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Strategic bidding in electricity pools with short-lived bids: an application to the Spanish market

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Abstract

We generalize von der Fehr and Harbord's [Econ. J. 103 (1993) 531] multi-unit auction model for the case of a deterministic demand allowing for any technology mix and elastic demand in order to account for demand-side bidding. We obtain a general characterization of the equilibrium and show that this is bounded above by the Cournot equilibrium. We simulate the Spanish electricity pool and show that price–cost margins substantially increased with the 1996 merger that took the industry from a six-firm structure to its current four-firm structure. Our results show that, in terms of market power, this is similar to a nearly symmetric duopoly. The introduction of demand-side bidding is not likely to change this situation.

JEL classificatio : L13; L94; K23

Keywords: Electricity pools; Bids; Market power

1. Introduction

Electricity pools are at the core of electricity deregulation processes throughout the world. After the pioneering case of England and Wales, several other spot wholesale markets for electricity were created in order to introduce competition into the generation of electricity. Argentina, California, the Scandinavian region,

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Spain and the states of Victoria and New South Wales in Australia currently have electricity spot markets in operation, while several are in the process of creation.[1]

The common characteristic of all electricity pools is that generators make bids to supply a given amount of electricity at a certain price. A market operator orders these bids from highest to lowest, constructing the market offer curve, and the intersection of this offer curve with a demand curve yields a price at which all trade occurs. An important characteristic of pool markets is the period of time for which bids are fixe and cannot be altered. In certain pools, such as the Argentinian pool, firm place bids every six months, in the England and Wales pool the bidding is daily, while in Spain, California and Nordpool firm submit bids for each hour.[2] In this paper we develop a methodology for the analysis of competition in electricity spot markets where firm make bids valid for short periods of time. We consider the bid life to be short when demand does not vary significantl during the period of time for which the bid is valid, i.e. when firm bid facing a certain demand.

In a seminal paper, Green and Newbery (1992) analyze the behavior of firm in the England and Wales electricity pool. These authors assume that firm have a continuously differentiable cost function and submit continuously differentiable bid functions to the pool and apply Klemperer and Meyer's (1989) results to obtain a range of equilibrium supply functions. Their analysis assumes that bids are fixe for a period during which demand shifts in a given interval. The equilibrium prices range from Cournot to perfect competition. They apply this methodology to simulate the England and Wales pool assuming that firm coordinate on the highest pricing equilibrium. Klemperer and Meyer (1989) show that any price above marginal cost can be sustained in a supply function equilibrium if there is no uncertainty. Accordingly, in pools where firm make bids for periods of time in which demand hardly varies, the supply function approach has extremely limited predictive power.[3]

Alternatively, von der Fehr and Harbord (1993) model electric pools as multi-unit auctions where generating firm face constant marginal costs up to capacity and demand is inelastic. They analyze a specifi example with two firm for deterministic and uncertain demand cases and extract some general conclusions. In this paper we generalize von der Fehr and Harbord's (1993) approach for

[1] Since this paper was written the UK Pool has been replaced by the New Electricity Trading Arrangements (NETA) which involve bilateral markets and a close to real time imbalance market, and the California power exchange has ceased operations.

[2] Pools may differ in several other features: they may or may not allow for demand-side bids, they may incorporate mechanisms to renumerate firm for non-variable costs (such as start-up and capacity costs), as well as to take into account technological restrictions (see von der Fehr and Harbord, 1997).

[3] Note that pool prices are based on day-ahead forecasts and not on ex-post demand realization. The only significan source of uncertainty comes from unexpected plant outages that affect residual demand. We assume that given the number of plants operating in a market, firm account for expected outage rates (as we do in our simulations).

the case of deterministic demand. In particular, we allow for multiple asymmetric firm with increasing step cost functions. We also allow for a downward sloping demand function that represents the existence of demand-side bidding. However, we do not model a double auction where consumers' behavior is determined endogenously. This effectively assumes price-taking behavior by consumers. For instance, in the Spanish case, this is justifie by the small size of eligible consumers with respect to total demand, and the fact that distributors, although large in aggregate, supply customers that face a fixe tariff and therefore are not price responsive.

We obtain a characterization of the pure strategy equilibria for this model and fin that firms asymmetries in size and technology significantl affect price–cost margins. In particular, very strong asymmetries lead to a single equilibrium price with a dominant fir where small firm behave competitively, while the market leader maximizes profit given its residual demand. Also, symmetric market structures generally lead to a single equilibrium price but to lower average price–cost margins. Intermediate situations lead to multiple equilibrium prices since any of several different firm can adopt a dominant role and set the market price.

We implement a simple algorithm to identify equilibria in a simulation for the Spanish pool. The object of the simulation is to identify problems of market power in the generation of electricity in Spain and, in particular, to quantify the effect of the 1996 merger that took the industry from a six-fir structure to a four-fir structure.

To our knowledge, the only previous attempts to simulate firms behavior in electricity pools with deterministic demand are those of Borenstein and Bushnell (1999) and Ocaña and Romero (1998) that use the Cournot model to simulate the Californian and the Spanish pools, respectively. The main drawback of this analysis is that it does not exploit all the information available on how firm interact in the pool; that is, it ignores the pool market institution.[4] It is reasonable to believe that taking into account the pool auction mechanism will lead to closer predictions of the generating firms strategic behavior. When comparing our results with those derived from the Cournot model, we observe that Cournot yields significantl higher mark-ups except when demand is very elastic or the industry is

[4] Several justification are given in Borenstein and Bushnell (1999) and Ocaña and Romero (1998) as to why the Cournot model could be a good approximation to fir behavior in the pool. First, Green and Newbery (1992) show that Cournot is an upper bound to prices in their model of the England and Wales pool. It must be noted that, in their model, prices only reach the Cournot level when demand is highest, and can be considerably below on average. Second, Wolak and Patrick (1996) argue that firm will not use prices as their strategic variable because bids that are significantl above cost will trigger a response by the regulator, and thus firm will use capacity as a strategic variable. Yet, it seems that the regulator is likely to respond to strategic use of capacity availability declarations (as it did in the England and Wales case), and that declaring a generator unavailable is a very crude mechanism for adjusting capacity given the demand variation that might exist in a 24 h period.

very fragmented, two situations which are extremely unlikely in the electricity industry.

The results of our simulation for the Spanish case show that market power measured by price–cost margins substantially increased with the 1996 merger that took the industry from a six-fir structure to its current four-fir structure. In fact, our simulation shows that the current situation is, in terms of market power, nearly equivalent to a symmetric duopoly. We also show that the introduction of demand-side bidding may not be enough to curb market power in the Spanish spot market for electricity.

