Capacity Competition in Electricity Markets*

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Abstract

We analyze a two-stage game where capacity-constrained electricity generators first choose how much capacity they make available and then compete in a uniform-price auction. We study how capacity withholding can be used strategically to enforce market power and how uniform auctions in the price game change the results of capacity constrained competition models. The uniform auction procedure gives strong incentives to capacity restriction. At equilibrium, however, power shortage never occurs.

Keywords: electricity markets, capacity choice, uniform auctions
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1 Introduction

Since the 90's, an increasing number of countries have organized wholesale markets for electricity. Although the market rules may differ from country to country, the trading of electricity is generally based on uniform price auction mechanisms, that is a system where every active producer receives the same price for every unit of output he is called for, as long as his bids were lower than the clearing price computed by the market operator (see von der Fehr and Harbord (1998) and Newbery (1999) for a comprehensive description of several international examples).

Though auctions in electricity markets have already been studied by several economists, yet an important feature of spot trading is the capacity availability decision. In fact, for technical reasons, such as equipment maintenance or failures, the installed capacity may not work at maximum operating level and the spot market rules oblige generators to announce which plants they are willing to use together with their offer prices. Beside technical reasons, the so-called "capacity declarations" also offer a strategic instrument for firms: by restricting capacity, operators can benefit from scarcity rents.[1] As Green (2004) explain: "[...] The term "withholding" is often used to describe the way in which generators could exploit market power. "Economic withholding" implies that a plant would not offer its output as soon as the market price was high enough to cover its costs of doing so, but would wait until the price had risen above its costs. "Physical withholding" implies that the plant's output is not made available to the market at any price. In both cases, the plants that are withheld from the market will generate less, and are likely to make less money, but the strategy can increase the company's profits by raising the price received by its other units." Our aim is to show that endogenizing capacity as a strategic variable not only takes into account real technological constraints, but also helps to understand when withholding production results in pricing above marginal cost, a possible outcome of the uniform price auction. Thus we study a two-stage game where capacity constrained electricity generators first choose how much capacity they make available and then compete in a uniform-price auction.

Assessing whether generators withhold capacity is an intriguing issue for real electricity markets, though proving it is a difficult task. Wolak and Patrick (1997) study the UK Pool during the first five years of its operation and affirm that capacity bids are a more "high-powered" instrument than price bids to manipulate spot market prices. By analyzing half-hourly bids and availability declarations, they conclude that National Power and PowerGen were strategically withholding capacity to increase prices. How-

[1] Notice that short-term capacity availability decisions are substantially different from the long-term investment as modelled by von der Fehr and Harbord (1997), Castro-Rodriguez et alii (2001).

ever, Green (2004) argues that availability figures do not provide conclusive evidence of strategic capacity withholding by British generators from 1990 to 2001,.and concludes that to look for this kind of evidence, prices and generation patterns must be examined.

Joskow and Kahn (2001) perform a simulation analysis showing that capacity withholding in the Californian spot market during the summer 2000 can explain - at least partially - the observed price increase. They find a substantial gap between maximum possible levels of generation and observed levels at peak hours. This gap cannot be explained by the California System Operator's requirements for ancillary services or by reasonable estimates of forced outages. Joskow and Kahn conclude that there is sufficient empirical evidence that the high observed prices reflect market power exercised by withholding capacity. On the contrary, Harvey and Hogan (2001a) cast some doubts about the empirical analyses assessing strategic withholding by the Californian companies; in particular, they criticize Joskow and Kahn's work in that they use publicly available data only. According to Harvey and Hogan, the public information do not reflect the real status of capacity usage and do not show whether capacity has been used to generate energy, or to provide ancillary services, or to alleviate congestion and to balance generation and load, as the system operator might require. Harvey and Hogan's view is not shared by the California Public Utilities Commission, whose investigation has concluded that five independent power producers - Duke, Dynergy, Mirant, Reliant and AES/Williams - withheld capacity from their California plants.[2]

Several theoretical papers show that generators are able to keep wholesale prices high as compared to their generation costs.[3] Von der Fehr and Harbord (1993) develop a sealed-bid multiple-unit auction model with particular reference to the UK Pool operating during the 90's. They show that inefficient pricing is the most likely outcome even if there is no collusive behavior. Motivated by the recent reform of the UK system, where each active producer is paid his own bid, and by the Californian debate in favor of price-differentiated mechanisms, Fabra et alii (2005) generalize the model proposed by von der Fehr and Harbord (1993) and compare discriminatory and uniform auctions in terms of prices and productive efficiency. Through comparative statics results, the authors show that the pricing mechanism in the electricity industry is heavily affected by the existence of capacity constraints in generation, like in Bertrand-Edgeworth models.[4] Fabra et alii

[2] California Public Utilities Commission, "Wholesale Generator Investigation Report", available at http://www.cpuc.ca.gov.

[3] We do not refer here to the set of studies that use standard Industrial Organization models of competition based on continuous and differentiable cost functions, like Bolle (1992), Green and Newbery (1992), Green (1996, 1999), Newbery (1998), Baldick and Hogan (2001).

