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Strategic decisions on bilateral bidding behavior: evidence from a wholesale electricity market

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Abstract This article analyzes the strategic bilateral bidding behavior in the Spanish electricity wholesale market (OMEL). The collection of data includes information regarding weekly averages of spot prices, the quantity bid in the wholesale market, the quantities purchased in the wholesale market and sold in the open market, and the behavior of conduct parameters for the period from January 2002 to April 2007 for the four largest firms of the Spanish electricity market: Endesa, Iberdrola, Unión Fenosa and Hidrocantábrico. This article employs the New Empirical Industrial Organization approach. The empirical analysis was based on the autoregressive distributed lag approach to cointegration and on the Toda–Yamamoto Granger causality tests to validate the standard version of the theoretical formulation of the standard Cournot model, and its theoretical extension, to encompass the hypothesis of the presence of bid interdependence for electricity quantities sold and bought in the Spanish electricity wholesale market. The results of cointegration and causality analysis reinforce the empirical results of the extended Cournot model with the inclusion of the two main bidding variables that solved the optimization problem of profit maximization for each of the four firms analyzed.

Keywords Bidding behavior · Electricity spot market · Spain · Cointegration · Toda–Yamamoto Granger causality

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1 Introduction

During the last decades after the liberalization process of the electricity sector, different market equilibrium models have been proposed and used to study and analyze the strategic iterations of cooperative and noncooperative approaches among participants in electricity markets. It is natural to pay special attention to the electricity market equilibrium problem given the cost structure by type of production technology for the generation of electricity and the prevalence of a small number of large participating companies that seek to maximize their profits in the restructured electricity markets. The Spanish OMEL market was specifically selected for this study as it has several players, such as Endesa, Iberdrola, Unión Fenosa, Hidrocantábrico, of different sizes, organizational structures and expertise. The Spanish electricity market has two main players: Endesa and Iberdrola. It functions in the following way: Purchase (sale) bids are ordered by decreasing prices. The market price corresponds to the highest price of the electric energy for which there is a purchase bid. This price is equal or superior to the price of the accepted sale bid. In this way, the market price corresponds to a marginal price. Endesa and Iberdrola's capacity of fixing marginal prices in the wholesale market cannot only be explained by their large installed capacity of electric energy output vis-à-vis the global capacity in the Spanish market. In addition, it is important to take into account the mix of technologies and output capacity of their production facilities. Indeed, the setting of sales bids in the pool for different time schedules is largely conditioned by the technology differences of the power plant's installed production capacity.

Technology plays a key role in the market as production power plants with high fixed costs and low variable costs that operate almost continuously coexist with plants with high variable costs, whose activity is continuous. These differences in technology cause each market player to have a different cost structure. Knowing that most production capacity investments are not replicable, as the readjustment of production capacity is almost impossible to achieve, these cost components and the technical constraints on the operations of the electricity system are factors that make it difficult to formulate and measure economic models in electricity markets. The design and modeling of electricity spot market demand and supply curves, and the formulation of market equilibrium, have shown significant progress.

One of the classic models used in this market equilibrium formulation is the Cournot oligopoly model, whose fundamental premises assume that market operators may use bidding strategies, so that each company can strategically decide the quantity to bid at any given moment of time, given their capacity constraints. In the specific OMEL electricity market, Endesa and Iberdrola play a pivotal role in the Spanish wholesale market. Their capacity is at least equal to the surplus of market supply that exists in peak demand periods. As a consequence, the joint supply of other producers is insufficient for the satisfaction of demand. Therefore, these pivotal firms can increase their prices to satisfy the demand, without being expelled from the market. In particular, the structural market characteristics, e.g., the fact of being a relatively homogeneous and transparent product, allows the market players to coordinate strategically among themselves, immediately detecting price divergences (Kühn and Machado 2004; Fabra 2003). The small electricity producers and other third players, when considered altogether, are not capable of setting market prices in the majority of time schedules. Beyond Endesa and Iberdrola, other Spanish electricity producers, namely Hidrocantábrico and Unión Fenosa, make their purchase and sale bids in the majority of the time schedules according to the prices set by the two dominant players. Given that the quantities offered above the marginal price are not sold in the daily market, the remaining operators, acknowledging the supply of Endesa and Iberdrola, always satisfy the demand. They tend to bid at a zero price since they know that all the electricity will be sold in the daily market at the marginal price set in the pool and not at the proposed bid price.

According to the specific strategic behavior characteristics of the OMEL market players during January 2002 to April 2007, the main objective of this paper is to validate both the standard theoretical Cournot model and its extended version of profit maximization for the Spanish electricity market. The quantity sold in the spot market and the quantity purchased in the spot market to be sold in the open market are going to be introduced as decision-making variables in the profit maximization function. This can lead to situations of information asymmetry (adverse selection) or even to strategic collusive behaviors, or to a follow-the-leader behavior in which purchase and sale bids are based on the leaders' behavior.

We propose a study that addresses the main problem that is related, on the one hand, to the set of quantities that electrical companies bid on the spot market, in view of their joint coordination, and, on the other hand, to simultaneously analyze how electrical companies operate in the open market. This leads to questions of whether these behaviors are not interrelated, given the net supplier and net demander positions of the two largest players, Endesa and Iberdrola, and their followers. This suggestion will be consolidated by modeling conjectural variations to maximize the profit function of electrical firms in the quantities game. For the optimal resolution of the problem we consider simultaneously the quantity sold in the OMEL market and the quantity purchased in this market for sale in the open market. Another objective is to empirically check, during the period 2002–2007, whether such strategic behavior is related to the will of the electrical companies to control the market or to increase their market power, thus reducing the effect of competition.

In order to achieve this goal, we propose a Cournot model expressed as a function of the determinants of the bidding game based on the New Empirical Industrial Organization (NEIO) approach. The empirical analysis used the autoregressive distributed lag (ARDL) approach to cointegration and the Toda–Yamamoto Granger causality tests to validate the standard version of the Cournot model together with the new Cournot approach. The latter specifically captures the dynamics of these approaches in the wholesale electricity spot market to reveal important behavior information for the open market that aims to explain the strategic decision-making process of the main players of this unregulated market.

The paper is organized as follows: Sect. 2 presents a review of the literature. Section 3 contains the theoretical model, methods and data. Section 4 presents the empirical results. Section 5 provides a discussion of the empirical results. Section 6 presents the conclusions.

2 Relevant literature review

The Spanish electricity market has been subject to close scrutiny. The intraday market bidding behavior led Furió and Lucia (2009) to conclude that power generators have a clear economic incentive to avoid being dispatched in the day-ahead market. Ciarreta and Espinosa (2010a) found that in the day-ahead market larger generators are able to increase prices above the competitive benchmark. Moutinho et al. (2011) concluded that prices of Brent are important in re-establishing price equilibrium. Ciarreta and Espinosa (2012) concluded that regulation affected wholesale prices considerably. Moutinho et al. (2014) contend that market power is present in the wholesale electricity market.

The studies of Kühn and Machado (2004), Ciarreta and Espinosa (2010a, b, 2012) and Fabra (2009) were very important in the analysis of how the liberalized electricity market functioned in Spain in the recent past, from 2002 to 2007, before the creation of the MIBEL market, as well as during the transition period to open competitiveness. Generically, as a consequence of the characteristics of these different production technologies, coal-powered units set prices mainly in periods of limited demand, while hydroelectric units are predominantly used as close as possible to periods of peak demand (Fabra 2009). Consequently, given that Endesa assures around 57% of electricity output from coal and Iberdrola is the dominant firm in adaptable hydroelectric output, both groups normally determine marginal market prices (Kühn and Machado 2004).

Kühn and Machado (2004) and Ciarreta and Espinosa (2010b, 2012) claim that the two largest duopolists, Endesa and Iberdrola, behave as net supplier and net demander, respectively. Fabra (2009) admitted the existence of collusion between these two players.

Other studies based on time series data use econometric approaches to estimate the actual level of market power. Fabra and Toro (2005) find substantial evidence of time-varying market power in the Spanish power sector. Based on changes in demand and cost conditions—which reflect changes in input costs, capacity availability and hydropower—Fabra and Toro (2005) show that the time series of prices are characterized by two significantly different levels, which may be the result of potential collusive behavior between the two Spanish market leaders (Endesa and Iberdrola).

The ex-ante assessment of market power potential and the actual measure of market power on market outcomes have been subject to extensive research. This reflects the crucial importance of these issues on the policymakers' agenda. Nevertheless, the results of most of these studies are sensitive to some assumptions, particularly those regarding the shape of the demand curve.

In other electricity markets, particularly in Britain, Green and Newbery (1992), using a supply function equilibrium model and assuming different values for the elasticity of demand (from 0.1 to 0.5), found that the duopoly implemented during the first years of deregulation in Britain was leaving considerable market power to the two incumbents. Using a linear supply function model (with demand elasticity equal to 0.25), Green (1996) examined the possible policies devoted to this issue and found that the regulator's chosen policy (partial divestiture) would lead to a substantial reduction in deadweight losses.

After examining electricity prices in the British market, Wolfram (1999) estimated price-cost markups to measure the presence of market power and estimated a Lerner Index of 0.24. However, after controlling the low elasticity of demand, the average adjusted Lerner Index dropped to 0.05. The results imply that prices, while higher than marginal costs, were not as high as implied by some theoretical economic models, as proposed by Borenstein and Bushnell (1999) and Green and Newbery (1992). Hjalmarsson (2000), for instance, extends the static Bresnahan–Lau (Bresnahan 1982; Lau 1982) model for the identification of market power to the dynamic case. This method estimates a parameter, which varies between 0 (perfect competition) and 1 (monopoly) and includes how far the actual price is from a perfectly competitive situation.

Regarding to the application of the conjectural variation models, Karp and Perloff (1989), Deodhar and Sheldon (1996) and Sexton and Zhang (2001) have introduced the dynamic nature of statistical approaches in basic models following the NEIO approach. Following Bresnahan (1982), Steen and Salvanes (1999) developed a new dynamic model and introduced an error correction mechanism that allows for the introduction of market dynamics as an adaptation from Bärsden (1989). This appears to be unrelated to economic reasoning, as it has econometric origins with underlying economic implications.

Furthermore, as posed by Martin (2002), the statistic formula represents a short-term solution to a long-term interaction, as it manages to capture patterns of average market behavior. As long-term steady-state balance cannot exist, short-term interaction becomes relevant. Accordingly, the determinants of the model are the explicit short-term variations of time series used to estimate the model. Clearly, this is not a purely dynamic formula but a sequence of statistical problems.

Genesove and Mullin (1998) and Bettendorf and Verboven (2000) investigated the level of sensitivity in the estimation of market power to the functional form of demand. While Bettendorf and Verboven (2000) found differences in conduct parameter values between logarithmic, linear and quadratic forms, Genesove and Mullin (1998) found that the conduct parameter is very similar between linear, log linear, quadratic and exponential form functions. They observed that if robust tests are conducted regarding the behavior of the demand and the relationship with the supply, such relationships may not be maintained.