Our simulation estimates variations in market power following changes in market and cost structure. This cannot be tested empirically because they have not taken place, or have taken place before the pool was in operation. However, some of the simulation results for the current four-fir structure could be contrasted with empirical observations, such as the identity of the fir that determines the system marginal price and the individual firms hourly production shares. Unfortunately, it is not possible to compare our simulation results with current data for two reasons. First, while the Spanish pool started operation in 1998, it is going through a transition period designed to allow firm to recover their stranded costs. We do not explicitly model this stranded cost recovery mechanism but rather analyse firms behavior in the pool once this transition period is over. Second, much of the necessary data is unavailable. The market operator only publishes the pool price and the total quantity despatched for each hour. Agents' individual bids, sales and purchases, as well as the identity of the fir that determines the system marginal price, are not publicly available.

2. The model

In this section we present a model of an electricity pool as a multiple unit firs price competitive auction with complete information.[5] The following notation is introduced in order to defin the strategy and payoff spaces. Let $I = \{1, \ldots, i, \ldots, f\}$ be the set of agents that operate in the pool, $U = \{1, \ldots, u, \ldots, m\}$ the set of generating units, and $U_i \subset U$ the set of generating units belonging to agent i. Let c_u, k_u, and q_u be define as u's constant unit cost, maximum generating capacity and unit output, respectively. Without loss of generality, assume $c_u \leqslant c_{u+1}$. We may then defin a firm' marginal cost function, $MC_i(q)$, by

$$MC_i(q) = \min_{u \in U_i} c_u,$$

[5] We model it as a firs price auction rather than a second price auction, because the price is set by the last bid that is accepted. We model the auction as competitive rather than discriminatory because all transactions take place at the same market clearing price. Finally, we assume complete information because the agents' payoff functions are common knowledge.

$$\text{s.t.} \sum_{g \in E_i(u)} k_g \geqslant q,$$

where $E_i(u) = \{g : g \in U_i \text{ and } c_g \leqslant c_u\}$. A firm’ cost function can be define as

$$C_i(q) = \int_0^q MC_i(x)\,\mathrm{d}x.$$

We should note that, following von der Fehr and Harbord (1993), this cost structure assumes that generating units have no start-up costs and constant marginal costs up to capacity.[6]

In each period, each generating unit’s strategy may be represented by a nondecreasing left continuous step function with a finit number of steps. By ordering these steps for all the generating units of a fir we obtain each firm’ bid function, $b_i(q) : [0,K_i] \rightarrow [0,p^{\max}]$, where $K_i = \Sigma_{u \in U_i} k_u$.[7] For notational convenience we will assume $b_i(0) = 0$. Analogously we may obtain the aggregate bid curve, which determines the bid of the most expensive unit necessary to produce output q, as $\bar{b}(q) : [0,K] \rightarrow [0,p^{\max}]$, where $K = \Sigma_{i \in I} K_i$.[8] We will assume that all firm are able to produce a strictly positive amount of electricity at a cost below $p^{\max}$, that is, $MC_j(q) < p^{\max}$ for some positive q and for all $j \in I$.

With respect to the demand side, two types of agents may submit bids to buy electricity in the pool. On the one hand, distributors sell energy to captive consumers subject to fixe tariffs and, therefore, non-responsive to the pool price. We assume that these distributors make fla bids at a given maximum price for all the electricity that their clients are expected to consume in a given period of time.

On the other hand, either eligible consumers or their suppliers may bid downward sloping demand functions reflectin their price responsive consumption. Additionally, a large consumer might bid strategically in order to exercise its market power and get lower prices from the pool. We will not consider this possibility given the fact that the demand of any individual consumer will be

[6] As noted by Kahn (1998), this limitation applies to all models of electricity pools that attempt to predict equilibrium behavior. As a reflectio of this limitation we use our model to predict changes in price–cost margins under alternative scenarios rather than the absolute level of prices.

[7] As in von der Fehr and Harbord (1993), $p^{\max}$ may be interpreted as the maximum accepted bid price in the pool, or as a price that would trigger regulatory intervention if observed.

[8] Formally, $\bar{b}(q)$ is define from the individual firms bid functions as follows:

$$\bar{b}(q) = \min_{x \in \Re^n} \max(b_1(x_1), \ldots, b_n(x_n)),$$

$$\text{s.t.} \sum_{i \in I} x_i = q,$$

where $x = (x_1, \ldots, x_n)$ is a vector of firms outputs.

negligible relative to total demand, and the fraction of demand that they can modulate will be even smaller. Accordingly, we will assume that eligible consumers behave as price takers. Under this assumption, demand-side bidding into the pool may be represented by the aggregate demand function, $D(p)$, which is the result of adding the non-responsive vertical demand of distributors and the downward sloping demand of eligible consumers or their suppliers. We will assume that this function has an inverse which we denote by $P(q)$.

The equilibrium price (called the system marginal price, SMP), $p^*(b)$, is determined by the intersection of the bid curve with the inverse demand function:[9]

$$p^*(b) = \max_q \{\bar{b}(q) : \bar{b}(q) \leq P(q)\}.$$

All trade in the pool takes place at the SMP, p^*.[10] Denoting the output that fir i is called upon to produce by $Q_i(b)$, we defin fir i's profit as

$$\pi_i(b) = Q_i(b)p^*(b) - C_i(Q_i(b)),$$

where $b = (b_1(q), \ldots, b_f(q))$ denotes the firms bid profile[11]

Generators that make offers at the SMP may be rationed. In these cases, the standard rule is to ration the marginal generating units proportionally. However, this leads to a problem of non-existence of equilibrium similar to that arising in a Bertrand game with asymmetric costs. Following von der Fehr and Harbord (1993) we assume rationing is efficient i.e., generators with a lower marginal cost are called on to produce first This assumption may not seem innocuous as it implies that the market operator knows the generators' cost functions. However, the set of equilibria of our game approximates the set of equilibria of a game where a proportional rationing rule is applied and firm must choose their bid prices on a finit grid, which is what occurs in actual pools.[12]

Finally, in order to characterize our equilibrium we refin our equilibrium set by eliminating any profil that involves generating units bidding below their marginal cost. It is easy to see that bidding below cost is a weakly dominated strategy for some firms

We will now characterize the pure strategy Nash equilibria of the model.[13] Our results generalize von der Fehr and Harbord's (1993) theoretical results under

[9] Note that, under this rule, the SMP cannot be set by demand bids. This is a feature of the Spanish pool. As pointed out by an anonymous referee, if demand could set the SMP then Cournot would always be a possible equilibrium of the game.