[4] The impact of firms' limited generation capacity on bidding strategies is further ex-

(2005) provide much of the results we use to characterize the equilibrium of the price game, at which capacity are exogenously given.

The strategic use of available capacity in two-stage games with uniform auctions has been analyzed by Le Coq (2002) in a duopoly model and by Ubeda (2004) in the more general uniform versus discriminatory auction debate. Considering all possible *cost/available capacity* configurations, both Le Coq and Ubeda conclude that firms will generally have incentives to withhold capacity. However, our paper differs from theirs in that we focus on a specific *cost/installed capacity* configuration. In our model, a generator is not obliged to declare all installed capacity as available, but decides on the amount of MW of electricity that is available. Hence the available capacity is an endogenous variable while the installed one is exogenous. The analysis of installed capacities, which may be larger than the "available" capacities, allow to explain clearly whether generators exert market power by declaring unavailable some production units.

Although we find multiple subgame perfect equilibria that cannot be eliminated by Pareto-dominance, all the outcomes are characterized by market price at the highest attainable value and most of them by production below installed capacity. Nevertheless, there is no power shortage, as long as the penalty rules that apply to generators when excess demand occurs do not give the wrong incentive to decrease capacity.

The paper is organized as follows. Section 2 is devoted to model setting. After a brief explanation of the price game (Section 3), we analyze the capacity choice (Section 4). Section 5 compares our results to those of capacity-constrained competition models and Section 6 concludes.

2 Model setting

To analyze competition in electricity markets, it is necessary to clarify the assumptions on supply and demand, but also on market rules and regulatory instruments. In what follows, we detail our hypotheses: Section 2.1 describes supply and demand characteristics, while Section 2.2 is devoted to market rules.

plored by Otto López (2000) who analyses a market where generators, submitting different bids for each next-day hourly market (like in Spain since1998), face a quasi certain demand. Otto López shows that, for a certain range of low costs, the firms bid strictly less under capacity constraint than in the unconstrained case. The expected equilibrium price, however, will not necessarily be close to the marginal cost because of capacity constraints. García-Martin (1999) refers to the same type of model to analyze the effects of the stranded costs investments recovrement and shows that this mechanism acts as a countervailing force to market power and high prices.

2.1 Supply and demand characteristics

Supply There are two generators labeled a and b, with installed capacity $\overline{K}_i$ $(i = a, b)$. The technology exhibits constant marginal costs c_i $(i = a, b)$ for production levels less than capacity, while production above capacity is infinitely costly. Arbitrarily, we assume $c_a < c_b$ and, whenever applicable, we use the parameter $\zeta = \frac{\hat{p}-c_a}{\hat{p}-c_b} > 1$ to measure firm a's cost advantage ($\hat{p}$ is the price cap; see Section 2.2 below). We also assume- for pure convenience - asymmetric installed capacities $\overline{K}_a > \overline{K}_b$, which means that the low generation-cost firm is also the one with the higher installed capacity. An example is given by hydro versus thermal electricity. Costs as well as installed capacity are common knowledge, which is broadly the case in wholesale electricity markets.

Each generator is not obliged to declare capacity as totally available: when firm i announces that $K_i(\leq \overline{K}_i)$ is available, she must be ready to produce up to K_i if the market operator dispatches her. The technical reason is that it is costly to prepare and to operate a generation plant. Since withholding capacity can also enforce anticompetitive behavior, we assume that firm i incurs no cost in declaring the availability of K_i. Generation costs will only be paid for the output effectively produced.

We also assume that power shortage can occur only if provoked by firms: the installed capacity is sufficient to provide the highest demand level.

Demand Demand D is totally inelastic: this mainly reflects the fact that hourly demand forecast announced by the Independent System Operator[5] (henceforth, ISO) are fixed quantities.[6]

For a given demand D, supply can appear as small or large ex-ante or ex-post. Ex-ante, demand is to be compared with the real or technical or natural generation capacities $\overline{K}_a$ and $\overline{K}_b$. Ex-post, demand has to be compared with the alleged or declared or strategic capacities K_a and K_b. Of course, because of the constraints $K_i \leq \overline{K}_i$ for $i = a, b$, the ex-post regime can only be a subset of the ex-ante regime.

2.2 Market rules

Bid Formats In energy markets, generators' bids must respect the legal format imposed by the system operator. For instance, price announcements are limited to a finite number of values by pre-defined ticks. On the contrary, no legal constraint is imposed on the quantity of energy the generator

[5] As we do not consider transmission problems, there is no reason to distinguish between the system operator, usually in charge of transmission congestion, and the market operator.

[6] Eligible customers are allowed to announce demand bids, which represent their maximum individual willingness to pay. As a result, the aggregate demand should exhibit some elasticity, but actually, observation shows that the price elasticity of demand is very low.

is willing to provide; but, as we have said, technical constraints as start-up cost or multi-unit equipment may cause discontinuity in the production decisions. We neglect these legal and technical constraints and consider price and capacity as continuous variables, ruling out the problem of optimization in integer numbers.