The main problem with purely dynamic models is that they are difficult to solve, as they require firm level data (Sheldon and Sperling 2003). In order to circumvent this limitation, Karp and Perloff (1989), and Deodhar and Sheldon (1996) used simplifications of quadratic linear games, which have been used in theoretical models of oligopoly (Dockner 1992; Karp and Perloff 1993), and help to solve the system and obtain a parameter of conduct. Clearly, the main innovation of dynamic models lies in the identification of the underlying strategic behavior of market participants (Corts 1999; Sheldon and Sperling 2003).

3 Theoretical model, methods and data

3.1 Model of the electricity spot market equilibrium problem

The market equilibrium of the electricity market is obtained by computing the profit maximization problem of the generating electricity firms, subject to their output constraints. This optimization problem can be formulated as follows (Lagarto et al. 2014):

$$\max_{\{q_{k,i}\}_{k\in K_i}} \pi_i = P(Q)q_i - \sum_{k\in K_i} C_{k,i}\left(q_{k,i}\right)$$
$$\text{subject to} \quad q_{k,i}^{\min} \leq q_{k,i} \leq q_{k,i}^{\max} \tag{1}$$

where π_i is the profit of generating firm i, $q_{k,i}$ is the quantity produced by power plant k owned by generating firm i, $P(Q)$ is the market clearing price, K_i is the set of power plants owned by generating firm i, Q is the market clearing quantity given by $\sum_{i\in I} q_i$ where I is the set of generating firms i, q_i is the quantity produced by generating firm i, $C_{k,i}\left(q_{k,i}\right)$ is the operational cost of power plant k owned by firm i, $q_{k,i}^{\min}$ and $q_{k,i}^{\max}$ are the minimum and maximum output limits of power plant k owned by firm i (see Lagarto et al. 2014).

The new problem in the OMEL spot electricity market is caused by the presence of bid interdependence for electricity quantities sold and bought from OMEL market. We believe that the behavior of the electrical power companies, particularly those with the greatest market share (i.e., Endesa and Iberdrola), can assume collusive behavior. Yet, we formulate a Cournot problem with the joint decision of these two variables for maximizing profit solution. According to the available historical data on the OMEL operator market site, one can also assess Endesa's and Iberdrola's net supplier and net demander position. It is possible to formulate the quantities' game as the focus of theoretical formulation of the problem, justifying the inclusion of the conjectural variations model. The conjecture translates firm i anticipating the rival's behavior before its behavior changes in the condition of maximizing the firm's profits.

The proposal of an oligopolistic model of conjectural variations allows the representation of various levels of competitive intensity among power firms operating in the spot market. These levels are parameterized in the conjecture that each company performs relative to the variation of the quantity produced by its rivals, in response to variations of its own quantity.

The Cournot equilibrium problem may be represented as a set of quantities that simultaneously satisfy the first-order condition of optimum amount q_{v_i} (quantity sold in the spot market) and q_{Cv_i} (quantity purchased in the spot market to sell in open market) for each firm i.

As the firm's objective is to maximize its profit, it is necessary to solve the following optimization problem:

$$\max_{\{q_{\mathrm{v}_i}, q_{\mathrm{Cv}_i}\}_{g\in G_i}} \pi_i = P\left[(Q)q_{\mathrm{v}_i} - (Q)q_{\mathrm{Cv}_i}\right] - \sum_{K\in K_i} C_{k,i}\left(q_{k,i}\right)$$
$$\text{subject to} \quad q_{k,i}^{\min} \leq q_{g,i} \leq q_{k,i}^{\max} \tag{2}$$

where π_i is the profit of firm i, being a function of quantities produced by the power plants owned by generating firm i; K_i is the set of power plants owned by generating firm i, $P(Q)$ is the market clearing price, where Q is market clearing net quantity given by $\sum_{i \in I} \left(q_{\mathrm{v}_i} - q_{\mathrm{Cv}_i} \right)$.

The Lagrange function of this optimization problem can be formulated as follows:

$$\lambda \left(q_{k,i}, \lambda_{1k,i}, \lambda_{2k,i} \right) = P \left[(Q) q_{\mathrm{v}_i} - (Q) q_{\mathrm{Cv}_i} \right] - \sum_{k \in K_i} C_{k,i} \left(q_{k,i} \right) + \sum_{k \in K_i} \lambda_{1k,i} \left[q_{k,i} - q_{k,i}^{\min} \right] + \sum_{k \in K_i} \lambda_{2k,i} \left[q_{k,i}^{\max} - q_{k,i} \right] \quad (3)$$

where $\lambda_{1k,i}$ and $\lambda_{2k,i}$ are the Lagrange multipliers associated with minimum and maximum output constraints of power plant k owned by generating firm i.

The Lerner Index is going to be defined for the following two situations: firstly, by applying the first-order condition of profit maximization for each firm i and considering the decision variable (q_{v_i}) and secondly by taking into consideration the optimization problem decision, with the quantity purchased in the spot market for sale in open market by each firm i represented by the variable (q_{Cv_i}).

3.2 Lerner Index for profit maximization considering the quantity sold in the spot market

The Lerner Index is going to be defined by applying the first-order condition of profit maximization for generating firm i and considering the decision variable (q_{v_i}).

The first solution of generation firm's maximization problem can be resolved using the Karush–Kuhn–Tucker (KKT) optimality conditions (see Lagarto et al. 2014):

$$\begin{aligned} &\text{KKT1}: \left(q_{k,i} - q_{k,i}^{\min} \right) \geq 0; \text{ and } \left(q_{k,i}^{\max} - q_{k,i} \right) \geq 0; \\ &\text{KKT2}: \exists_{\lambda_{1k,i}, \lambda_{2k,i} \geq 0}; \lambda_{1k,i} \left[\left(q_{k,i} - q_{k,i}^{\min} \right) \right] = 0; \text{ and } \lambda_{2k,i} \left[\left(q_{k,i}^{\max} - q_{k,i} \right) \right] = 0; \\ &\text{KKT3}: P(Q) \frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}} + \frac{\partial P(Q)}{\mathrm{d}q_{k,i}} q_{\mathrm{v}_i} - C'_{k,i}(q_{k,i}) + \lambda_{1k,i} - \lambda_{2k,i} = 0; \end{aligned} \quad (4)$$

where $C'_i(q_{k,i}) = MC_{k,i}$ is the marginal cost of power plant k owned by firm i; $\lambda_{1k,i}$ and $\lambda_{2k,i}$ are Lagrange multipliers associated with the restriction conditions; the ratio $\frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}}$ represents the change in the total quantity sold of firm i when a power plant owned by generating firm i changes its quantity and therefore is equal to one. The ratio $\frac{\partial P(Q)}{\mathrm{d}q_{k,i}}$ can be decomposed into a direct and indirect contribution, expressed mathematically by:

$$\frac{\partial P(Q)}{\partial q_{k,i}} = \frac{\mathrm{d}P(Q)}{\mathrm{d}Q} \frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{v}_i}} \frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}} + \frac{\mathrm{d}P(Q)}{\mathrm{d}Q} \frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{v}_{-i}}} \frac{\mathrm{d}q_{\mathrm{v}_{-i}}}{\mathrm{d}q_{\mathrm{v}_i}} \frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}}, \quad (5)$$

where $q_{\mathrm{v}_{-i}}$ is the quantity produced by generating firm −i (which represents the rivals of the generating firm in OMEL spot market).

The first term in (4), $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{v}_i}}\frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}}$, represents the direct effect on the market clearing price of a change in quantity sold of power plant k owned by generating firm i. Once a change occurs in power plant k, quantity $q_{k,i}$ causes a similar change in the quantity of firm i produced by plant k, and in its turn, a similar change occurs in the market net quantity dQ. The first term the equality $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{v}_i}}\frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}}$ can be rewritten as $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}$.

The second term of (5), $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{v}_{-i}}}\frac{\mathrm{d}q_{\mathrm{v}_{-i}}}{\mathrm{d}q_{\mathrm{v}_i}}\frac{\mathrm{d}q_{\mathrm{v}_i}}{\mathrm{d}q_{k,i}}$, can be seen as the indirect effect on the market clearing price of a change in quantity of power plant k owned by firm i. The ratio $\frac{\mathrm{d}q_{\mathrm{v}_{-i}}}{\mathrm{d}q_{\mathrm{v}_i}}$ represents the belief of firm i of the way in which rivals change their quantities in response to a change in its own quantity sold.

This belief is named the conjectural variation of firm i and is denoted by the conjectural variation parameter θq_{v_i}. Equation (4) becomes:

$$\frac{\partial P(Q)}{\partial q_{k,i}}=\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}+\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\left(\theta q_{\mathrm{v}_i}\right)=\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\left(1+\theta q_{\mathrm{v}_i}\right). \tag{6}$$

Substituting (6) in (4), we obtain the equation that represents the market equilibrium in OMEL market:

$$P(Q)+\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\left(1+\theta q_{\mathrm{v}_i}\right)q_{\mathrm{v}_i}-C'_{k,i}\left(q_{k,i}\right)+\lambda_{1k,i}-\lambda_{2k,i}=0. \tag{7}$$

This condition (7) may be transformed into the following expression of the Lerner Index:

$$\frac{P(Q)-MC_i}{P(Q)}=\left(1+\theta q_{\mathrm{v}_i}\right)\frac{sq_{\mathrm{v}_i}}{\alpha} \tag{8}$$

in which sq_{v_i} represents the market share of firm i given by q_{v_i}/Q and α represents the demand elasticity given by $\partial Q/Q\times P/\partial P$.

3.3 Lerner Index for profit maximization considering the quantity purchased in the spot market for sale in open market

The Lerner Index is going to be defined by applying the first-order condition of profit maximization for generating firm i and considering the decision variable (q_{Cv_i})

The firm's maximization in second condition problem can be solved using the next KKT optimality conditions:

$$\mathrm{KKT1}:\left(q_{k,i}-q_{k,i}^{\min}\right)\geq 0;\ \text{and}\ \left(q_{k,i}^{\max}-q_{k,i}\right)\geq 0$$
$$\mathrm{KKT2}:\exists_{\lambda_{1k,i},\lambda_{2k,i}\geq 0};\ \lambda_{1k,i}\left[\left(q_{k,i}-q_{k,i}^{\min}\right)\right]=0=0;$$

$$\text{and } \lambda_{2k,i}\left[\left(q_{k,i}^{\max} - q_{k,i}\right)\right] = 0$$

$$\text{KKT3}: P(Q)\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}} + \frac{\partial P(Q)}{\mathrm{d}q_{k,i}} q_{\mathrm{Cv}_i} - C'_{k,i}(q_{k,i}) + \lambda_{1k,i} - \lambda_{2k,i} = 0. \quad (9)$$

The ratio $\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}}$ represents the change in the total quantity purchased in the spot market for sale in open market of generating firm i when a power plant k owned by firm i changes its quantity and therefore is equal to one.