[10] Given that the bid curve can be discontinuous, the bid and inverse demand function may not cross. In this case there will be excess demand at the SMP. We assume demand is rationed efficiently

[11] For notational convenience, where this does not lead to confusion, we will write Q_i and p^* to mean $Q_i(b)$ and $p^*(b)$.

[12] Proof of this result is available from the authors upon request.

[13] We do not consider the possibility of mixed strategy equilibria. Instead we show that a pure strategy equilibrium always exists and compute all pure strategy equilibria.

deterministic demand, which is the appropriate assumption for pool institutions where bids are submitted for short periods. The theoretical results obtained will allow us to develop a tractable search algorithm in order to fin the equilibria in our subsequent simulation.

Let us suppose b is a pure strategy equilibrium that results in a SMP of p^*. We refer to a fir as *marginal* when it is bidding in some capacity at the marginal price, p^*, which is at least partially accepted. Our firs result states that if a fir i is marginal then any other fir $j \neq i$ behaves as a price taker.[14] Defin $O_i(p) = \max\{q : q \in [0,K_i]$ and $MC_i(q) < p\}$. This is the minimum output of a price taking fir when the price is p.

Theorem 1. *Let b be a pure strategy equilibrium that results in a SMP of p^*. If frm i is marginal, then $Q_j \geqslant O_j(p^*)$ for any $j \neq i$.*

Proof. See Appendix A.

The proof shown in Appendix A is based on the fact that if any fir $j \neq i$ has unused capacity that can generate at a cost $c < p$, it can bid in this capacity at some price $p - \epsilon$, $\epsilon > 0$ sufficientl small. This may lower the SMP by ϵ but it will increase fir j's output by a strictly positive amount that does not depend on ϵ. There are some important implications that can be derived from Theorem 1.

Let us denote by $v_i(p)$ the maximum profit that fir i can achieve when the SMP is p and all other firm are acting as price takers:

$$v_i(p) = \begin{cases} p(D(p) - O_{-i}(p)) - C_i(D(p) - O_{-i}(p)), & \text{if } O_i(p) \geqslant D(p) - O_{-i}(p) > 0, \\ pO_i(p) - C_i(O_i(p)), & \text{if } D(p) - O_{-i}(p) > O_i(p) > 0, \\ 0, & \text{otherwise,} \end{cases}$$

where $O_{-i}(p) = \Sigma_{j \neq i} O_j(p)$. The firs line corresponds to a case where fir i can supply the residual demand with generating units that have marginal costs below price p. In this case, $O_{-i}(p) = Q_{-i}$ since fir $j \neq i$ cannot sell any extra output above $O_j(p)$ by bidding it at price p, because of the efficien rationing rule. The second line corresponds to a case where fir i cannot supply the residual demand with generating units that have marginal costs below price p. Accordingly, $pO_i(p) - C_i(O_i(p))$ are the maximum profit it can achieve. Notice that, in this case, residual demand is not satisfie if firm supply only $\Sigma_{j \in I} O_j(p)$. In order for p to be the SMP, it must be the case that, for at least one firm $Q_j > O_j(p)$.

[14] By price taking behaviour we imply that they bid low enough to discourage the price-setting fir undercutting their bids, as in von der Fehr and Harbord (1993).

Corollary 1. *Let b be a pure strategy equilibrium that results in a SMP of* p^*. *If frm i is marginal, then*

$$\pi_i(b) = v_i(p^*),$$

and

$$\pi_j(b) = \max_q\{p^* q - C_j(q)\},$$

for all $j \neq i$.

Corollary 1 implies that, if we are in equilibrium, the SMP and the identity of a marginal fir uniquely determine equilibrium payoffs. Note that if more than one fir is marginal then by Theorem 1 every fir behaves as a price taker with respect to p^*, i.e., $(p^*, Q_1, \ldots, Q_f)$ constitutes a competitive equilibrium.

Given our refinemen of the equilibrium, if a fir bids in all its capacity at a price of p it can obtain profit of at least $v_i(p)$, thus payoffs in equilibrium are bounded below by $\max_p v_i(p)$. On the other hand, if fir i is marginal, its profit are given by $v_i(p^*)$, thus it must be the case that $p^* \in \arg\max v_i(p)$. Since there are f firms and given that the arg max of $v_i(p)$ may not be unique, this yields $f \times \#(\arg\max v_i(p))$ possible candidates for SMP (and the corresponding payoffs) in a pure strategy equilibrium. Note that we are not excluding any equilibrium that involves more than one fir being marginal.

The following theorem characterizes which of these SMP-payoff combinations are part of a pure strategy equilibrium.[15] Let $\hat{\pi}_i(p)$ be a payoff vector of the form

$$\hat{\pi}_{ii}(p) = v_i(p),$$

and

$$\hat{\pi}_{ij}(p) = \max_{q \in [0, D(p)]} pq - C_j(q),$$

for $j \neq i$.

Theorem 2. *There is a pure strategy equilibrium in which frm i is marginal, the SMP is* p^* *and frms' payoffs are given by the vector* $\hat{\pi}_i(p^*)$ *if and only if* $\max_{p \in [0, p^{max}]} v_j(p) \leq \hat{\pi}_{ij}(p^*)$ *for all* $j \in I$ *and* $D(p^*) - O_{-i}(p^*) > 0$.

Proof. See Appendix A.

This theorem implies that given a candidate equilibrium where fir i is marginal and sets a price of $p^* \in \arg\max v_i(p)$ the only relevant deviation by any other fir $j \neq i$ is to become marginal and set a price in $\arg\max v_j(p)$. It cannot be

[15] We do not characterize the strategies played in a pure strategy equilibrium as there may be several strategy profile that are payoff equivalent and lead to the same system marginal price.

profitabl to deviate from price taking behaviour to become marginal if this results in a lower price. This implies that the highest of the candidates for SMP, which we denote by $\overline{p}^*$, is always an equilibrium. Formally, let $\overline{p}^* = \max_i\{p : p \in \arg\max_p \pi_i(p)$ and $D(p) - O_{-i}(p) > 0\}$ and suppose that the maximum is achieved for $i = i^*$, then by Theorem 2 there is a pure strategy equilibrium that results in a SMP $\overline{p}^*$ and payoffs of $\hat{\pi}_i(\overline{p}^*)$. This guarantees the existence of a pure strategy equilibrium for our game.