Price-cap We suppose that there exists an upper limit to bids, denoted by $\hat{p}$ that can be interpreted as a regulated maximum price or as the reservation price of consumers as estimated by the ISO.

Determination of the system marginal price We limit our attention to uniform-price auctions; at equilibrium, all participants are paid the same unit price, that is the clearing price or the "system marginal price" (SMP). When bids are ordered by increasing values, the SMP is the value of the last bid necessary to equate demand and supply. When demand is low, the clearing price is the bid B_i fixed by the low bidder. For a medium demand, the clearing price is fixed by the firm with the higher generation capacity. With a high demand, the equilibrium price is the bid fixed by the high bidder. It results that, depending on the declared capacities K_a and K_b, and depending on the demand value D, we have very different conditions of price competition. In all cases, however, demand is allocated first to the lower bidder and the higher bidder serves the residual, if any.

Tie-breaking rules If firms announce the same price p, we assume that generators are despatched proportionally to their available capacity, which means that the gross revenue of firm i is $pD\frac{K_i}{\sum_j K_j}$.[7] We also consider, as an alternative rule, the efficient tie-breaking mechanism, under which whenever the two generators submit equal offer prices, the low cost firm is called into operation first, and the competitor is left serving the residual demand.

Shortage penalty What occurs in the D^E regime where demand cannot be totally supplied? Under pure market mechanisms, the price should be $\hat{p}$, each firm i receiving revenue $\hat{p}K_i$, and demand being rationed. Shortages in California during Summer 2000 have shown that the political consequences of black-outs are dramatic, hence market rules should be designed to avoid them. In fact, the so-called "load-serving entities", responsible for retailing, must pay some penalties for unserved demand once the real-time dispatch has occurred (Crampton and Sotft, 2005). This is a motivation to analyze the impact of alternative penalty rules on firms' withholding strategies, assuming that generators are responsible for serving final demand, since in our model we do not consider distributors. We assume that, when a shortage

[7] This is for instance the rule used by the Spanish ISO.

occurs, the ISO requires firms to sell all their available capacity at a price $\widetilde{p} \leq \widehat{p}$ and to pay a fixed penalty S.

Notice that our hypothesis on the shortage penalty is different from the so-called capacity payments, whose impact is considered, for instance, in von der Fehr et alii (1997). The capacity payment rule makes firms' profit an increasing function of firm's own capacity and a decreasing function of the difference between demand and the total declared capacity. This reward scheme can create incentives for collusion and free riding[8], whereas our penalty rule makes withholding unattractive.

2.3 Timing of the game

In spot markets, suppliers submit pairs (B_i, K_i) that give the minimum unit price B_i at which supplier i is willing to produce up to the associated quantity K_i MW. However, if price bids can adjust very quickly to any information relevant to competition strategies, capacity cannot. Due to technological inflexibility, firms must plan their capacity availability *before* submitting simultaneously price and quantity bids. Hence we assume that, even if market rules oblige generators to submit day-ahead price and quantity bids at the same time, firms actually decide quantities before deciding on prices. The bidder can commit to a price almost instantaneously while he needs technical lags before committing to capacities. For this reason, we consider realistic to keep separate the decision on K_i and the decision on B_i. Additionally, we assume that the choice of K_i is observable by j before choosing B_j. This can be justified by bidders' expertise and by the information disseminated by market operators.[9] We focus on capacity availability decisions, neglecting the duration of suppliers' offer prices. The latter topic has been quite extensively studied in the literature on electricity auctions (see in particular García-Diaz and Marín, 2003 and Fabra et alii, 2005).

At the time where generators decide on the capacity availability and price bids, demand forecast is a crucial variable. We assume that firms know the value of D when choosing capacities and prices; therefore, they

[8] "Capacity payments" are a feature of some electricity systems including Spain, Argentina and Australia. However, recently they have been widely criticised (see Newbery, 1997, Wolak and Patrick, 1997) and abandoned in the newly-designed England and Wales pool. In order to avoid shortage, other systems, as the New-York ISO and the PJM Interconnection, have organised decentralised capacity markets and imposed capacity obligations (and penalties if those obligations are unattended) to load-serving entities. The Colombian ISO is considering to organise reliability contracts which include penalties for those bids that are not backed by adequate generation capacity.

[9] For instance, since July 2001, the Californian ISO makes publicly available a list of all power plants located in the State that are not operational due to planned or unplanned outages. The snapshot of the "non-operational generating units" is updated four times a day, on the basis of the information communicated by generators. The list comprises very detailed information on the unavailable plants, including the name of the generation unit which is being reported upon.

play a two-stage game:

i) firms a and b announce the available capacities $K_a \leq \overline{K}_a$ and $K_b \leq \overline{K}_b$;

ii) knowing these capacities, the firms submit their bids B_a and B_b.

Given the capacity and price bids, the ISO matches demand and supply and generators are paid.

