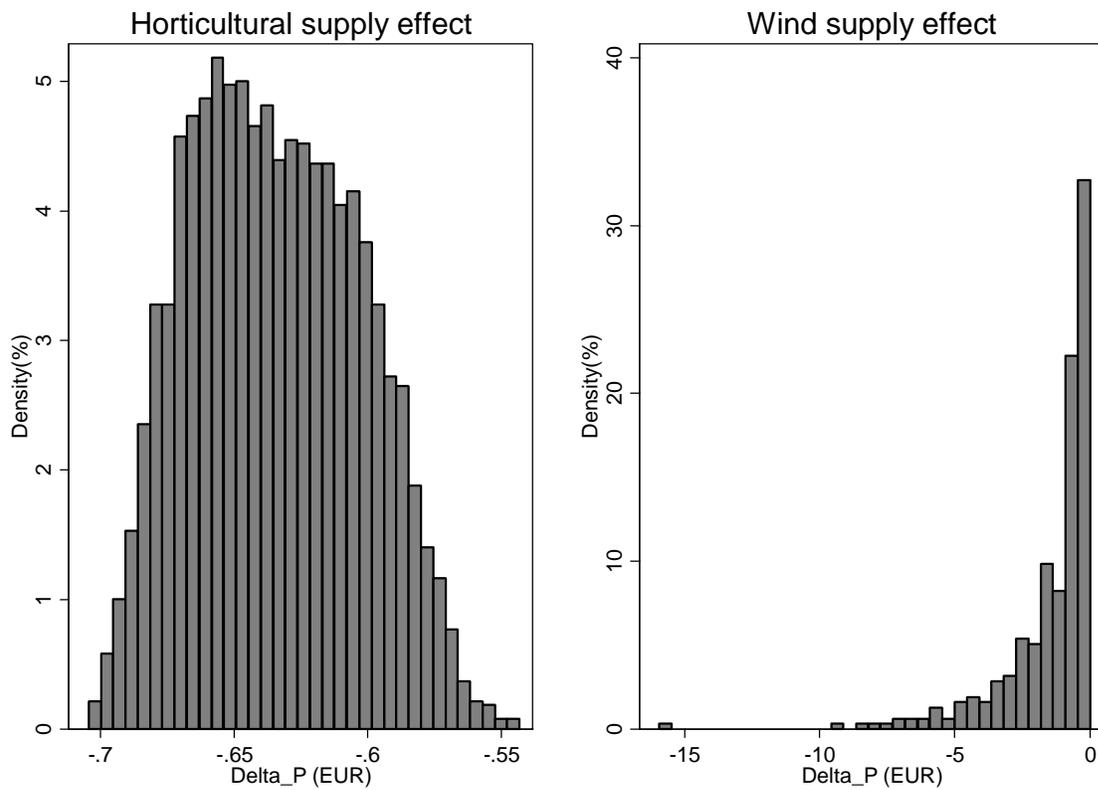
$$Q^f = \frac{N(N-1)E[\xi]}{N^2+1} - \frac{(\gamma+\delta)(N-1)C}{N^2+1} \quad (\text{A.13})$$

We plug this value of  $Q^f$  in (A.8) and get the equation which we estimate in section 4:<sup>16</sup>

$$Q^R \frac{N+1}{N} = \frac{N(N+1)}{N^2+1} (\alpha - Q^W + X\beta) - \frac{N+1}{N^2+1} C(\gamma + \delta) + \varepsilon \quad (\text{A.14})$$

## Appendix B

**Histograms for the effect of horticultural supply and wind supply on electricity spot price changes**



<sup>16</sup> Note that  $E[\xi] = \alpha + X\beta - Q^W$

## Appendix C

Histograms for the effect of horticultural supply and wind supply on changes in the Lerner index