Corollary 2. *A pure strategy equilibrium to the game always exists.*

We will now compare the equilibria of our model to those resulting from a Cournot equilibrium. This is of interest since Cournot has been used to approximate fir behavior in pool markets where bids are short-lived.[16] We will prove that the price that results from a Cournot equilibrium is greater than or equal to any equilibrium price of our model. In particular, the Cournot model yields significantl higher mark-ups except when demand is very elastic or the industry is very fragmented. Neither of these situations is common in electricity markets. This suggests that Cournot models clearly overestimate market power in electricity pools where firm bid facing a certain demand.

Assume that the inverse demand function for a given time period, $P(q)$, is strictly decreasing and concave. Note that from the definitio of technology, $C_i(q)$ is strictly increasing, convex, and left continuous, and that all the firm are capacity constrained. Let us denote the minimum price that results in a Cournot equilibrium by $\underline{p}^{\mathrm{C}}$.

Theorem 3. *Under the previous assumptions,* $\underline{p}^C \geqslant \overline{p}^*$.

Proof. See Appendix A.

3. The simulation

For a given period, the simulation is conducted as follows. We defin G_i as the set of non-differentiable points of $v_i(p)$. G_i includes $p^{\max}$, c_u for all $u \in U_{-i}$ and all the prices where the profit are kinked due to the discontinuity of the marginal cost function of fir i. By assuming demand is differentiable from Theorem 2 we obtain Corollary 3.

Corollary 3. *Let* p_1 *and* p_2 *be two consecutive prices in* G_i. *If* $M_i > 0$ *and* $p_1 < p^* < p_2$, *then* p^* *verif es the following f rst-order condition*:

[16] Borenstein and Bushnell (1999) for California and Ocaña and Romero (1998) for Spain.

$$D'(p^*)(p^* - C'(D(p^*) - O_{-i}(p^*))) + (D(p^*) - O_{-i}(p^*)) = 0.$$

Let F_i be the set of prices that verify the previous first-orde condition for some $i \in I$. Payoffs for a pure strategy equilibrium can be uniquely characterized by a marginal fir i and a marginal price $p^* \in G_i \cup F_i$. The firs step in our simulation is to compute a $\#(G_i \cup F_i) \times f$ matrix with the payoffs for all the possible (p^*,i) pairs. We then apply Theorem 2 to identify which (p^*,i) configuration and payoffs correspond to a pure strategy equilibrium of the game.

3.1. Comparative statics

The previous methodology allows us to obtain some comparative static results for our model. We will explore two simple examples. Our examples involve an industry with two firms A and B. Each fir owns 100 plants that can be ranked by their marginal costs from lowest to highest. The costs of plants $2k$ and $2k - 1$ are given by k. We take $p^{\max} = 100$; this limits prices to the marginal cost of the less efficien plant. We calculate our equilibria for inelastic demands that range from 10 to 50% of total installed capacity, which remains unchanged and equal to 200. Our base case involves two identical firms In particular, all plants have generating capacity equal to unity, odd plants belong to fir A and even plants belong to fir B. In the following examples we alter the size and ownership structure of the plants and see how a departure from the symmetric structure affects the equilibria. The industry technological structure, however, will remain unchanged throughout.

The results are presented in terms of price–cost margins which is a general measure of market power.[17] However, it is also important to notice that, in all the cases presented, there is some degree of productive inefficiency since some of the price-setting firm' generating units with marginal costs below the SMP are not operating in equilibrium.

The effects of asymmetries in size are analyzed in Fig. 1. The symmetric case is compared to two situations with the same ownership structure and total installed capacity. In these two cases, fir B's plants have 50 and 75% capacity of fir A's plants, respectively. We can observe that the initial effect of introducing capacity asymmetries is the appearance of multiplicity of equilibria: a high price equilibrium with the large fir setting the marginal price and a low price equilibrium with the small fir setting the marginal price. In our example, the difference between the highest and the lowest price rises with asymmetry until the asymmetry is such that the equilibrium that involves the small fir setting the marginal price disappears and uniqueness of equilibrium re-emerges. Thus, although the effect of small asymmetries on market power is ambiguous, since the symmetric equilib-

[17] Price–cost margins are define as the SMP marginal cost differential of the price setting fir as a percentage of SMP.

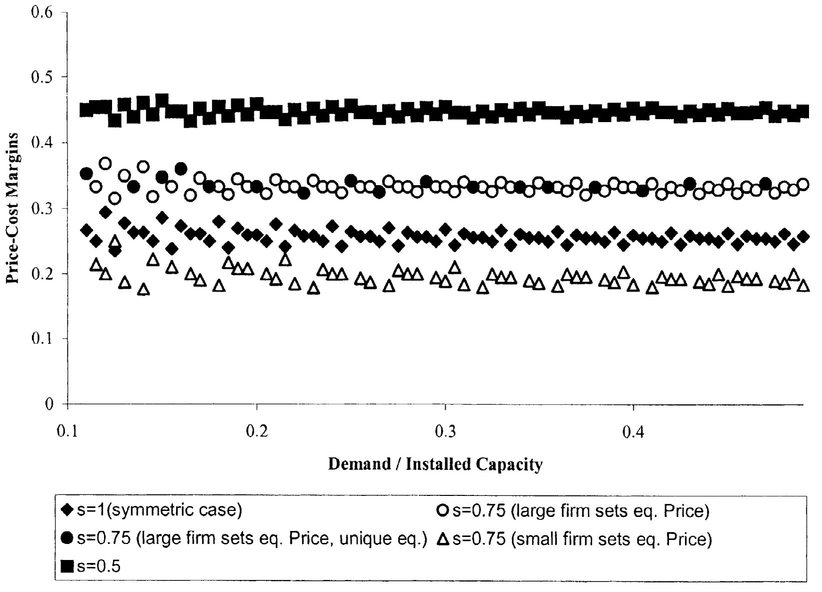

Fig. 1. The effect of size differences on price–cost margins. This example involves inelastic demand, two firms 100 plants each and three alternative market structures. A given firm' plants are of the same capacity and can be ranked by marginal costs from lowest to highest. Plants $2j$ and $2j-1$ have a constant marginal cost of j. In each scenario, contemplated total capacity is the same and fir 2's capacity is s times fir 1's capacity.

rium price lies between the high and the low price equilibria, large asymmetries unambiguously lead to higher prices. Furthermore, we should notice that, when demand grows, prices rise, but, in this specifi case, because of the particular technology mix, price–cost margins remain stable.