3 Price competition

In this section, we determine the price equilibria corresponding to each regime of demand, given the available capacity declared by the generators. This is a necessary step before we can focus on the stage of competition in capacity. Lemma 1 describes the equilibrium profits of the price competition game that we consider at the capacity choice stage, most of the results lean on Proposition 1 proven by Fabra et alii (2005). In this latter work, the results focus on critical thresholds of the market demand, which is treated as a random variable. In our model, as D is deterministic, it is useful to restate the price competition game outcomes in order to make clear the role of capacity availability and ex-post demand regimes:

Lemma 1 *The equilibrium profits of the price competition game are as follows:*

i) for $K_a < (D - K_b)$ and $K_b < D$, there is ex-post excess demand $\left(D^E\right)$; firms' profits are:

$$\pi_i = (\widetilde{p} - c_i)K_i - S \quad i = a, b \quad \widetilde{p} \leq \widehat{p}, S \geq 0. \tag{1}$$

ii) for $(D - K_b) \leq K_a < \frac{\zeta}{\zeta - 1}(D - K_b)$ and $K_b < D$, there is ex-post high demand $\left(D^H\right)$; firms' mixed-strategy profits are:

$$E\pi_a = (\widehat{p} - c_a)(D - K_b) \quad , \quad E\pi_b = (\widehat{p} - c_b)(D - K_a) \tag{2}$$

iii) for $\frac{\zeta}{\zeta - 1}(D - K_b) \leq K_a < D$ and $K_b \geq D$, there is ex-post medium demand regime with the high-cost firm b having the capacity advantage $\left(D_b^M\right)$; firms' profits are:

$$\pi_a = (\hat{p} - c_a)K_a \quad , \quad \pi_b = (\hat{p} - c_b)(D - K_a) \tag{3}$$

iv) for $K_b < \frac{D}{\zeta} < D \leq K_a$, there is ex-post medium demand regime with the low-cost firm a having the capacity advantage (D_a^M); firms' profits are:

$$\pi_a = (\hat{p} - c_a)(D - K_b) \quad , \quad \pi_b = (\hat{p} - c_b)K_b \tag{4}$$

v) for $K_b \geq \frac{D}{\zeta}$ and $K_a > D$ there is ex-post low demand regime D^L; firms' profits are:

$$\pi_a = (c_b - c_a)D \quad , \quad \pi_b = 0 \tag{5}$$

Proof. See the Appendix. ■

In the Appendix we show that for $K_a \leq \frac{\zeta}{\zeta-1}(D - K_b)$ there exist two set of pure strategy equilibria that are outcome equivalent to D_a^M and D_b^M. The multiplicity of equilibria in the high demand regime creates some difficulties for the analysis of capacity choice. Hereafter, we assume that in the ex-post high demand regime, firms play in mixed strategies and their expected profits are given by equation (2) to preserve firms' symmetry.[10] Those profits corresponds to the limit case in which the high cost firm never bids the price cap and the industry profits are minimized (see Fabra et alii, 2005, Proposition 1)[11]: this would discourage firms from creating ex-post high demand regime.

Price game under efficient tie-breaking Under the assumption that the generators' marginal costs are observable, an alternative rule to break ties is efficiency: when firms bid the same price, the low cost firm is called into operation first, and the competitor is left serving the residual demand. In our model, the introduction of the efficient tie-breaking rule does not affect the equilibria of the price game, as the following shows:

Lemma 2 *When the efficiency rule is used to break ties in offer prices, the price equilibrium and the profits for all the competition regimes remain as in Lemma 1.*

Proof. See the Appendix. ■

Efficient tie-breaking is not a remedy against high mark-up in the price game, as potential advantages from calling first into operation the low cost firm are offset by the uniform price mechanism with inelastic demand.

The plane of the declared capacities (K_a, K_b) is partitioned in five zones. Figure 1 summarizes firms' profits depending on the values of K_a and K_b that we will consider in the capacity game below.

[10] Le Coq (2002) considers the two possible pure strategy equilibria.

[11] In the Appendix we show that a possible outcome of the high demand price game in mixed strategy is the Bertrand equilibrium (see Corollary 1), but as both generators must be despatched to serve the demand, the least efficient firm is not excluded from the market. In some sense, the inefficient firm is protected by the efficient one against losses due to low bids. This result should be taken into account when econometricians try to evaluate the cost function using bid records. We also show (see Corollary 2) that capacities play an important role in the characterization of the *first-order stochastic dominance* of the mixed strategies.