The ratio $\frac{\partial P(Q)}{\mathrm{d}q_{k,i}}$ can be decomposed into a direct and indirect contribution, expressed mathematically, as follows:

$$\frac{\partial P(Q)}{\partial q_{k,i}} = \frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{Cv}_i}}\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}} + \frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{Cv}_{-i}}}\frac{\mathrm{d}q_{\mathrm{Cv}_{-i}}}{\mathrm{d}q_{\mathrm{Cv}_i}}\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}}. \quad (10)$$

The first term in (10), $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{Cv}_i}}\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}}$, now represents the direct effect on the market clearing price of a change in quantity purchased in the spot market for sale in open market of power plant k owned by generating firm i. Once a change occurs in power plant k, quantity $q_{k,i}$ causes a similar change in the quantity purchased in the spot market for sale in open market of firm i, and in turn, a similar change occurs in the market net quantity $\mathrm{d}Q$. Thus, the first term in (10) can be expressed by the following equality $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{\mathrm{Cv}_i}}\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}} = \frac{\mathrm{d}P(Q)}{\mathrm{d}Q}$.

The second term in (8), $\frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\frac{\mathrm{d}Q}{\mathrm{d}q_{Cv-i}}\frac{\mathrm{d}q_{\mathrm{Cv}_{-i}}}{\mathrm{d}q_{\mathrm{Cv}_i}}\frac{\mathrm{d}q_{\mathrm{Cv}_i}}{\mathrm{d}q_{k,i}}$, can be seen as the indirect effect on the market clearing price of a change in quantity of power plant k owned by firm i. The ratio $\frac{\mathrm{d}q_{\mathrm{Cv}_{-i}}}{\mathrm{d}q_{\mathrm{Cv}_i}}$ represents the belief held by firm i of the way in which its rivals will change their purchases in the spot market for sale in open market in response to a change in its own quantity.

This belief, termed the conjectural variation of firm i, is denoted by the conjectural variation parameter $\theta q_{C_{vi}}$. Equation (10) becomes:

$$\frac{\partial P(Q)}{\partial q_{k,i}} = \frac{\mathrm{d}P(Q)}{\mathrm{d}Q} + \frac{\mathrm{d}P}{\mathrm{d}Q}\left(\theta q_{\mathrm{Cv}_i}\right) = \frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\left(1 + \theta q_{\mathrm{Cv}_i}\right). \quad (11)$$

Substituting (11) in (9), we obtain the second equation that represents the second condition of market equilibrium in the OMEL market.

The third KKT condition can be rewritten in the following way:

$$P(Q) + \frac{\mathrm{d}P(Q)}{\mathrm{d}Q}\left(1 + \theta q_{\mathrm{Cv}_i}\right) q_{\mathrm{Cv}_i} - C'_{k,i}(q_{k,i}) + \lambda_{1k,i} - \lambda_{2k,i} = 0. \quad (12)$$

This condition may be easily transformed into the following expression of the Lerner Index:

$$\frac{P(Q) - MC_i}{P(Q)} = \left(1 + \theta q_{\mathrm{Cv}_i}\right)\frac{s q_{\mathrm{Cv}_i}}{\alpha} \quad (13)$$

in which sq_{Cv_i} represents the new market share of firm i given by q_{Cv_i}/Q, and α represents demand elasticity given by $\partial Q/Q \times P/\partial P$.

As a result of the Lerner Indexes generated in Sects. 3.2 and 3.3, the two conjectural variation parameters proposed (θ) allow for a flexible representation of the various competitive behaviors exhibited by firms according to the decision variables of the noncooperative game. The resolution of the third KKT condition of profit maximization leads us to two types of conduct parameters. If θq_{v_i} and θq_{Cv_i} assume the value -1, it means that the behavior of firm i is perfectly competitive. When the values of θq_{v_i} and θq_{Cv_i} equal zero, this case represents the Cournot competition outcome. With values of $0 \leq \theta q_{\mathrm{v}_i}, \theta q_{\mathrm{Cv}_i} \leq -1$ an intermediate competitive regime exists. Collusive behavior between firms may be represented by values of θq_{v_i} and θq_{Cv_i} greater than zero.

3.4 Methods

To validate the proposed theoretical formulation, we consider that the conjectural variations require anticipated reactions in a context of simultaneous and static decision. This inconsistency can only be overcome by (oligopolistic) dynamic games, which underpin the choice of cointegration with time series data. First we analyzed the integration order of the variables. We studied the stationarity of the series by applying conventional unit root tests such as the Augmented Dickey–Fuller (ADF). Conventional unit root tests have low power and are biased if they do not take into account structural break points. Therefore, we also employ the endogenous one-break unit root test of Zivot and Andrews (1992) which allows for one break in the intercept and trend. This method treats the occurrence of the break data as unknown and tests the unit root against the alternative trend-break stationary process with a structural break. The ADF test is a unit root test used to identify the non-stationarity of the item series sample.

Moreover, we apply the KPSS test as a confirmatory test for testing a null hypothesis that an observable time series is stationary around a deterministic trend. Instead of using the conventional version of the KPSS test, we employ a robust version of the KPSS. The effect of neglected seasonal variation on ADF and KPSS is shown in the literature (Demetrescu and Hassler 2005). The KPSS is more robust to seasonal variations provided that the long-run variance is based on a sufficiently large bandwidth. Along with the application of non-robust unit root tests, such as the ADF unit root test, commonly found in commercial packages, we compute a robust test, namely the robust KPSS test (de Jong et al. 2007; Pelagatti and Sen 2013; Bosco et al. 2010) to confirm the findings of the unit root tests.

3.4.1 Autoregressive distributed lag bounds tests

The ARDL bounds testing approach to cointegration proposed by Pesaran et al. (2001) is an econometric method that can be applied regardless whether underlying regressors are purely integrated of order one or integrated of order zero, hence stationary. This means that the pretesting problems associated with conventional cointegration, which require that variables that are not stationary, can be overlooked. The approach involves estimating the conditional error correction version of the ARDL model for the dependent variable representing the market price in the open market (*POmel*).

We estimate the three general specifications, referred to as Specification 1, Specification 2A and Specification 2B. In order to make these specifications clear, we defined the variables in the following way: POmel is a hourly clearing price in the Spanish spot electricity market; q_{v} is the quantity sold in the spot market by each agent; q_{Cv} is the quantity purchased in the spot market for sale in open market by each agent; the agents are going to be referred to as End (Endesa), Iber (Iberdrola), UF (Unión Fenosa), Hidro (Hidrocantábrico); θ is going to be the conjectural variation parameter, in which θq_{v} is associated with the quantity sold in the spot market by each agent and θq_{Cv} is associated with the quantity purchased in the spot market for sale in open market by each agent.

Specification 1 contains $\theta_1 q_{\mathrm{v}}$, the conjectural variation parameter proposed to allow for a flexible representation of the various competitive behaviors exhibited by firm i according to the quantity sold in market, and q_{v}, specifically the quantity sold in the spot market by firm i, and which, in this Specification 1, stands for the decision variable of the noncooperative game to analyze the spot price effect and quantities sold, *ceteris paribus*. To implement the bounds test for cointegration, the following unrestricted regression equation is formulated for Specification 1:

$$\begin{aligned}
\Delta \mathrm{POmel}_t = {} & \alpha_1 + \delta_1 \mathrm{POmel}_{t-1} \\
& + \delta_2 \theta_1 q_{\mathrm{v}} \mathrm{End}_{t-1} + \delta_3 q_{\mathrm{v}} \mathrm{End}_{t-1} \\
& + \delta_4 \theta_1 q_{\mathrm{v}} \mathrm{Iber}_{t-1} + \delta_5 q_{\mathrm{v}} \mathrm{Iber}_{t-1} \\
& + \delta_6 \theta_1 q_{\mathrm{v}} \mathrm{UF}_{t-1} + \delta_7 q_{\mathrm{v}} \mathrm{UF}_{t-1} \\
& + \delta_8 \theta_1 q_{\mathrm{v}} \mathrm{Hidro}_{t-1} + \delta_9 q_{\mathrm{v}} \mathrm{Hidro}_{t-1} \\
& + \sum_{i=1}^{n} \delta_{10i} \Delta \mathrm{POmel}_{t-i} \\
& + \sum_{i=0}^{n} \delta_{11i} \Delta \theta_1 q_{\mathrm{v}} \mathrm{End}_{t-i} + \sum_{i=0}^{n} \delta_{12i} \Delta q_{\mathrm{v}} \mathrm{End}_{t-i} \\
& + \sum_{i=0}^{n} \delta_{13i} \Delta \theta_1 q_{\mathrm{v}} \mathrm{Iber}_{t-i} + \sum_{i=0}^{n} \delta_{14i} \Delta q_{\mathrm{v}} \mathrm{Iber}_{t-i} \\
& + \sum_{i=0}^{n} \delta_{15i} \Delta \theta_1 q_{\mathrm{v}} \mathrm{UF}_{t-i} + \sum_{i=0}^{n} \delta_{16i} \Delta q_{\mathrm{v}} \mathrm{UF}_{t-i} \\
& + \sum_{i=0}^{n} \delta_{17i} \Delta \theta_1 q_{\mathrm{v}} \mathrm{Hidro}_{t-i} + \sum_{i=0}^{n} \delta_{18i} \Delta q_{\mathrm{v}} \mathrm{Hidro}_{t-i} + \varepsilon_t .
\end{aligned} \tag{14}$$

In Specification 2A, the Cournot equilibrium problem proposed may be represented as a set of quantities that simultaneously satisfy the first-order condition of optimum amount, which is the quantity sold in the spot market, and the quantity purchased in the spot market to sell in open market for each firm i. This specification contains $\theta_{2A}q_v$, namely a proposed conjectural variation parameter to allow for a second flexible representation of the various competitive behaviors exhibited by firm i according to the profit maximization in order to determine the quantity sold in market, and q_v which is the quantity sold in the spot market by firm i, to assess the price impact only and the quantities sold, *ceteris paribus*, as follows:

$$\begin{aligned}\Delta \text{POmel}_t = {} & \alpha_1 + \delta_1 \text{POmel}_{t-1} \\ & + \delta_2 \theta_{2A} q_v \text{End}_{t-1} + \delta_3 q_v \text{End}_{t-1} \\ & + \delta_4 \theta_{2A} q_v \text{Iber}_{t-1} + \delta_5 q_v \text{Iber}_{t-1} \\ & + \delta_6 \theta_{2A} q_v \text{UF}_{t-1} + \delta_7 q_v \text{UF}_{t-1} \\ & + \delta_8 \theta_{2A} q_v \text{Hidro}_{t-1} + \delta_9 q_v \text{Hidro}_{t-1} + \sum_{i=1}^{n} \delta_{19i} \text{POmel}_{t-i} \\ & + \sum_{i=0}^{n} \delta_{11i} \Delta \theta_{2A} q_v \text{End}_{t-i} + \sum_{i=0}^{n} \delta_{12i} \Delta q_v \text{End}_{t-i} \\ & + \sum_{i=0}^{n} \delta_{13i} \Delta \theta_{2A} q_v \text{Iber}_{t-i} + \sum_{i=0}^{n} \delta_{14i} \Delta q_v \text{Iber}_{t-i} \\ & + \sum_{i=0}^{n} \delta_{15i} \Delta \theta_{2A} q_v \text{UF}_{t-i} + \sum_{i=0}^{n} \delta_{16i} \Delta q_v \text{UF}_{t-i} \\ & + \sum_{i=0}^{n} \delta_{17i} \Delta \theta_{2A} q_v \text{Hidro}_{t-i} + \sum_{i=0}^{n} \delta_{18i} \Delta q_v \text{Hidro}_{t-i} + \varepsilon_t. \end{aligned} \tag{15}$$