Fig. 2 studies the effect of cost asymmetries. The symmetric case is compared to a situation with the same set of plants in terms of size and technology, but a different ownership structure. In particular, we assume that the two firm own the same number of plants but fir B has a less efficien plant structure. In particular, grouping the firm in sets of eight consecutive plants, fir A owns the four most efficien and fir B the four least efficien in each set (for instance, fir A owns plants 1–4, fir B owns plants 5–8, fir A owns plants 9–12, fir B owns plants 13–16, etc.). Once again, we observe that a departure from the symmetric case leads to a multiplicity of equilibria. In general, the identity of the fir setting the highest equilibrium price depends on demand, but, on average, equilibrium prices set by the most efficien fir are above prices set by the least efficient The symmetric case equilibrium price always lies below the equilibrium prices set by the most efficien fir and, on average, it lies below the equilibrium prices set by

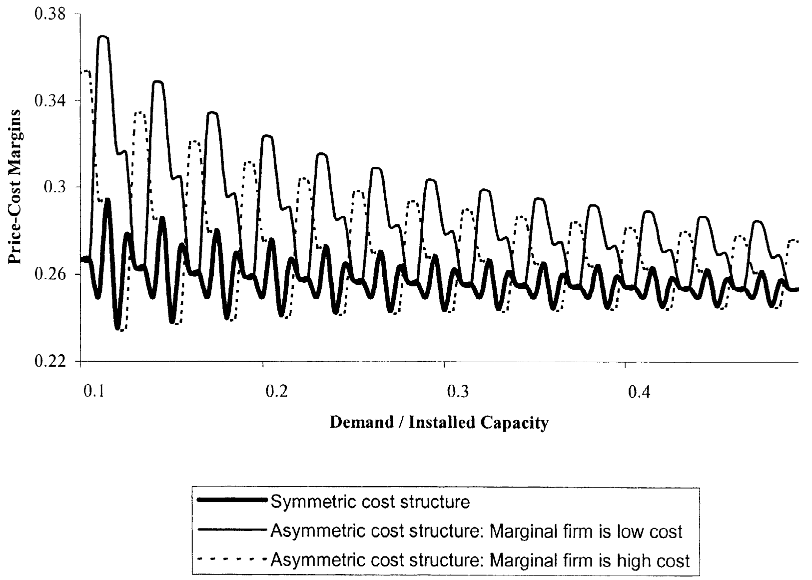

Fig. 2. The effect of cost differences on price–cost margins. This example involves inelastic demand, two firms 100 plants each and two alternative cost structures. All the plants are of the same capacity, and can be ranked by marginal costs from lowest to highest. Plants $2j$ and $2j-1$ have a constant marginal cost of j. The symmetric structure involves fir 1 owning the even numbered plants and fir 2 having odd numbered plants. The asymmetric structure involves firm owning sets of four consecutive plants with fir 1 having the four most efficient

the least efficien firm Accordingly, this simple example suggests that asymmetries in costs lead to higher prices on average.[18]

3.2. Simulations of the Spanish market

3.2.1. Market structure and rules of the pool

In 1997, a plan for the liberalization of the Spanish electricity market was approved. It called for gradual liberalization of generation and supply activities, but continued regulation of transmission and distribution.[19] In January 1998, the Spanish electricity pool began operation.[20] The set of agents that may participate in

[18] It should be noted that the cyclical behaviour in mark-ups, especially evident in Fig. 2, is due to the discontinuous (step function) nature of the firms marginal cost functions. The competitive price jumps as demand moves from one step to the next, but prices do not necessarily. This leads to reductions in the price–cost margins when demand jumps from one step to the next.

[19] Transmission refers to high tension lines while distribution refers to low tension lines. A supplier is an agent who buys electricity in the pool, pays a fee for its transmission, and sells it to a fina consumer.

[20] Currently, the pool is going through a transition period in order to permit firm to recover their stranded costs. This period was expected to last at least until 2003, when it would be reviewed.

this pool are generating firms distributors, suppliers, and eligible consumers. The pool is organized as a double auction where agents may submit bids to the market operator both to buy and to sell energy.[21] Each day is divided into 24 hourly bidding periods. Each generating unit submits a set of price–quantity pairs. Each of these pairs is interpreted as an offer to generate that level of production at that price or greater. On the demand side, suppliers and large consumers can submit their buying bids to the pool specifying some quantity of electricity and the maximum price that they are willing to pay for it.

In each period the market operator constructs an offer and a demand curve and a market clearing algorithm is used to determine which generating units are to produce, how much each agent can consume and the market clearing price for each period, the system marginal price, SMP. The SMP is determined by the highest selling bid that is dispatched. Any capacity offered at a price below the SMP is accepted and the generators that make offers at this price are rationed proportionately. On the demand side, any bid to buy at a price above the SMP is accepted but the set of lowest bids among them, which may be rationed proportionately.[22] This market clearing process is complicated by several mechanisms designed to satisfy constraints that generating units may include in their offer bids.[23]

Currently, there are four generating firm in Spain: Grupo Endesa, Iberdrola, Unión Fenosa and Hidrocantábrico. This configuratio is the result of several mergers. The last, and one of the most important, mergers took place in 1996 when Endesa took control of two other important public firms Table 1 presents the capacity shares of firm and technologies in the Spanish system.

Note that the industry is very concentrated, with the two largest firm controlling 83% of the generating capacity and 80% of the distribution. Another

Table 1
Capacity shares of Spanish electricity generators and distributors (1997)

	G. Endesa	Iberdrola	U. Fenosa	Hidrocant.	Total
Thermal	28.7	11.8	7.0	2.9	50.4
Nuclear	8.8	8.2	1.9	0.4	19.4
Hydro	11.2	15.1	3.1	0.8	30.2
Generation	48.8	35.1	12.0	4.1	100.0
Distribution	41.0	39.0	16.0	4.0	100.0

Source: Comisión Nacional del Sistema Eléctrico, Annual Report, 1997.

[21] See Ley del Sector Eléctrico (27/11/97), and subsequent legislation.

[22] Note that because the supply function is discrete and the fact that the SMP is determined by a selling bid, it is possible that there is excess demand at a price greater than the SMP.

[23] The Spanish pool allows each generating unit to add three types of constraints to the previous offers. These are minimum revenue, non-divisible offers and maximum load gradient constraints. They have been designed to ensure that generating units have non-negative profit when they face start-up costs as well as to account for technological restrictions. None of these constraints is included in the analysis below since we do not consider the possibility of start-up costs in our model.

important feature is that hydro power represents more than 30% of installed capacity. Finally, notice that there is vertical integration between generators and distributors.