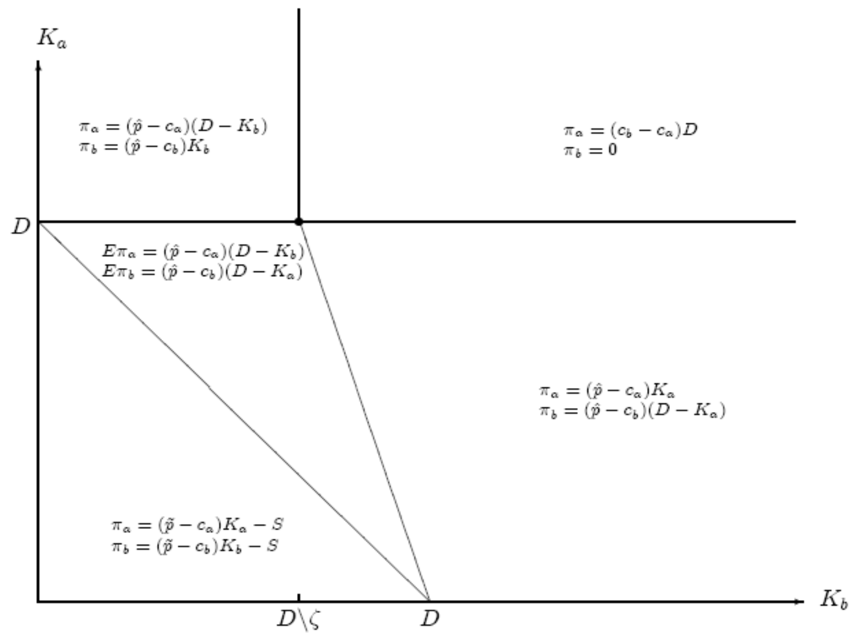

Figure 1: Profits as functions of capacity declarations

4 Capacity choice

To analyze the capacity game when demand is known by the operators at the moment they announce their capacity availability, we start describing the choice process when no generator is ex-ante constrained by capacity, and then we extend the analysis to the cases of ex-ante medium and high demand forecast. Recall that for the game in capacity, we assume that adding-up the installed capacity of each firm is sufficient to provide the whole demand, and that the low generation cost firm a is also for convenience the one with the highest installed capacity.

4.1 Low demand

We first consider the case where the ISO announces that demand will be $D < \overline{K}_b$, which means that both firms have enough capacity to supply the whole demand individually.

As we can infer from Figure 1,

- if firm a thinks b will declare $K_b \geq D$, for $K_a < D$ she will be in a D_b^M regime with profit $(\widehat{p} - c_a)K_a$ and for $K_a \geq D$, she will be in a D^L regime with profit $(c_b - c_a)D$ which is independent from K_a;

- if firm a thinks that b will declare $\frac{D}{\zeta} < K_b < D$, with $K_a < D - K_b$, she will be in the D^E regime, earning $\pi_a = (\widetilde{p} - c_a)K_a - S$, which increases with K_a and gives firm a the incentive to increase her capacity up to $K_a = D - K_b$. With $D - K_b \leq K_a < \frac{\zeta}{\zeta-1}(D - K_b)$, she will be in the D^H regime, earning $E\pi_a = (\widehat{p} - c_a)(D - K_b)$. For $D > K_a > \frac{\zeta}{\zeta-1}(D - K_b)$, she ends-up in a medium regime with profit equal to $\pi_a = (\widehat{p} - c_a)K_a$. Finally, increasing its capacity, for $K_a \geq D$ she will be in the equivalent of a low demand regime with profit $(c_b - c_a)D$. Clearly, when $\frac{D}{\zeta} \leq K_b < D$ firm a attains the highest profit by declaring a capacity above the line $K_a = \frac{\zeta}{\zeta-1}(D - K_b)$. Within this zone, firm a earns $\pi_a = (\widehat{p} - c_a)K_a$ which increases with K_a;

- if firm a thinks that b will declare $K_b = \frac{D}{\zeta}$, with $0 \leq K_a < D$ she will be in an excess demand or high demand regime earning at most $\pi_a = (\widehat{p} - c_a)(D - K_b)$. With $K_a \geq D$, she will be in a D^L-like regime, earning $\pi_a = (c_b - c_a)D$.

- if firm a thinks that b will declare $K_b < \frac{D}{\zeta}$, with $K_a < D - K_b$, she will be in the D^E regime, earning $\pi_a = (\widetilde{p} - c_a)K_a - S$, which increases with K_a and gives firm a the incentive to increase her capacity up to $K_a = D - K_b$. With $D - K_b < K_a < D$, she will be in the D^H regime, earning $E\pi_a = (\widehat{p} - c_a)(D - K_b)$, and for larger values $K_a > D$, she will be in a D_a^M regime, with profit $\pi_a = (\widehat{p} - c_a)(D - K_b)$.

The comparison of the profit values allows to establish that if firm a thinks that b will declare $K_b > \frac{D}{\zeta}$, she can avoid fierce competition by choosing $D - \epsilon$; for $K_b \leq \frac{D}{\zeta}$, the low demand regime is impossible, and firm a bids any value above $D - K_b$.

Summarizing, the best response of firm a is as follows:

$$K_a(K_b) = \begin{cases} D - \epsilon & \text{if } \overline{K}_b \geq K_b > \frac{D}{\zeta} \\ K_a \in \left[D - K_b, \overline{K}_a\right] & \text{if } K_b \leq \frac{D}{\zeta} \end{cases}$$

where ϵ is a positive number arbitrarily small (see Figure 2).[12]

[12] Recall that we treat capacity as a continuos variable. In real electricity markets, choosing a capacity level equal to $D - \epsilon$ can be realized by shutting down the smallest production unit that ensures total production by the generator at a level slightly below the announced demand.