In Specification 2B, we include $\theta_{2B}q_{Cv}$, namely the proposed conjectural variation parameter to allow for a second flexible representation of the various competitive behaviors exhibited by firm i according to the profit maximization in order to determine the quantity purchased in the spot market to sell in open market, and q_{Cv} representing the quantity purchased in the spot market to sell in open market, where we assess the impact on price only and on the quantities purchased, *ceteris paribus*, as shown by the equation below:

$$\begin{aligned}\Delta \text{POmel}_t = {} & \alpha_1 + \delta_1 \text{POmel}_{t-1} + \delta_2 \theta_{2B} q_{Cv} \text{End}_{t-1} \\ & + \delta_3 q_{Cv} \text{End}_{t-1} + \delta_4 \theta_{2B} q_{Cv} \text{Iber}_{t-1} \\ & + \delta_5 q_{Cv} \text{Iber}_{t-1} + \delta_6 \theta_{2B} q_{Cv} \text{UF}_{t-1} + \delta_7 q_{Cv} \text{UF}_{t-1} \\ & + \delta_8 \theta_{2B} q_{Cv} \text{Hidro}_{t-1} + \delta_9 q_{Cv} \text{Hidro}_{t-1} \\ & + \sum_{i=1}^{n} \delta_{10i} \text{POmel}_{t-i} + \sum_{i=0}^{n} \delta_{11i} \Delta \theta_{2B} q_{Cv} \text{End}_{t-i} \\ & + \sum_{i=0}^{n} \delta_{12i} \Delta q_{Cv} \text{End}_{t-i} + \sum_{i=0}^{n} \delta_{13i} \Delta \theta_{2B} q_{Cv} \text{Iber}_{t-i} \end{aligned}$$

$$+ \sum_{i=0}^{n} \delta_{14i} \Delta q_{\mathrm{Cv}}\mathrm{Iber}_{t-i} + \sum_{i=0}^{n} \delta_{15i} \Delta \theta_{2\mathrm{B}} q_{\mathrm{Cv}}\mathrm{UF}_{t-i}$$
$$+ \sum_{i=0}^{n} \delta_{16i} \Delta q_{\mathrm{Cv}}\mathrm{UF}_{t-i} + \sum_{i=0}^{n} \delta_{17i} \Delta \theta_{2\mathrm{B}} q_{\mathrm{Cv}}\mathrm{Hidro}_{t-i}$$
$$+ \sum_{i=0}^{n} \delta_{18i} \Delta q_{\mathrm{Cv}}\mathrm{Hidro}_{t-i} + \varepsilon_t. \qquad (16)$$

All the equations above contain POmel_t, the dependent variable, followed by the first difference operator Δ and the set of all explanatory variables, and ε_{t}, the white noise error term. From the above specifications, $\delta_1, \ldots, \delta_{18}$ are the long-run parameters. Lag selection is selected by a criterion such as the Akaike Information Criterion (hereafter AIC). The joint significant F-test or Wald statistic of the lagged level variables is employed for investigating the existence of a long-run behavior among the variables.

The test for cointegration is carried out by testing the null hypothesis of having no cointegration, H_0: $\delta_1 = \delta_2 = \cdots = \delta_9 = 0$ is tested against the alternative hypothesis, H_1: $\delta_1 \neq \delta_2 \neq \cdots \neq \delta_9 \neq 0$, using the F-test. The variables are said to be cointegrated if the null hypothesis of no cointegration is rejected. Otherwise, the variables are not cointegrated. For this purpose, the two sets of critical values, one for the upper bound and another for the lower bound, are those tabulated by Pesaran et al. (2001). If the computed F-statistic exceeds the upper bound of the critical values, then the null hypothesis of no cointegration is rejected. If it is less than the lower bounds value, then the null hypothesis cannot be rejected, but if it falls between the two levels of the bands, the cointegration test becomes inconclusive.

3.4.2 *Toda–Yamamoto causality approach*

The Granger representation theorem is conventionally applied by estimating vector autoregressive (VAR) models. Granger (1986) shows that if a pair of integrated of order one series are cointegrated, then there must be at least a unidirectional causation (indeed causation can also be bidirectional). This test is only valid if the series are I(1) or are not integrated of different orders. Toda and Yamamoto (1995) propose a simple procedure when economic time series are either integrated of different orders, or non-cointegrated or when we have both cases. This approach is known as the Toda and Yamamoto augmented Granger causality procedure, which allows testing for causality between integrated variables based on asymptotic theory. This procedure requires the estimation of an "augmented" VAR, which guarantees the asymptotic distribution of the Wald statistic, namely an asymptotic χ^2 distribution, since the testing procedure is robust to the integration and cointegration process properties.

Two steps are involved when implementing the procedure. The first step includes determination of the optimal lag length (p) and the maximum order of integration ($d_{\max}$) of the variables in a system, and the error terms that are assumed to be white noise. In this study, we use the Akaike and Schwarz information criteria for the lag order selection. In addition, we employ the Zivot and Andrews (1992) test to determine the maximum order of integration. The second step involves estimating an "augmented" VAR in levels. After determining the maximal order of integration of the variables and the optimal lag length of the system, we construct a VAR with all variables in levels and include a total of $(p + d)$ lags.

3.5 Data

The collection of data included the following information: daily spot prices, quantity bid in wholesale market, quantity purchased in wholesale market for sale in open market, and the behavior of conduct parameters from January 2002 until April 2007, prior to the beginning of the MIBEL electricity market. The initial data consist of daily averages of hourly observations (24-h average) of demand and supply for each agent (Endesa, Iberdrola, Unión Fenosa, Hidrocantábrico) for the production and demand of each unit in the Spanish wholesale electricity market. However, the daily averages of electricity prices and quantities show a very strong seven-day periodic pattern and periodic seasonal variation. Furthermore, price trends are buried into high-variance leptokurtic short-term noise. These characteristics are expected to greatly affect the size and power of all our tests. To overcome this problem and to reduce the effects of the aforementioned features of electric prices and quantities, we worked on weekly means instead of daily averages to smooth the seven-day periodicity and average out the strong noise of price time series. This brings the sample down to a total of 208 observations (52 months). This data transformation is appropriate since we are looking for long-run movements and relations among series.

The marginal costs of power generation were obtained for all electricity production units in the portfolio, which were then ranked in ascending merit-order effect based on their marginal costs. We are using constant marginal costs and thus a linear cost function. In order to maximize profits, producers start generating from plants with the lowest marginal cost. As soon as demand increases, new production units are brought on line to meet the demand following the order of merit. Conversely, with changes in fuel and carbon prices new marginal costs are recalculated and new merit orders are reanalyzed.

The different electricity production technologies used by the power plants have significantly influenced the daily periods. We used the daily spot prices of fuel, coal and gas to compute the marginal costs. Data of major fuel sources (oil, coal, gas) were retrieved from the Systems and Energy Section database from a national university.

Information regarding market price, quantity offered for each agent in the wholesale market, and quantity purchased by each agent in the wholesale market and sold in the open market was obtained from OMEL database. Based on Lagarto et al. (2010), it was possible to calculate the power plant marginal cost using the following expression: $\mathrm{MC}_{p,\mathrm{fuel}} = (f \times cf)/(\mathrm{LHV} \times \eta_p)$, where $\mathrm{MC}_p = \mathrm{MC}_{p,\mathrm{fuel}} + \mathrm{MC}_{p,\mathrm{CO_2}}$, MC_p is the marginal cost of power plant p in €/MW; $\mathrm{MC}_{p,\mathrm{fuel}}$ is the marginal cost of power plant p due to fossil fuel costs in €/MW; f is the fossil fuel price in €/t; cf is a conversion factor equal to 859845 kCal/MW; LHV is the Lower Heating Value in kCal/t; and η_p is power plant efficiency in %.

The marginal cost of power plant $_p$, $\mathrm{MC}_{p,\mathrm{CO_2}}$,—which was zero for the 2002–2005 period—due to CO_2 emissions cost in €/MW, is given by: $\mathrm{MC}_{p,\mathrm{CO_2}} = P_{\mathrm{CO_2}} \times$

$ee_p \times 10^{-3}$, where P_{CO_2} is the CO_2 emission price in €/t; ee_p is the power $_p$ specific emission of CO_2 in Kg CO_2/MW.

4 Empirical results

Descriptive statistics are presented in Tables 13, 14 and 15 (see "Appendix"), and the pairwise correlations between all the variables included in Specifications 1 and 2 are presented in Tables 1, 2 and 3. The results reveal that variables included in the econometric specifications are found to be normally distributed for all specifications. The pairwise correlations for Specification 1 indicate that quantity sold in spot market and conduct parameter ($\theta_1 q_v$) by each generator (Endesa, Iberdrola, Unión Fenosa) are positively correlated with the spot price (POmel) while negative correlation is found between quantity sold in spot market by Hidrocantábrico generator and POmel. Other important findings of pairwise correlations in Specification 1 show that quantity sold in spot market is negatively correlated with conduct parameter ($\theta_1 q_v$) for Endesa

Table 1 Correlation matrix for Specification 1

	POmel	$\theta_1 q_v$End	q_vEnd	$\theta_1 q_v$Iber	q_vIber	$\theta_1 q_v$UF	q_vUF	$\theta_1 q_v$Hid	q_vHid
POmel	1.000								
$\theta_1 q_v$End	0.845	1.000							
q_vEnd	−0.080	−0.442	1.000						
$\theta_1 q_v$Iber	0.844	0.789	−0.110	1.000					
q_vIber	0.305	0.337	−0.042	0.076	1.000				
$\theta_1 q_v$UF	0.795	0.806	−0.231	0.777	0.302	1.000			
q_vUF	0.517	0.446	0.149	0.484	0.288	0.155	1.000		
$\theta_1 q_v$Hid	0.902	0.873	−0.244	0.853	0.328	0.817	0.448	1.000	
q_vHid	−0.340	−0.444	0.357	−0.457	−0.096	−0.372	−0.182	−0.644	1.000