3.2.2. Data

The data used in the simulations has been taken from the *Comisión Nacional del Sistema Eléctrico* (CNSE) and includes information at the plant level on fuel,[24] operation and maintenance costs as well as ownership structure. In order to account for outage rates, firms generation capacity is reduced by 12.75% for thermal generators and by 14.75% for nuclear plants (outage rates provided by CNSE). Data on hourly 1998 demand was obtained from the web page of the market operator, *Compañía Operadora del Mercado Eléctrico*. We divide the range of demand into 50 identical intervals and take the median demand in each of these intervals. Our calculations are based upon these 50 representative demand values. When aggregating our results we take into account the different frequencies in each interval. From our observed demands we subtract net imports for 1998.

Total hydro generation was set to 33,168 GWh, which is the observed value for 1997.[25] Maximum hydro flow for each fir were provided by CNSE. Minimum flow were set to 5% of the firms maximum hydro flow this is consistent with minimum daily flow for 1995–1997 (data provided by CNSE).

3.2.3. Hydro generation

According to Bushnell (1998) the main feature that distinguishes hydro from other technologies is that it allows firm to shift electricity generation between different time periods. In essence, it permits firm to store electricity. In regulated welfare maximizing environments hydro is used in periods of high demand in order to "shave" demand peaks, avoiding the need to use high marginal cost peaking units.[26]

The strategic aspects of hydro scheduling have been dealt with in the context of a Cournot model by Scott and Read (1996), who analyze a multi-period model where one fir controls all the hydro storage capacity. In each period this fir interacts with a number of thermal generators in a Cournot market. Bushnell (1998) extends Scott and Read's methodology to allow for multiple firm with hydro capacity and for the existence of fringe firms Using a methodology similar to the previous two works, Ocaña and Romero (1998) also analyze hydro

[24] Spanish generators are subject to mandatory quotas for domestic coal consumption. This is not taken into account in our simulation. Fuel cost for coal is treated as the international price plus transportation to the plant.

[25] We have tested the effect of using values of 25,000 and 35,000 GWh. This has a small effect on the absolute level of price–cost margins, and their relative change across scenarios. The average annual hydro generation in the 1993–1997 period was 28,500 GWh.

[26] Hydro is also used to adjust to small unexpected shifts in demand given its high degree of modulation. This is a more technical aspect of water use that is beyond the scope of this paper.

production in a model of Cournot competition. The main result that is derived from the previous papers with respect to the scheduling of water is that firm will depart from a competitive allocation of hydro by shaving their marginal revenue instead of demand, which leads to a flatte hydro allocation. The intuition is that firm will deviate from the competitive allocation by transferring water from periods where their market power is high to periods where their market power is low.[27]

A general treatment of hydro scheduling in multi-unit auction models is beyond the scope of this paper. As we have noted previously, our results show that our model has a closer relation with the dominant fir   model than with Cournot. In a dominant fir   model, fringe firm will take prices as given and, to the extent that higher demand results in higher prices, will allocate water in a peak shaving manner.[28] The dominant fir   will use hydro in a strategic manner equating its marginal cost across periods. In our simulation we will assume that all firm allocate hydro production in a peak-shaving manner. This is what price-takers would do, therefore, in the light of the previous analysis; our assumption will introduce a downward bias on our measure of market power.

3.2.4. Demand-side bidding

Given observed demand for a particular hour t, q_t, we need to specify a pool demand function $D_t(p)$ for this hour. If there is no demand-side bidding in the pool, then pool demand will simply be constant at q_t for any price. However, if there is a fraction of consumers that are allowed to engage in demand-side bidding, then the demand function will be decreasing with respect to price. The problem that arises in specifying $D_t(p)$ is that it will be determined by demand responsiveness to prices, which depends on pumped storage and on eligible consumers' ability to adjust their electricity consumption in a given hour. We must compensate the lack of information that we have on demand-side bidding behavior with some reasonable assumptions.

We assume that the demand function is linear and that the maximum change that may occur in demand in any given hour, $D_t(0) - D_t(p^{\max})$, is a fixe percentage M of the average observed hourly demand during a year, $\overline{q}$:

$$D_t(0) - D_t(p^{\max}) = M\overline{q}.$$

This, along with linearity, implies that demand takes on the form $D_t(p) = a_t - bp$, where b is constant for every period and is given by

[27] Garcia et al. (2001) deal with this problem in a more general context.

[28] As noted by Bushnell (1998) the presence of price taking firm will create a ''kink'' in demand. This may lead a price setting dominant fir   to choose to lower its price when demand grows. We have not observed this feature in our results. In most, if not all, cases a larger demand is associated with a larger market price.

$$\frac{M\bar{q}}{p^{\max}}.$$

Let q_t be the observed demand in an hour. We may then express the constant term as $a_t = q_t + \delta$, where δ is a parameter that we use for calibration purposes. Finally, we assume that aggregate demand for a year will be constant in equilibrium regardless of the level of eligible consumers. This assumption reflect the widespread belief that aggregate demand is non-responsive to prices in the short run. Thus for a given assumption on the percentage of observed demand that is responsive to price, M, we calibrate δ so that, in equilibrium, annual aggregate production corresponds with observed demand. If there is multiplicity we take the lowest price since we are interested in a lower bound on market power.[29] Our calibration of δ controls for the ''size effect'' that would result if we were to keep a_t constant and to increment the slope of the demand b.[30]

3.2.5. Results

Fig. 3 presents the results of simulating the model with the Spanish generating plants and electricity demand. We allow for different market structures and degrees of demand responsiveness to prices. In particular, scenario 1 corresponds to the market structure before the last merger wave in 1996, i.e., the operating firm are Iberdrola, U. Fenosa, Sevillana, FECSA, Hidrocantábrico and Grupo Endesa. Scenario 2 corresponds to the structure after the last merger wave in 1996, i.e., Grupo Endesa takes control of Sevillana and FECSA. Finally, scenario 3 corresponds to a hypothetical case in which we assume a merger among U. Fenosa, Hidrocantábrico and Iberdrola. The reason for looking at this scenario is to analyze the case of a duopoly with two firm of similar size.