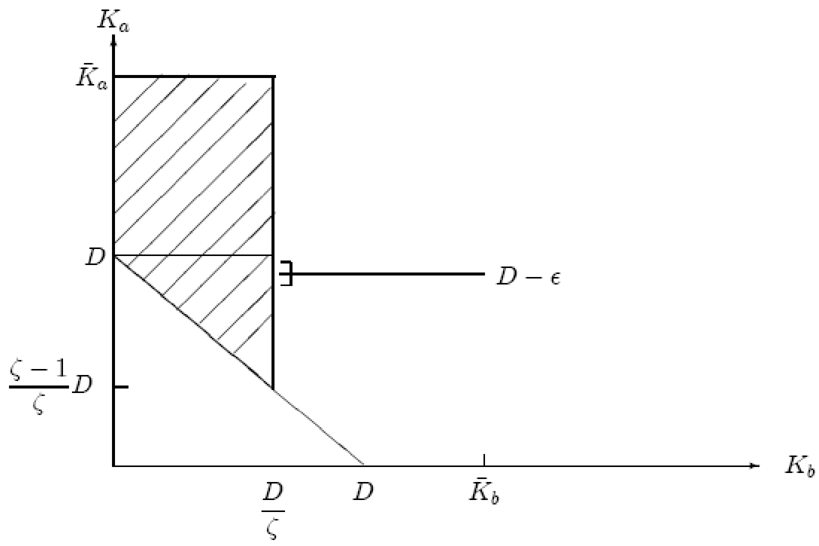

Figure 2: Ex-ante low demand. Firm a's best response function in the capacity subgame.

The best response function of firm b is slightly different.

- When $K_a > D$, firm b will be in a low demand regime, earning nothing, if he declares $K_b \geq \frac{D}{\zeta}$; for capacity below $\frac{D}{\zeta}$, firm b obtains a positive profit, $\pi_b = (\widehat{p} - c_b)K_b$, which is the medium demand regime with firm a having the capacity advantage.
- If firm b thinks that a will declare $K_a = D$, with $0 \leq K_b < D$ she will be in a D_a^M regime earning $\pi_b = (\widehat{p} - c_b)K_b$. With $K_b \geq D$, she will be in a D^L regime, obtaining zero profit.
- When $K_a < D$, for $K_b < D - K_a$, she earns the excess demand profit, that is $\pi_b = (\widetilde{p} - c_b)K_b - S$. Hence firm b has an incentive to increase capacity. For $K_b \geq D - K_a$, firm b earns $E\pi_b = (\widehat{p} - c_b)(D - K_b)$: this is the profit she obtains with the price equilibrium in mixed strategies in the high demand regime, as well as with the price equilibrium in pure strategies under the medium regime, where firm b has the capacity advantage.

We can now characterize firm b's best response (see Figure 3):

$$K_b(K_a) = \begin{cases} \frac{D}{\zeta} - \epsilon & \text{if } \overline{K}_a \geq K_a \geq D \\ K_b \in \left[D - K_a, \overline{K}_b\right] & \text{if } K_a < D \end{cases}$$

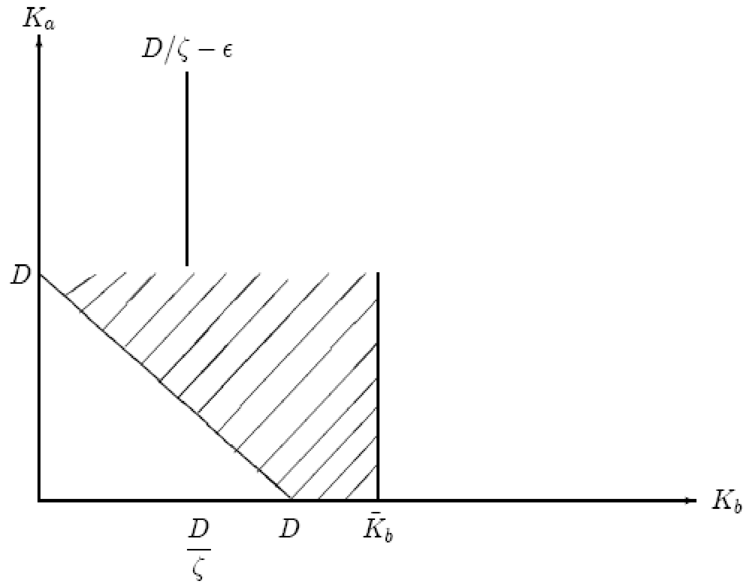

Figure 3: Ex-ante low demand. Firm b's best response in the capacity subgame.