Table 2 Correlation matrix for Specification 2A

	POmel	$\theta_{2A} q_v$End	q_vEnd	$\theta_{2A} q_v$Iber	q_vIber	$\theta_{2A} q_v$UF	q_vUF	$\theta_{2A} q_v$Hid	q_vHid
POmel	1.000								
$\theta_{2A} q_v$End	0.013	1.000							
q_vEnd	−0.080	−0.034	1.000						
$\theta_{2A} q_v$Iber	−0.287	−0.038	−0.034	1.000					
q_vIber	0.305	−0.065	−0.042	−0.096	1.000				
$\theta_{2A} q_v$UF	−0.001	0.022	−0.005	0.005	−0.110	1.000			
q_vUF	0.517	−0.051	0.149	−0.067	0.288	0.019	1.000		
$\theta_{2A} q_v$Hid	0.033	0.053	−0.034	0.001	0.105	−0.025	−0.061	1.000	
q_vHid	0.340	−0.043	0.357	0.004	−0.096	−0.039	−0.182	0.037	1.000

Table 3 Correlation matrix for Specification 2B

	POmel	$\theta_{2B}q_{Cv}$End	q_{Cv}End	$\theta_{2B}q_{Cv}$Iber	q_{Cv}Iber	$\theta_{2B}q_{Cv}$UF	q_{Cv}UF	$\theta_{2B}q_{Cv}$Hid	q_{Cv}Hid
POmel	1.000								
$\theta_{2B}q_{Cv}$End	−0.015	1.000							
q_{Cv}End	0.236	−0.067	1.000						
$\theta_{2B}q_{Cv}$Iber	0.271	−0.022	0.027	1.000					
q_{Cv}Iber	0.306	−0.108	0.865	0.046	1.000				
$\theta_{2B}q_{Cv}$UF	−0.002	0.010	−0.072	0.008	−0.101	1.000			
q_{Cv}UF	0.547	−0.058	0.517	0.082	0.549	−0.078	1.000		
$\theta_{2B}q_{Cv}$Hid	−0.034	0.049	0.091	−0.003	0.136	0.025	−0.016	1.000	
q_{Cv}Hid	−0.357	0.053	0.175	−0.054	0.101	0.042	−0.262	−0.033	1.000

and Hidrocantábrico, while positive correlation is found between quantity sold in spot market to conduct parameter ($\theta_1 q_v$) for Iberdrola and Unión Fenosa.

Table 2 presents the pairwise correlation for Specification 2A and reveals that quantity sold in spot market by Iberdrola, Unión Fenosa and Hidrocantábrico is positively correlated with POmel, while the conduct parameters ($\theta_{2A} q_v$) of Endesa and Unión Fenosa present a negative correlation coefficient with POmel. In Specification 2B, as shown in Table 3, the findings of pairwise correlation show that quantity purchased in spot market for the open market selling operation by Endesa, Iberdrola and Unión Fenosa is positively correlated with POmel, whereas the conduct parameters ($\theta_{2B} q_{Cv}$) of Endesa, Unión Fenosa and Hidrocantábrico are negatively correlated with POmel. We note that there is negative correlation between quantity purchased in the spot market to sell in the open market by Hidrocantábrico with POmel, and a positive one between Iberdrola's conduct parameter ($\theta_{2B} q_{Cv}$) and POmel. Table 3 also indicates that the quantity purchased in the spot market to sell in open market by Iberdrola is negatively correlated with Endesa's conduct parameter

According to Moutinho et al. (2014), during this time span, Endesa had an incentive to under-produce in order to increase the price received for the net electricity sold to the market, whereas Iberdrola over-produced based on an oligopsonistic incentive to reduce the price paid for the infra-marginal units purchased from the spot market. This is also according to Kühn and Machado (2004) who contend that Endesa's "net supplier" and Iberdrola's "net demander" underpin the market power exercised according to these firms' behavior as net demanders or net suppliers.

4.1 Results of unit root tests

We tested the non-stationarity and stationarity hypothesis for all series in our analysis through the conventional ADF unit root test and KPSS unit root test and the non-conventional KPSS unit root test (robust version), as shown in Table 4.

While the null hypothesis in ADF tests has non-stationarity as a premise, the KPSS test has stationarity as H_0. In conventional unit root testing, the rejection of one of the tests is usually consistent with the non-rejection of the other (Dickey and Fuller 1979). In the present case, as the data are de-trended, we use the robust version of the KPSS test to complement the conventional versions of the ADF and KPSS tests. Overall, the regular KPSS tests reject the null of stationarity on levels, but they do not reject it on first differences. Altogether, the unit root tests reveal that the variables are integrated of order zero or of order one.

The results of Zivot–Andrews structural break trended unit root test are reported in Table 5. The empirical evidence discloses mixed results and entails that the series are not integrated higher than that of order two. Overall, the unit root tests seem to converge toward the conclusion that the data are I(0) or I(1). If we want to model the data appropriately with the ARDL/Bounds testing methodology of Pesaran et al. (2001), we can use it with a mixture of I(0) and I(1) data. If variables are I(2), such data will invalidate the methodology. In the present case, since the variables present a mixed order of integration, we proceed with the ARDL testing approach.

Table 4 Results of unit root test

Variables	ADF with constant (conventional)	ADF with trend (conventional)	KPSS with constant	KPSS with constant and trend	Robust KPSS with constant	Robust KPSS with constant and trend
POmel	−2.886**	−3.589**	0.800***	0.403***	0.118	0.047
ΔPOmel	−10.986***	−11.122***	0.344	0.079	10.764**	0.435**
q_{Cv}End	−11.665***	−11.644***	1.658***	0.097***	0.036	0.035
Δq_{Cv}End	−12.378***	−12.346***	0.157	0.057	7.010**	1.088**
q_{v}End	−4.697***	−4.691***	0.336	0.270***	0.152	0.151**
Δq_{v}End	−11.665***	−11.644***	0.114	0.073	31.666**	2.781**
q_{Cv}Iber	−13.150***	−13.184***	1.582***	0.103	0.220	0.155**
Δq_{Cv}Iber	−7.178***	−7.236***	0.191	0.068	6.553	2.453
q_{v}Iber	−3.849***	−3.787**	0.125***	0.083***	0.059	0.040
Δq_{v}Iber	−13.609***	−13.604***	0.029	0.029	8.893	0.969**
q_{Cv}UF	−5.320***	−5.261***	0.957***	0.588***	0.059	0.029
Δq_{Cv}UF	−8.742***	−8.747***	0.086	0.079	3.082**	0.227**
q_{v}UF	−4.712***	−4.986***	0.579***	0.141***	0.199	0.131**
Δq_{v}UF	−5.320***	−5.261***	0.064	0.053	1.108**	1.170**
q_{Cv}Hid	−1.744	−1.618	0.984	0.261***	0.038	0.037
Δq_{Cv}Hid	−7.632***	−7.654***	0.126	0.071	0.771**	0.733**
q_{v}Hid	−2.249	−2.194	0.402***	0.091	0.130	0.081
Δq_{v}Hid	−6.576***	−6.585***	0.091	0.057	8.917**	0.918**
$\theta_1 q_{\mathrm{v}}$End	−0.899	−1.667	0.562***	0.420***	0.305	0.040
$\Delta\theta_1 q_{\mathrm{v}}$End	−11.705***	−5.430***	0.234	0.091	9.761**	2.581**
$\theta_{2\mathrm{A}} q_{\mathrm{v}}$End	−14.715***	−14.712***	0.112	0.051	0.152	0.144**
$\Delta\theta_{2\mathrm{A}} q_{\mathrm{v}}$End	−8.366***	−8.344***	0.225	0.223	9.661**	0.907**
$\theta_1 q_{\mathrm{v}}$Iber	−1.782	−3.001	0.740***	0.319***	0.062	0.053

Table 4 continued

Variables	ADF with constant (conventional)	ADF with trend (conventional)	KPSS with constant	KPSS with constant and trend	Robust KPSS with constant	Robust KPSS with constant and trend
$\Delta\theta_1 q_V$Iber	−9.471***	−9.571***	0.271	0.079	7.375**	0.286**
$\theta_{2A} q_V$Iber	−3.964	−4.224**	0.162***	0.085***	0.306	0.049
$\Delta\theta_{2A} q_V$Iber	−6.020***	−6.022***	0.024	0.020	11.766**	2.553**
$\theta_1 q_V$UF	0.336	−0.291	0.586***	0.403***	0.056	0.057
$\Delta\theta_1 q_V$UF	−11.504***	−11.662***	0.370	0.019	4.905**	0.970**
$\theta_{2A} q_V$UF	−14.409***	−14.467***	0.196	0.044	0.056	0.056
$\Delta\theta_{2A} q_V$UF	−8.460***	−8.439***	0.500	0.500	1.837**	1.789**
$\theta_1 q_V$Hid	0.132	−0.175	0.435***	0.393***	0.344	0.037
$\Delta\theta_1 q_V$Hid	−3.915**	−4.314***	0.378	0.096	2.145**	2.108**
$\theta_{2A} q_V$Hid	−14.691***	−14.951***	0.469**	0.030	0.023	0.023
$\Delta\theta_{2A} q_V$Hid	−9.341***	−9.318***	0.171	0.173	5.137**	0.521**
$\theta_{2B} q_{CV}$End	−14.833***	−14.831***	0.112	0.051	0.223	0.045
$\Delta\theta_{2B} q_{CV}$End	−8.412***	−8.390***	0.225	0.223	9.174**	1.018**
$\theta_{2B} q_{CV}$Iber	−3.716***	−3.851**	0.162***	0.085***	0.052	0.052
$\Delta\theta_{2B} q_{CV}$Iber	−11.853***	−11.866***	0.024	0.020	8.891**	1.415**
$\theta_{2B} q_{CV}$UF	−14.406***	−14.464***	0.196	0.044	0.041	0.041
$\Delta\theta_{2B} q_{CV}$UF	−8.461***	−8.439***	0.500	0.004	10.351**	1.086**
$\theta_{2B} q_{CV}$Hid	−14.614***	−14.865***	0.469**	0.030	0.029	0.027
$\Delta\theta_{2B} q_{CV}$Hid	−8.965***	−8.943***	0.171	0.173	2.478**	0.522**
Critical values						
1% level	−3.461 −4.002	−3.462 −4.003	0.739	0.216	0.739	0.216
5% level	−2.875 −3.431	−2.875 −3.431	0.463	0.146	0.463	0.146