In turn, linear demand functions are constructed from our observed demand as explained before. We run our simulations for alternative demand slope scenarios with M ranging from 0% (inelastic demand) to 40%. When there is multiplicity of equilibria, results for the minimum equilibrium price are reported. Fig. 3 presents yearly average price–cost margins for all the scenarios considered. We observe that price–cost margins are lower in scenario 1, where market structure is more fragmented, while the highest price–cost margins arise in scenario 2. Scenario 3, which corresponds to a duopoly structure, leads to lower price–cost margins than

[29] Given that $\arg\max\, \pi_i(p)$ may have more than one element, a marginal rise in δ does not necessarily imply a marginal rise in aggregate production in equilibrium; it may actually result in a discontinuous drop in production. What this implies is that the existence of a δ that keeps aggregate production constant is guaranteed, but it may not be unique. Given that we are interested in a lower bound on market power, in our calibrations we fin the smallest of such values of δ.

[30] The linear demand assumption would lead to very high elasticities if prices were allowed to rise. This is not the case in our model because there is a restriction on the maximum price generators may bid, $p^{\max}$.

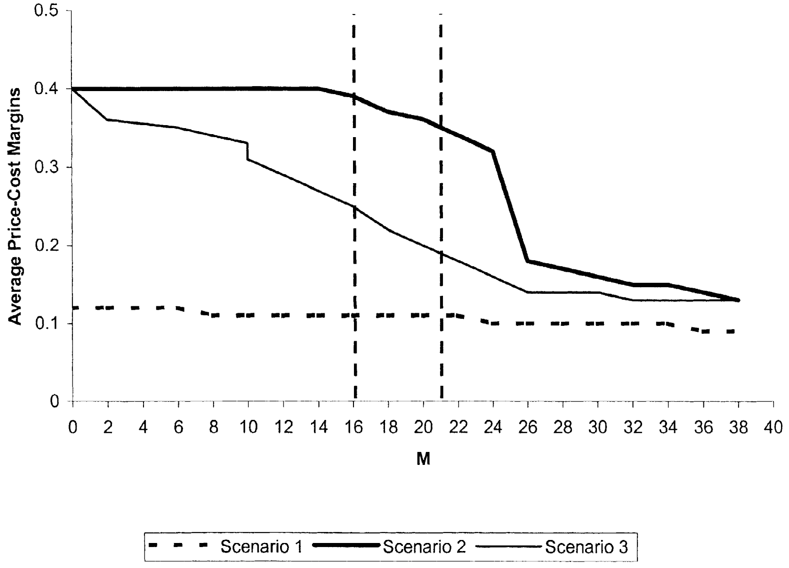

Fig. 3. The effect of demand responsiveness on average price–cost margins.

scenario 2 even though it represents a more concentrated market structure. This occurs because, in scenario 2, in most cases, there is a unique equilibrium with the large dominant fir setting the marginal price. In contrast, in scenario 3 the market structure is more symmetric, leading to a greater multiplicity of equilibria. Because only the minimum equilibrium price is reported, this results in scenario 3 having lower price–cost margins (see Fig. 1 for a detailed example with a similar situation). In all the scenarios, an increase in *M* causes price–cost margins to fall. This effect is very small in scenario 1 where price–cost margins are lower. As *M* increases, price–cost margins tend to converge in all the scenarios. This suggests that changes in market concentration must be evaluated according to the value of *M*. In particular, the last merger that took the Spanish industry from scenario 1 to scenario 2 would be particularly worrying for a small *M*, since price–cost margins rise by a factor of 4, while a value of the slope parameter above 25% would imply that this merger had a much smaller effect on market power. We will now deal with the problem of selecting a reasonable value of *M*.

A value of *M* greater than zero reflect the fact that a fraction of demand might be price responsive. The two elements that can lead to a price responsive demand are pumped storage and hourly modulability on the side of eligible consumers. In 1998, pumped storage represented 1.1% of total demand that was dispatched and eligibility was negligible.[31] In our model, for a given equilibrium price, *p*, price

[31] Data provided by CNSE.

responsive demand as a percentage of total demand is given by $[D_t(0) - D_t(p)]/D_t(p)$. Using our model, for each value of M, it is possible to calculate the percentage of demand that is price responsive in a year. This allows us to relate the observed value of pumped storage demand (that was the only price responsive demand in that year) with a value for M of 16% under the 1998 four-fir structure (scenario 2).

Current eligibility represents 50% of total demand, but the percentage of eligible consumers' demand that may change with the price in a given hour is not likely to be greater than 10%. Under this assumption the maximum variability in demand, in response to price changes due to eligible consumers, will not be higher than 5% of total demand. Adding this to the value obtained for pumped storage yields an upper bound of 21% for M.[32] Accordingly, we conclude that, under any reasonable value for M, the merger of Endesa with Sevillana and FECSA had a large and significan impact on market power. Moreover, our simulation shows that the current situation is worse in terms of market power to a nearly symmetric duopoly, with the three smallest firm merging.[33] The latter result shows the limitations of a simple concentration index analysis. This is consistent with our previous simulations that show that a greater size symmetry leads to lower price–cost margins.[34]

4. Conclusions

In this paper we extend the results of von der Fehr and Harbord (1993) to analyze an electricity pool with short bidding periods. The model also accounts for the effect of demand-side bidding by including a positively sloped demand. We obtain a characterization of the pure strategy equilibria for this model and we implement a simple algorithm to identify them. Our theoretical results suggest that asymmetries among generating firms both in size and costs, play a crucial role in determining prices, leading to higher price–cost margins and, in many cases, to multiplicity of equilibria. In the presence of strong asymmetries there is a unique equilibrium where the small firm act as price takers and the large fir maximizes profit given its residual demand as in the dominant fir model. When comparing the predictions of our model to those of a Cournot model, we fin that the latter yields higher prices than the former. This coincides with the results of Green and

[32] In the year 2003, eligibility will rise to include all consumers. It is not very likely that this will add much to the hourly price responsiveness of demand, since small consumers are not likely to be able to modulate demand in one hour.

[33] This is due to the fact that the duopoly structure leads to a multiplicity of equilibria and we are providing results for the minimum equilibrium prices. In any case, given that the maximum equilibrium prices coincide in scenarios 2 and 3, a simple average of the maximum and minimum equilibrium prices would result in lower market power under the duopoly structure.

[34] We are assuming throughout the analysis that small companies do not jointly act strategically.

Newbery (1992) where Cournot is an upper bound to equilibrium prices and suggests that the Cournot model overestimates market power in pool markets.

We simulate our model for the Spanish electricity market in order to measure market power under the current market structure and to analyze the effect of the 1996 merger that took the industry from a six- to a four-fir structure. We fin that market power measured by price–cost margins is very high in the Spanish pool and that most of this market power can be attributed to the 1996 merger.