Consequently, we can establish the following:

Proposition 1 *If none of the generators is naturally capacity constrained ($D < \overline{K}_b < \overline{K}_a$), there are three families of equilibria for the capacity choice game:*

i) $(K_a^*, K_b^*) = \{K_a, K_b \diagup K_a < D,\ K_b \leq \frac{D}{\zeta},\ K_a + K_b \geq D\}$

ii) $K_a^* \geq D, \qquad K_b^* = \frac{D}{\zeta} - \epsilon$

iii) $K_a^* = D - \epsilon, \quad K_b^* \geq \frac{D}{\zeta}$

Proof. The proof is directly obtained by intersecting the two best response functions. ■

Table 1 summarizes the results of Proposition 1.[13]

[13] Table 1 (as well as the following Tables 2 and 3) does not consider ex-ante "very-high-demand regime" since we have excluded this case by hypothesis.

ex-ante demand regime	Low $\bar{K}_a > \bar{K}_b > D$		
ex-post regime	i) High	ii) Medium D_a^M	iii) Medium D_b^M
capacity bids	$K_a^* < D$ $K_b^* \leq D/\varsigma$ $K_a^* + K_b^* \geq D$	$K_a^* > D$ $K_b^* = \frac{D}{\varsigma} - \varepsilon$	$K_a^* = D - \varepsilon$ $K_b^* > \frac{D}{\varsigma}$
capacity withholding by *a*	yes	likely	yes
capacity withholding by *b*	yes	yes	likely
expected profits for *a*	$(\hat{p} - c_a)(D - K_b^*)$	$(\hat{p} - c_a)\frac{\zeta - 1}{\zeta} D$	$(\hat{p} - c_a)D$
expected profits for *b*	$(\hat{p} - c_a)(D - K_a^*)$	$(\hat{p} - c_a)\frac{D}{\varsigma}$	0

Table 1. Ex-ante low demand: subgame perfect equilibria

In type $i)$ equilibria, we are in an ex-post high demand regime. The two other sets of equilibria give medium demand regime. In type $ii)$ with firm a having an advantage in capacity, the expected profits are respectively $\pi_a^* = (\widehat{p} - c_a)\left(\frac{\zeta-1}{\zeta}\right) D$ and $\pi_b^* = (\widehat{p} - c_b)\frac{D}{\zeta}$. In type $iii)$ equilibria, profits are $\pi_a^* = (\widehat{p} - c_a)D$, $\pi_b^* = 0$.

It is unfortunately impossible to eliminate some of the equilibria by a Pareto-dominance argument: each generator is better-off when the other one has the advantage in capacity and fixes the SMP at $\widehat{p}$. Moreover, generator i prefers to sell all capacity in the D_j^M regime than earning the D^H profit with only one fraction of the demand.

These remarks imply that mixed strategies equilibria are very likely in the capacity game and there is a strong incentive for generators to agree on market sharing. If the players can coordinate their capacity bids somewhere in the set $K_a^* + K_b^* = D$, generator a who has a cost advantage can use the credible threat to bid $K_a^* = D$ that guarantees at worst $\pi_a = (c_b - c_a)D$ in order to obtain a capacity advantage and the consequent profit advantage. Consequently she will deny any agreement such that $K_a^* \leq \frac{c_b - c_a}{\widehat{p} - c_a} D = \left(\frac{\zeta-1}{\zeta}\right) D$. All these implicit or explicit agreements are obviously forbidden. But the model shows that the high mark-up resulting from the uniform price system gives strong incentives to transform a natural low demand regime into a medium or high demand regime by withholding capacities.

4.2 Medium and High demands

When $\overline{K}_b$ and $\overline{K}_a$ become binding, leading to natural medium and high demand regimes, some equilibria of the preceding section are eliminated. However, given that firm b's reaction functions switches at $\frac{D}{\zeta}$, there is an additional degree of freedom: even when "naturally" capacity-constrained (i.e. $\overline{K}_b < D$), the small firm can still have an actually unconstrained best reaction function. For example, if the ISO announces an ex-ante medium demand regime, the capacity constraint of generator b puts downward pressure to firms' choice only if $\overline{K}_b$ is lower than $\frac{D}{\zeta}$, as the following Proposition points out (see Table 2):

Proposition 2 *When the smaller generator is naturally constrained and the larger is not ($\overline{K}_b < D < \overline{K}_a$), the equilibria of the capacity game are as follows:*
i) if $\overline{K}_b < \frac{D}{\zeta}$, *the equilibria are* $(K_a^*, K_b^*) = \{K_a, K_b / K_a < D,\ K_b < \frac{D}{\zeta},\ K_a + K_b \geq D\}$;

ii) if $\frac{D}{\zeta} \leq \overline{K}_b$, *there are three families of equilibria:*
1) $(K_a^*, K_b^*) = \{K_a, K_b / K_a < D, K_b \leq \frac{D}{\zeta}, K_a + K_b \geq D\}$
2) $K_a^* \geq D, \qquad K_b^* = \frac{D}{\zeta} - \epsilon$
3) $K_a^* = D - \epsilon, \quad \frac{D}{\zeta} < K_b^*$