The level of statistical significance is 1% denoted by *** and 5% denoted by **

Table 5 Zivot–Andrews structural break unit root test

Variable	At level		At 1st difference	
	t-statistic	Time break	t-statistic	Time break
POmel	−5.218***	1-08-2005	−11.227	3-05-2005
q_VEnd	−4.987***	4-06-2005	−11.787	2-02-2003
q_VUF	−5.774***	1-03-2005	−8.219	1-06-2005
q_VHid	−4.779***	4-03-2005	−7.085**	3-04-2004
q_VIber	−4.359**	3-06-2004	−13.793**	2-02-2003
$\theta_1 q_V$End	−3.686***	4-07-2005	−11.928	4-01-2005
$\theta_1 q_V$UF	−3.730***	2-07-2003	−11.815	3-06-2003
$\theta_1 q_V$Hid	−5.452***	3-03-2005	−13.716	3-05-2005
$\theta_1 q_V$Iber	−5.493***	1-03-2005	−11.289	3-11-2004
q_{CV}End	−3.284**	2-02-2004	−10.636	1-01-2003
q_{CV}UF	−4.732***	3-04-2005	−16.403	3-02-2004
q_{CV}Hid	−5.297***	4-03-2005	−8.130**	2-08-2004
q_{CV}Iber	−2.745	2-03-2005	−13.354	1-08-2005
$\theta_{2A} q_V$End	−14.911	3-06-2005	−9.449***	1-07-2005
$\theta_{2A} q_V$UF	−14.695	2-07-2005	−9.533***	4-08-2005
$\theta_{2A} q_V$Hid	−15.085	1-04-2005	−9.019	4-05-2005
$\theta_{2A} q_V$Iber	−4.479***	3-03-2003	−11.956***	3-01-2003
$\theta_{2B} q_{CV}$End	−15.056	3-06-2005	−9.489***	1-07-2005
$\theta_{2B} q_{CV}$UF	−14.692	2-07-2005	−9.536***	4-08-2005
$\theta_{2B} q_{CV}$Hid	−14.984	3-05-2005	−8.923	4-05-2005
$\theta_{2B} q_{CV}$Iber	−4.413	1-12-2003	−12.318***	3-01-2003

The level of statistical significance of 1% is denoted by *** and 5% is denoted by **. The critical value at 1% is −5.34 and at 5% is −4.93. The maximum lag order is 6. The unit root test has a structural break in the intercept. The time break is dated in the following manner: The first number indicates the week and the second indicates the month, followed by the number of the year

The selection of the optimal number of lags in the VAR estimation for all econometric specifications was based on a set of optimal lag length selection tests. The LR test statistic, the final prediction error, the Schwarz Information Criterion and the Hannan–Quinn information criterion persistently indicate an optimal lag structure of ten lags for Specification 1 and four lags for Specification 2A and Specification 2B. The optimal lag length is contingent on the number of observations. In conclusion, the option was for stricter criteria (Schwarz Information Criterion), within the parsimonious specification of the VAR model, conditional to the diagnostic tests set out below.

4.2 Results of cointegration tests

The cointegration results for Specifications 1, 2A and 2B are shown in Tables 6, 7 and 8. The results are not conclusive or in favor of cointegration for Specification

Table 6 ARDL bounds test for investigating long-run equilibrium relationships among the variables in Specification 1

Cointegration equations	ARDL specification	F-statistic	k	Cointegration
POmel, $\theta_1 q_v$End, q_vEnd, $\theta_1 q_v$Iber, q_vIber, $\theta_1 q_v$UF, q_vUF	ARDL (1,1,2,1,2,1,3)	3.150	6	Non-conclusive
POmel, $\theta_1 q_v$End, q_vEnd, $\theta_1 q_v$Iber, q_vIber, $\theta_1 q_v$Hid, q_vHid	ARDL (5,6,1,1,1,6,3)	1.907	6	No
POmel, $\theta_1 q_v$Iber, q_vIber, $\theta_1 q_v$UF, q_vUF, $\theta_1 q_v$Hid, q_vHid	ARDL (1,1,1,3,1,1,1)	4.174	6	Yes

The level of statistical significance is 5%. Figures in parenthesis show the number of lag selected based on the AIC. The maximum lag length is set to 4. For the bounds test, the asymptotic critical value bounds are taken from Pesaran et al. (2001), page 300, Table CI(iii) unrestricted intercept and no trend with max lags k in dependent variable and regressors equal to 6. The low bound, I(0), is 3.15/2.45/2.12, and the upper bound, I(1), is 4.43/3.61/3.23 at 1%, 5% and 10%, respectively

Table 7 ARDL bounds test for investigating long-run equilibrium relationships among the variables in Specification 2A

Cointegration equations	ARDL specification	F-statistic	k	Cointegration
POmel, $\theta_{2A}q_v$End, q_vEnd, $\theta_{2A}q_v$Iber, q_vIber, $\theta_{2A}q_v$UF, q_vUF	ARDL (1,0,1,5,1,5,1)	0.817	6	No
POmel, $\theta_{2A}q_v$End, q_vEnd, $\theta_{2A}q_v$Iber, q_vIber, $\theta_{2A}q_v$Hid, q_vHid	ARDL (1,0,1,5,1,6,1)	1.463	6	No
POmel, $\theta_{2A}q_v$Iber, q_vIber, $\theta_{2A}q_v$UF, q_vUF, $\theta_{2A}q_v$Hid, q_vHid	ARDL (1,2,1,6,1,6,1)	1.239	6	No

The level of statistical significance is 5%. Figures in parenthesis show the number of lag selected based on the AIC. The maximum lag length is set to 4. For the bounds test, the asymptotic critical value bounds are taken from Pesaran et al. (2001), page 300, Table CI(iii) unrestricted intercept and no trend with max lags k in dependent variable and regressors equal to 6. The low bound, I(0), is 3.15/2.45/2.12, and the upper bound, I(1), is 4.43/3.61/3.23 at 1%, 5% and 10%, respectively

2A since the reported F-statistics are below the lower critical bound generated by Pesaran et al. (2001). The same conclusions apply, even though partially, to the results for Specification 1. Specification 2B provides more conclusive results and favors cointegration among the variables under scrutiny. The null hypothesis for all the tests is the existence of no cointegration since the computed critical values reported in Table 8 are higher. In all the tested relationships proposed, the null hypothesis of no cointegration among the variables has not always been rejected at the 1% significance level. However, we have been able to identify three cointegration equations that are over our econometric specifications. The variables in the regression equations identified in Table 6 and Table 8 seem to have a cointegration relation, i.e., a long-run equilibrium relationship. Table 6 indicates one relationship among electricity price, conduct parameters $\theta_1 q_v Iberdrola$, $\theta_1 q_v$ *UniónFenosa*, and $\theta_1 q_v Hidrocantabrico$, and quantity sold in the spot market by Iberdrola, Unión Fenosa and Hidrocantábrico.

Table 8, which contains the results of cointegration testing for Specification 2B, indicates two relationships. One of the cointegration relationships is between electricity price, conduct parameters $\theta_{2B}q_{Cv}$Endesa, $\theta_{2B}q_{Cv}$Iberdrola, and $\theta_{2B}q_{Cv}$UnionFenosa, and quantity sold in the spot market by Endesa, Iberdrola, and Unión Fenosa, and the other cointegration relationship is between electricity price, conduct parameters $\theta_{2B}q_{Cv}$Iberdrola, $\theta_{2B}q_{Cv}$UnionFenosa, and $\theta_{2B}q_{Cv}$Hidrocantabrico, and quantity sold in the spot market by Iberdrola, Unión Fenosa and Hidrocantábrico.

4.3 Results of multivariate causality tests

The existence of a long-run relationship between the variables suggests that there must be Granger causality in at least one direction. According to Figs. 1, 2 and 3, the Granger causality results obtained with the Toda–Yamamoto method are dynamically stable.

Table 8 ARDL bounds test for investigating long-run equilibrium relationships among the variables in Specification 2B

Cointegration equations	ARDL specification	F-statistic	k	Cointegration
POmel, $\theta_{2B} q_{Cv}$End, q_{Cv}End, $\theta_{2B} q_{Cv}$Iber, q_{Cv}Iber, $\theta_{2B} q_{Cv}$UF, q_{Cv}UF	ARDL (2,0,2,0,2,5,1)	5.126	6	Yes
POmel, $\theta_{2B} q_{Cv}$End, q_{Cv}End, $\theta_{2B} q_{Cv}$Iber, q_{Cv}Iber, $\theta_{2B} q_{Cv}$Hid, q_{Cv}Hid	ARDL (4,0,1,0,0,6,1)	3.117	6	No
POmel, $\theta_{2B} q_{Cv}$Iber, q_{2BCv}Iber, $\theta_{2B} q_{Cv}$UF, q_{Cv}UF, $\theta_{2B} q_{Cv}$Hid, q_{Cv}Hid	ARDL (6,0,3,5,6,6,1)	3.727	6	Yes

The level of statistical significance is 5%. Figures in parenthesis show the number of lag selected based on the AIC. The maximum lag length is set to 4. For the bounds test, the asymptotic critical value bounds are taken from Pesaran et al. (2001), page 300, Table CI(iii) unrestricted intercept and no trend with max lags k in dependent variable and regressors equal to 6. The low bound, I(0), is 3.15/2.45/2.12, and the upper bound, I(1), is 4.43/3.61/3.23 at 1%, 5% and 10%, respectively

Table 9 Toda–Yamamoto causality test results for Specification 1

	POmel	$\theta_1 q_v$End	q_vEnd	$\theta_1 q_v$Iber	q_vIber	$\theta_1 q_v$UF	q_vUF	$\theta_1 q_v$Hid	q_vHid
POmel		0.400	0.456	0.049	0.028	3.394*	1.134	0.317	3.202*
$\theta_1 q_v$End	1.290		3.065*	1.045	1.043	4.941**	0.619	0.580	0.863
q_vEnd	0.016	0.118		0.202	0.240	2.606	0.085	0.079	4.876**
$\theta_1 q_v$Iber	5.901**	1.259	5.945		6.769***	14.884***	1.114	4.916**	0.265
q_vIber	1.210	1.975	0.039	0.487		0.760	0.421	2.228	3.600*
$\theta_1 q_v$UF	0.449	7.237***	1.503	1.920	0.165		0.439	2.031	1.984
q_vUF	0.106	0.674	0.126	4.232**	1.262	0.911		0.122	0.842
$\theta_1 q_v$Hid	2.099	3.618*	0.560	0.008	2.503	0.298	1.545		0.214
q_vHid	1.973	2.724*	0.083	2.050	3.113*	0.445	0.017	7.189***	

Modified Wald Chi-square statistics are displayed. *, ** and *** indicate statistical significance at 10, 5 and 1 % levels, respectively. The specification is free of serial correlation and autoregressive conditional heteroskedasticity

Tables 9, 10 and 11 report the results of Granger causality within Toda–Yamamoto framework for all known model specifications.

Table 12 summarizes bivariate and the univariate causality under the Toda–Yamamoto framework. Mainly, we found univariate causality relationships among the variables and specifications of the econometric models. However, there is a causality relationship that runs from the conduct parameter $\theta_1 q_v$UniónFenosa to $\theta_1 q_v$Endesa and from $\theta_1 q_v$Endesa to $\theta_1 q_v$UniónFenosa. Contrary to the bidirectional causality relationship found in the empirical analysis, the unilateral causality relationships are better supported by the findings related to cointegration.