The approach we have developed in this paper provides a methodological alternative to Cournot analysis of market power in pool markets which involve short-lived bids. An interesting extension would be to examine how well our model can approximate the mixed strategy equilibrium that arises when firm have long-lived bids. If it were found to give an adequate approximation to mixed strategy equilibria, and given that our model is relatively simple, it would then represent a general alternative to Cournot for pool market simulations.

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Appendix A

Proof of Theorem 1. Let us defin by M_i the output of fir i that is offered at a price of p^* *and is accepted*.[35] Formally,

$$M_i = Q_i - \max\{q : b_i(q) < p^*\}.$$

Suppose that $Q_j < O_j(p^*)$ for some $j \neq i$. Defin $k = \min(O_j(p^*) - Q_j, M_i)$ and consider the following deviation for fir j:

$$\hat{b}_j(q) = \begin{cases} p^* - \epsilon, & q \leq Q_j + k, \\ p^{\max}, & q > Q_j + k. \end{cases}$$

This will give fir j profit of *at least* $(p^* - \epsilon)(Q_j + k) - C_j(Q_j + k)$. This can be rewritten as

[35] Notice that M_i only includes the output of fir i's marginal units that is accepted, not of any unit that bids at a price below the marginal price.

$$\pi_j(\hat{b}_j, b_{-j}) = \pi_j(b) - \epsilon Q_j + \int_{Q_j}^{Q_j+k} [p^* - \epsilon - MC_j(q)]\, \mathrm{d}q.$$

Given that $p^* > MC_j(q)$ for any positive $q \leqslant Q_j + k$, we have that $\int_{Q_j}^{Q_j+k}[p^* - MC_j(q)]\, \mathrm{d}q$ is equal to some constant $A > 0$. Thus

$$\pi_j(\hat{b}_j, b_{-j}) = \pi_j(b) - \epsilon(Q_j + k) + A.$$

For small enough $\epsilon > 0$, $\pi_j(b) < \pi_j(\hat{b}_j, b_{-j})$. □

Proof of Theorem 2. Suppose there is a pure strategy equilibrium in which fir i is marginal, the SMP is p^* and firms payoffs are given by the vector $\hat{\pi}_i(p^*)$. Given the assumption that rules out bidding below marginal cost, any fir $j \in I$ may deviate to selling all its capacity at a price which maximizes its residual demand and obtain profit of at least

$$\max_{p \in [0, p^{\max}]} v_j(p).$$

This proves the implication in one direction. Now suppose $\max_{p \in [0, p^{\max}]} v_j(p) \leqslant \hat{\pi}_{ij}(p^*)$ and $D(p^*) - O_{-i}(p^*) > 0$. We will construct a strategy profil that yields profit of $\hat{\pi}_i(p^*)$ and prove it is an equilibrium. Consider a strategy profil b where the strategy for fir i is given by

$$b_i(q) = \begin{cases} p^*, & q \leqslant O_i(p^*), \\ MC_i(q), & q > O_i(p^*), \end{cases}$$

and all other firm except i bid all their capacity at marginal cost. Suppose that the SMP under profil b, p', is greater than p^*; this implies that

$$v_i(p') \geqslant p' O_i(p^*) - C_i(O_i(p^*)) > p^* O_i(p^*) - C_i(O_i(p^*)) \geqslant v_i(p^*),$$

which leads to a contradiction. It must be the case then that profil b results in a SMP of p^*. We have then that $\pi_j(b) = \hat{\pi}_{ij}(p^*)$ for all $j \in I$.

Under profil b, fir i is making profit of $\max_{p \in [0, p^{\max}]} v_i(p)$ and its rivals are behaving as price takers, thus fir i has no profitabl deviation given its rivals' strategies.

Suppose there exists a fir $j \neq i$ that has a profitabl deviation from b. It cannot result in a system marginal price below p^* since fir j is obtaining profit of $\max_q p^* q - C_j(q)$. The deviation must result in a price above p^* and deviation profit for fir j are then bounded above by $\max_p v_j(p)$. □

Proof of Theorem 3. By Theorem 1 and Corollary 1 we know that if more than one fir is marginal then we obtain a perfectly competitive outcome. Let us suppose that only one firm i, is marginal and it is setting a marginal price of $\overline{p}^*$.

We denote the production of fir i in this equilibrium by Q^*_i, and the aggregate production of its rivals by Q^*_{-i}.

Let $q' = \arg\max_q P(q + Q^*_{-i})q - C_i(q)$ and $p' = P(q' + Q^*_{-i})$; we will begin by proving that $q' \leqslant Q^*_i$. Suppose that $q' > Q^*_i$, we then have that $p' < P(Q^*_i + Q^*_{-i}) \leqslant \bar{p}^*$ and

$$P(q' + Q^*_{-i})q' - C_i(q') = p'(D(p') - Q^*_{-i}) - C_i(D(p') - Q^*_{-i}) \leqslant v_i(p').$$

We may then write

$$\begin{aligned} P(q' + Q^*_{-i})q' - C_i(q') &\leqslant v_i(p') \leqslant v_i(\bar{p}^*) \\ &= P(Q^*_i + Q^*_{-i})(Q^*_i + Q^*_{-i}) - C_i(Q^*_i + Q^*_{-i}). \end{aligned}$$

Given that $P(q + Q^*_{-i})q - C_i(q)$ is a concave function of q this leads to a contradiction.

Let us denote the Cournot equilibrium productions corresponding to $\underline{p}^C$ by q^C_i and Q^C_{-i}. Following Amir (1996) let us now defin the Cournot best response function of fir i when its rivals produce Q_{-i} in terms of the aggregate industry production $z(Q_{-i})$:

$$z(Q_{-i}) = \arg\max_{q \geqslant Q_{-i}} (q - Q_{-i})P(q) - C_i(q - Q_{-i}).$$

Amir (1996) shows that $z(Q_{-i})$ is a decreasing function (see proof of Theorem 2.3).[36]

Let us assume that $\underline{p}^C < \bar{p}^*$, by properties of a Cournot equilibrium $Q^C_{-i} \leqslant O_{-i}(\underline{p}^C)$ and thus $Q^C_{-i} \leqslant O_{-i}(\bar{p}^*) \leqslant Q^*_{-i}$. We then have that

$$Q^*_i + Q^*_{-i} \geqslant q' + Q^*_{-i} = z(Q^*_{-i}) \geqslant z(Q^C_{-i}) = Q^C_{-i} + q^C_i,$$

which leads to a contradiction. □

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[36] It is easy to see that the objective function is strictly concave in z and thus that $z(Q_{-i})$ is single valued.

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