Table 10 Toda–Yamamoto causality test results for Specification 2A

	POmel	$\theta_{2A}q_V$End	q_VEnd	$\theta_{2A}q_V$Iber	q_VIber	$\theta_{2A}q_V$UF	q_VUF	$\theta_{2A}q_V$Hid	q_VHid
POmel		10.140**	6.402*	17.035***	2.426	20.436***	1.497	2.980	2.549
$\theta_{2A}q_V$End	3.276		0.672	0.035	4.157	5005.003***	0.470	0.622	1.119
q_VEnd	5.565	2.084		3.006	3.771	4.613	1.235	2.946	13.004***
$\theta_{2A}q_V$Iber	0.480	2.512	11.458***		6.152	4.322	5.002	0.638	1.517
q_VIber	2.940	10.603	0.246	2.701		0.601	1.128	5.394	2.637
$\theta_{2A}q_V$UF	1.287	0.734	3.045	0.036	0.537		1.672	0.340	1.917
q_VUF	0.533	7.154	0.023	7.817	2.297	4.879		1.084	6.097
$\theta_{2A}q_V$Hid	9.292**	1.361	0.780	0.202	2.440	4.060	2.659		0.506
q_VHid	1.342	1.654	5.891	0.170	4.639	1.204	0.261	11.839***	

Modified Wald Chi-square statistics are displayed. *, ** and *** indicate statistical significance at 10, 5, and 1 % levels, respectively. The specification is free of serial correlation and autoregressive conditional heteroskedasticity

Table 11 Toda–Yamamoto causality test results for Specification 2B

	POmel	$\theta_{2B}q_{Cv}$End	q_{Cv}End	$\theta_{2B}q_{Cv}$Iber	q_{Cv}Iber	$\theta_{2B}q_{Cv}$UF	q_{Cv}UF	$\theta_{2B}q_{Cv}$Hid	q_{Cv}Hid
POmel		10.660**	9.289**	6.273*	15.133***	14.451***	2.824	2.720	2.555
$\theta_{2B}q_{Cv}$End	2.436		0.079	0.504	0.480	4749.160***	0.157	1.596	2.367
q_{Cv}End	5.560	1.845		0.814	6.202	0.120	1.999	1.111	3.347
$\theta_{2B}q_{Cv}$Iber	0.053	2.900	9.357**		13.288***	0.605	2.033	1.438	3.369
q_{Cv}Iber	3.651	8.656**	0.042	5.442		0.440	1.375	7.002*	15.866***
$\theta_{2B}q_{Cv}$UF	0.431	0.747	1.018	0.013	1.822		1.119	1.048	1.092
q_{Cv}UF	1.776	2.801	0.983	0.398	0.612	3.218		1.857	0.801
$\theta_{2B}q_{Cv}$Hid	7.067*	3.091	0.580	0.242	0.459	2.245	3.271		0.130
q_{Cv}Hid	0.878	6.638*	1.506	1.866	2.612	5.959	1.632	9.502**	

Modified Wald Chi-square statistics are displayed. *, ** and *** indicate statistical significance at 10, 5, and 1 % levels, respectively. The specification is free of serial correlation and autoregressive conditional heteroskedasticity

Table 12 Bivariate and univariate Toda–Yamamoto causality tests

	Bivariate	Univariate
Specification 1		
Endesa versus Iberdrola		$\theta_1 q_v$Iber → POmel; $\theta_1 q_v$Iber → q_vIber; $\theta_1 q_v$End → $\theta_1 q_v$End
Endesa versus Unión Fenosa	$\theta_1 v$UF ↔ $\theta_1 v$End	$\theta_1 q_v$End → q_vEnd; POmel → $\theta_1 q_v$UF
Endesa versus Hidrocantábrico		$\theta_1 q_v$End → q_vEnd; POmel → q_vHid; q_vEnd → q_vHid; $\theta_1 q_v$Hid → $\theta_1 q_v$End; q_vHid → $\theta_1 q_v$End; q_vEnd → $\theta_1 q_v$Hid
Iberdrola versus Unión Fenosa		$\theta_1 q_v$Iber → POmel; $\theta_1 q_v$Iber → q_vIber; q_vUF → $\theta_1 q_v$Iber; $\theta_1 q_v$Iber → $\theta_1 q_v$UF; POmel → $\theta_1 q_v$UF
Iberdrola versus Hidrocantábrico		$\theta_1 q_v$Iber → POmel; $\theta_1 q_v$Iber → q_vIber; $\theta_1 q_v$Iber → $\theta_1 q_v$Hid; POmel → q_vHid; q_vIber → q_vHid; q_vHid → q_vIber; q_vHid → $\theta_1 q_v$Hid
Unión Fenosa versus Hidrocantábrico		POmel → $\theta_1 q_v$UF; POmel → q_vHid; q_vHid → $\theta_1 q_v$Hid
Specification 2A		
Endesa versus Iberdrola		POmel → $\theta_{2A} q_v$End; POmel → $\theta_{2A} q_v$Iber; POmel → q_vEnd; $\theta_{2A} q_v$Iber → q_vEnd
Endesa versus Unión Fenosa		POmel → $\theta_{2A} q_v$End; POmel → q_vEnd; POmel → $\theta_{2A} q_v$UF; $\theta_{2A} q_v$End → $\theta_{2A} q_v$UF
Endesa versus Hidrocantábrico		POmel → $\theta_{2A} q_v$End; POmel → q_vEnd; q_vEnd → q_vHid; $\theta_{2A} q_v$Hid → POmel
Iberdrola versus Unión Fenosa		POmel → $\theta_{2A} q_v$Iber; POmel → $\theta_{2A} q_v$UF
Iberdrola versus Hidrocantábrico		POmel → $\theta_{2A} q_v$Iber; q_vHid → $\theta_{2A} q_v$Hid; $\theta_{2A} q_v$Hid → POmel
Unión Fenosa versus Hidrocantábrico		$\theta_{2A} q_v$Hid → POmel; POmel → $\theta_{2A} q_v$UF; q_vHid → $\theta_{2A} q_v$Hid
Specification 2B		
Endesa versus Iberdrola		POmel → $\theta_{2B} q_{Cv}$End; POmel → q_{Cv}End; POmel → q_{Cv}Iber; POmel → $\theta_{2B} q_{Cv}$Iber; $\theta_{2B} q_{Cv}$Iber → q_{Cv}End; q_{Cv}Iber → $\theta_{2B} q_{Cv}$End; $\theta_{2B} q_{Cv}$Iber → q_{Cv}Iber
Endesa versus Unión Fenosa		POmel → $\theta_{2B} q_{Cv}$End; POmel → q_{Cv}End; POmel → $\theta_{2B} q_{Cv}$UF; $\theta_{2B} q_{Cv}$End → θ_{2BCv}UF

Table 12 continued

	Bivariate	Univariate
Endesa versus Hidrocantábrico		POmel $\rightarrow$ $\theta_{2B}q_{Cv}$End; POmel $\rightarrow$ q_{Cv}End; $\theta_{2B}q_{Cv}$Hid $\rightarrow$ POmel; q_{Cv}Hid $\rightarrow$ $\theta_{2B}q_{Cv}$End; q_{Cv}Hid $\rightarrow$ $\theta_{2B}q_{Cv}$Hid
Iberdrola versus Unión Fenosa		POmel $\rightarrow$ $\theta_{2B}q_{Cv}$Iber; POmel $\rightarrow$ q_{Cv}Iber; POmel $\rightarrow$ $\theta_{2B}q_{Cv}$UF; $\theta_{2B}q_{Cv}$Iber $\rightarrow$ q_{Cv}Iber
Iberdrola versus Hidrocantábrico		POmel $\rightarrow$ $\theta_{2B}q_{Cv}$Iber; POmel $\rightarrow$ q_{Cv}Iber; $\theta_{2B}q_{Cv}$Iber $\rightarrow$ q_{Cv}Iber; q_{Cv}Iber $\rightarrow$ $\theta_{2B}q_{Cv}$Hid; q_{Cv}Iber $\rightarrow$ q_{Cv}Hid; $\theta_{2B}q_{Cv}$Hid $\rightarrow$ POmel; q_{Cv}Hid $\rightarrow$ $\theta_{2B}q_{Cv}$Hid
Unión Fenosa versus Hidrocantábrico		POmel $\rightarrow$ $\theta_{2B}q_{Cv}$UF; $\theta_{2B}q_{Cv}$Hid $\rightarrow$ POmel; q_{Cv}Hid $\rightarrow$ $\theta_{2B}q_{Cv}$Hid

5 Discussion of the results

The cointegration results confirm the theoretical model (Cournot model) of the proposed conjectural variations. The results of the Toda–Yamamoto causality confirm the cause–effect relationship among the variables proposed in the study. The results obtained through Specification 1 seem to indicate that both Endesa and Unión Fenosa act as dominant players. The empirical evidence seems to suggest that for Unión Fenosa, the bid is made in the OMEL market and not in the open market. The results provided by Specification 2B confirm the importance of the bidding decisions related to the quantities purchased in the OMEL market, whereas the estimation results of Specification 2A do not support this view. The competitive behavior between the electricity producers with the largest market share may have several explanations. The interdependence of the spot and the open market in this market liberalization period helps explain the competitive behavior changes, with potential market power increases and the admissibility of tacit collusion. The effects on the closing price in the spot market translate to the same variation. Moreover, that majority of sales bids are lower than the majority of purchase bids in the OMEL market for sale in the open market; otherwise, the strengthening of the market power can occur. The same net supplier (Endesa) and net demander (Iberdrola) behaviors are consistent with what has been referenced by Ciarreta and Espinosa (2012) and Kühn and Machado (2004), and reinforce the idea of collusion advanced by Fabra and Toro (2005) and Fabra (2009). The results also provide an answer to the Cournot problem formulated in this study, since the bidding quantity, the strategic interdependence of the quantity sold in the spot market and the quantity purchased in the spot market to sell in open market are verified by statistical significance of the conduct parameter θq_{Cv} both through the cointegrating relationships and the causal inferences.

Given this finding, we believe that the OMEL market price has an influence upon the bidding behavior, with firms coordinating their competitive purchasing and selling arrangements. This is the case between the two main electrical companies (i.e., the leaders in each type of bidding within a certain period) and their remaining followers.

The study found long-run relationships between the variables in the case of the Spanish electricity market. This may suggest that results of causality and cointegration are also indicative of the joint inclusion of two main bidding variables to solve the optimization problem of profit maximization for each electrical company that operates in the Spanish electricity market. The results also contribute to validate the proposed extension of the standard Cournot model and to justify its overall appropriateness.

Moreover, this market trend toward competitive behavior is based on the adjustments that the electricity firms with a dominant position had to take as a result of the market regulation rules implemented to maintain the market stability. During the period analyzed, the CTC compensatory mechanism prevailed in the market, in which compensatory mechanisms for the sunk costs of electricity producers basically smoothed out the fluctuations of the final price of electricity in the pool. As such, it behaves as a maximum price. However, CTCs also constitute a control mechanism of capacity payments requiring a certain level of activity investment in the various technologies over time. The implementation of this compensatory mechanism created incentives for the purchase and sale of electricity with low price bids. However, as mentioned by Fabra and Toro (2005), its main disadvantage was that it did not promote competition as foreseen with the liberalization of the market because it discouraged the entry of new players into the market and reinforced the dominant position of large producers, leading to a plausible price war and reinforcing the existence of collusion. Moreover, the CTC payment was conditional on an average pool price under 36.06 €/MW. As referred by Ciarreta and Espinosa (2012), if the average price of the electricity producer exceeded that amount, all subsequent revenues obtained with this higher price were subtracted from future CTC payments.

During the last few months before the integration of the Portuguese and Spanish markets, these same acts of tacit collusion between the two largest electrical companies were questioned and sustained by a decrease in concentration justifying, conversely, that price breaks appeared to be linked to the integration of the Portuguese and Spanish markets. As such, companies with the largest share in the electricity spot market may have anticipated a structural change, particularly for electricity producers, as they had to adapt to and learn from this new reality (Lagarto et al. 2014).

6 Conclusions

The present investigation is based on the NEIO approach in the context of a typical oligopolistic market, as is the case of OMEL Spanish electricity market. The main objective of this study was to assess the adequacy of the two proposed models to study the competitive behavior of electricity production companies in the market before the integrated MIBEL market was in full operation. It corresponds to a historical period without regulatory changes in the functioning of the market, but the interdependence of the spot market and the open market deserves to be analyzed. This purpose was carried out showing behavioral outcomes associated with the simultaneous placing of bids in the spot market carried out by the four main electricity production companies in the market—Endesa, Iberdrola, Unión Fenosa and Hidrocantábrico—which can influence the price in both markets.

The Toda–Yamamoto Granger causality results show that Iberdrola's conduct parameter is negatively influenced by Endesa, and Endesa's conduct parameter is negatively influenced by Iberdrola's conduct parameter, which is consistent with what was theoretically expected. In this relationship, Iberdrola's purchase bids in the spot market for sale in open market tend to follow Endesa's purchase bids in the spot market for sale in open market.

Since the results underline a bivariate relationship between Endesa and Unión Fenosa, it is plausible to admit that Endesa influences Unión Fenosa's behavior, because the quantity sold in the spot market by Endesa influences the quantity sold in the spot market for sale in open market by Unión Fenosa. And the quantity purchased in the spot market for sale in the open market by Endesa influences the quantity purchased in the spot market for sale in the open market by Unión Fenosa.

The specificity of the asymmetrical behavior between these players is justified by their dominant position, almost splitting the spot market evenly, according Moutinho et al. (2014). Consequently, as the joint supply of the other players is insufficient to satisfy the demand, the pivotal companies, Endesa and Iberdrola can increase their prices as a consequence of the demand.

However, the remaining players, aware that the supply of main players is necessary to fulfill the demand throughout all time schedules, tend to bid at price zero, since they acknowledge that all the electricity supplied by them will be sold daily at the marginal price set in the pool market. As a consequence, the two largest players can use their important output mix in order to present flexible bids according to the demand and supply forecasts. In compensation, small players, whose output mix is reduced, lack the capacity to set competitive or sufficiently flexible bids. For these players, the option to bid their output at a price zero when large players claim high prices is the easiest way for selling the largest possible quantity.

Based on these specificities, and on the structural characteristics of the Spanish electricity market, we believe that the strategic coordination of this group of players can be easily implemented when there are huge bidding differences, as it is easy to detect high price bidders.

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Appendix

See Tables 13, 14 and 15 and Figs. 1, 2 and 3.

Table 13 Descriptive statistics Specification 1

	POmel	$\theta_1 q_v$End	q_vEnd	$\theta_1 q_v$Iber	q_vIber	$\theta_1 q_v$UF	q_vUF	$\theta_1 q_v$Hid	q_vHid
Mean	4.348	−0.983	9.1512	−0.975	6.017	−0.946	2.742	−0.871	2.519
Median	4.044	−0.985	9.224	−0.978	5.954	−0.954	2.661	−0.878	1.531
Maximum	7.641	−0.939	10.884	−0.934	9.129	−0.799	4.222	−0.490	7.531
Minimum	3.606	−0.998	6.705	−0.993	4.251	−0.996	1.834	−0.990	0.808
SD	0.921	0.0124	0.781	0.011	0.896	0.034	0.429	0.098	1.888
Skewness	1.721	1.559	−0.379	1.195	0.799	1.958	0.996	1.120	1.294
Kurtosis	5.370	5.134	3.365	4.222	3.780	8.695	4.188	4.572	2.967
Jarque−Bera	152.074	124.250	6.167	62.711	27.556	416.047	46.868	65.193	58.314
Probability	0.000	0.000	0.046	0.000	0.000	0.000	0.00000	0.000	0.000
Sum	908.679	−205.446	1912.455	−203.8270	1257.490	−197.677	573.115	−182.026	526.393
Sum Sq. Dev.	176.618	0.032	126.803	0.027	166.814	0.244	38.244	2.023	741.533
Observations	208	208	208	208	208	208	208	208	208

Table 14 Descriptive statistics Specification 2A

	POmel	$\theta_{2A}q_{V}$End	q_{V}End	$\theta_{2A}q_{V}$Iber	q_{V}Iber	$\theta_{2A}q_{V}$UF	q_{V}UF	$\theta_{2A}q_{V}$Hid	q_{V}Hid
Mean	4.348	−0.547	9.151	−1.052	6.017	42.702	2.742	−1.685	2.519
Median	4.043	−0.926	9.224	−1.052	5.954	−1.155	2.660	−1.026	1.531
Maximum	7.641	69.464	10.884	0.701	9.129	9235.360	4.222	27.885	7.531
Minimum	3.606	−5.696	6.705	−1.678	4.251	−48.259	1.834	−106.995	0.808
SD	0.921	4.975	0.781	0.154	0.896	638.947	0.429	10.112	1.888
Skewness	1.721	13.459	−0.379	7.365	0.799	14.351	0.996	−7.156	1.294
Kurtosis	5.370	189.520	3.365	86.463	3.780	206.978	4.188	68.621	2.967
Jarque−Bera	152.074	309270.8	6.163	62551.85	27.556	369502.1	46.868	39282.89	58.314
Probability	0.000	0.000	0.046	0.000	0.000	0.000	0.000	0.000	0.000
Sum	908.679	−114.221	1912.455	−219.902	1257.490	8924.648	573.115	−352.194	526.393
Sum Sq. Dev.	176.618	5148.005	126.803	4.953	166.814	84916757	38.244	21268.73	741.533
Observations	208	208	208	208	208	208	208	208	208

Table 15 Descriptive statistics Specification 2B

	POmel	$\theta_{2B}q_{Cv}$End	q_{Cv}End	$\theta_{2B}q_{Cv}$Iber	q_{Cv}Iber	$\theta_{2B}q_{Cv}$UF	q_{Cv}UF	$\theta_{2B}q_{Cv}$Hid	q_{Cv}Hid
Mean	4.348	−3.419	3.194	−0.756	3.242	−178.875	0.836	1.137	1.250
Median	4.044	−1.475	3.095	−0.760	3.158	−0.234	0.771	−0.833	0.645
Maximum	7.641	43.913	4.794	1.165	4.484	115.940	1.579	288.145	3.832
Minimum	3.606	−374.984	1.683	−6.625	1.575	−37436.42	0.300	−65.965	0.286
SD	0.921	26.348	0.623	0.503	0.482	2589.608	0.290	28.151	1.181
Skewness	1.721	−13.501	0.313	−7.935	0.148	−14.352	0.857	6.725	1.1966
Kurtosis	5.370	191.133	3.084	94.450	3.236	206.986	2.993	61.430	2.589
Jarque−Bera	152.074	314573.3	3.466	75022.28	1.244	369530.1	25.595	31305.91	51.345
Probability	0.000	0.000	0.177	0.000	0.537	0.000	0.000	0.000	0.000
Sum	908.679	−714.543	667.635	−158.080	677.625	−37384.83	174.634	237.612	261.230
Sum Sq. Dev.	176.618	144394.9	80.712	52.645	48.225	0.000	17.505	164833.0	290.298
Observations	208	208	208	208	208	208	208	208	208

Fig. 1 Inverse roots of AR characteristic polynomial for Specification 1

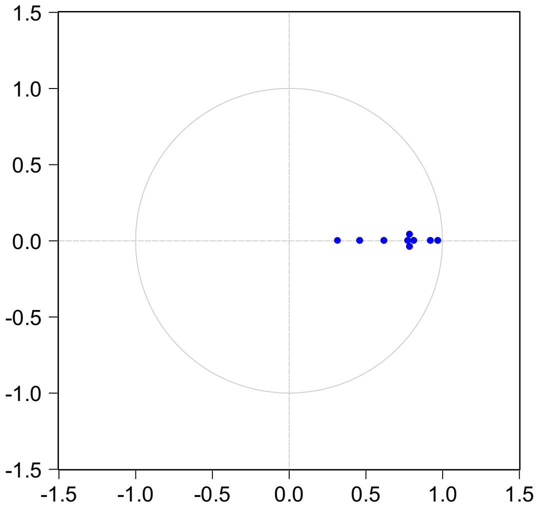
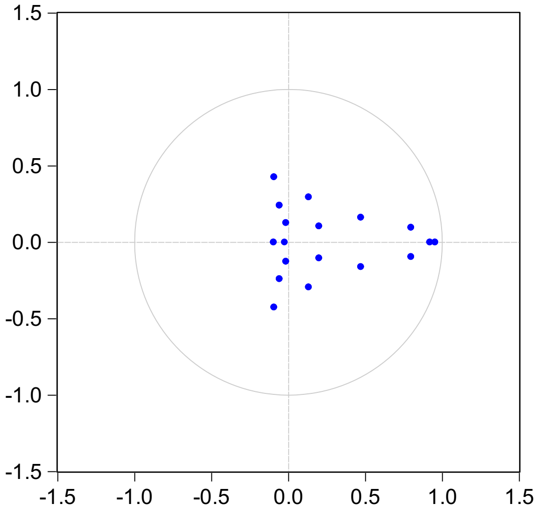


Fig. 2 Inverse roots of AR characteristic polynomial for Specification 2A



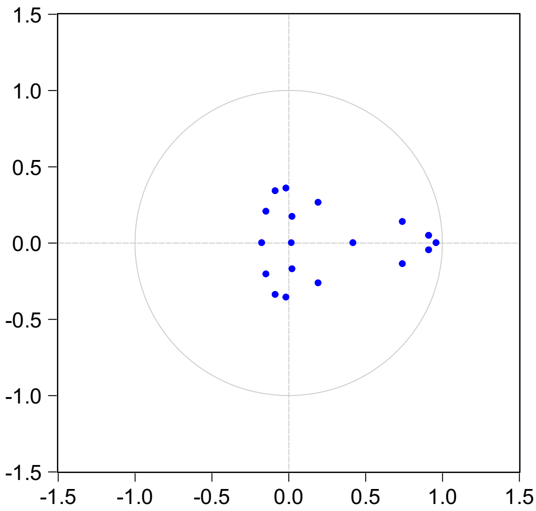


Fig. 3 Inverse roots of AR characteristic polynomial and VAR residual serial correlation for Specification 2B

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