Proof. The proof is similar to that of Proposition 1. ■

ex-ante demand regime	Medium $\frac{D}{\varsigma} < \bar{K}_b < D < \bar{K}_a$			Medium $\bar{K}_b < \frac{D}{\varsigma} < D < \bar{K}_a$
ex-post regime	i) High	ii)Medium D_a^M	iii) Medium D_b^M	i) High
capacity bids	$K_a^* < D$ $K_b^* \leq D / \varsigma$ $K_a^* + K_b^* \geq D$	$K_a^* \geq D$ $K_b^* = \frac{D}{\varsigma} - \in$	$K_a^* = D - \in$ $K_b^* > \frac{D}{\varsigma}$	$K_a^* < D$ $K_b^* \leq \bar{K}_b$ $K_a^* + K_b^* \geq D$
capacity withholding by a	yes	likely	yes	likely
capacity withholding by b	yes	yes	likely	likely
expected profits for a	$(\hat{p} - c_a)(D - K_b^*)$	$(\hat{p} - c_a)\frac{\zeta - 1}{\zeta} D$	$(\hat{p} - c_a)D$	$(\hat{p} - c_a)(D - K_b^*)$
expected profits for b	$(\hat{p} - c_b)(D - K_a^*)$	$(\hat{p} - c_b)\frac{D}{\varsigma}$	0	$(\hat{p} - c_b)(D - K_a^*)$

Table 2. Ex-ante medium demand: subgame perfect equilibria

If the small generator is severely capacity constrained, only high demand equilibria arise. If, despite the capacity constraint, firm b can bid $\frac{D}{\zeta}$ (or slightly less), all the outcomes of Proposition 1 are likely, though now, as $\overline{K}_b < D$, the medium demand regime with b having the capacity advantage disappears.

In any case, the set of conflicting Pareto superior equilibria is reduced to the segment $K_a^* + K_b^* = D$ with $K_b^* \in \left[0, \overline{K}_b\right]$. If generators could agree on capacity bids, we have seen at the end of Section 4.1 that firm a could decline to bid $K_a^* \leq \left(\frac{\zeta-1}{\zeta}\right) D$. As now $\overline{K}_b < \frac{D}{\zeta}$, the efficient negotiation set would be reduced at the advantage of a, since at worst she could obtain the low regime profit.

Similarly to the previous case, when the ISO announces a natural D^H regime, only strategic high demand and excess demand regimes are feasible ex-post. The definition of the equilibrium set depends on whether $\overline{K}_b$ lies below or above $\frac{D}{\zeta}$.

Proposition 3 *If both generators are naturally constrained ($\overline{K}_b < \overline{K}_a < D < \overline{K}_a + \overline{K}_b$), the equilibria of the capacity game are:*
$(K_a^*, K_b^*) = \{K_a, K_b / K_a \leq D,\ K_b \leq \left\{\min(\overline{K}_b, \frac{D}{\zeta})\right\},\ K_a + K_b \geq D\}$

Proof. The proof is similar to that of Proposition 1. ■

Table 3 summarizes the results of Proposition 3.

ex-ante demand regime		High $\bar{K}_a + \bar{K}_b > D > \bar{K}_a$
ex-post regime		High
capacity bids		$K_a^* \leq \bar{K}_a$ $K_b^* \leq \{\min(\bar{K}_b, D/\varsigma)\}$
capacity withholding	by a	likely
	by b	likely
expected profits	for a	$(\hat{p} - c_a)(D - K_b^*)$
	for b	$(\hat{p} - c_b)(D - K_a^*)$

Table 3. Ex-ante high demand: subgame perfect equilibria

4.3 Capacity withholding

The outcome of our two-stage game suggests several results regarding the strategic withholding of production capacity. When demand is "naturally" low, the players face the largest set of possibilities. They could even restrict their capacities to create artificial scarcity. Common sense suggest that, if penalties for energy shortage were very severe (e.g. leaving generators with zero profits), their interest would be to avoid an ex-post excess demand regime. But, they also want to avoid the ex-post low demand regime that would create fierce competition. Consequently, the outcome of the game will be ex-post high or medium demand regimes. At least one of the players withhold capacity; both do so in the ex-post high demand regime.

When the ISO announces an ex-ante medium demand regime, at equilibrium the ex-post high demand regime may occur, implying that generators can strategically restrain capacity. If the low generator is severely constrained, the high demand equilibrium is the only possible outcome of the game.

Clearly, absent any capacity cost, withholding is very likely as it is weakly Pareto superior for firms. The only case where both firms might dump their installed capacity on the market, by bidding $K_a^* = \overline{K}_a$ and $K_b^* = \overline{K}_b$, is when both generators are ex-ante constrained. However, firm b will surely withhold if it can bid $K_b^* = \frac{D}{\zeta}$ (that is, when $D > \overline{K}_b \geq \frac{D}{\zeta}$). If there was no cost-advantage (i.e. $\zeta = 1$), this case would not arise.

More generally, when firms are symmetric, the set of equilibria is smaller.[14] Although capacity withholding is still likely to occur, there is one exception: when the ex-post regime is medium demand with a having the capacity advantage, firm b never restrains capacity. In fact, leaving a to be the market leader reduces the opportunities for b to use capacity bids strategically.

As also Ubeda (2004) notices, when endogenizing capacity in a two-stage game with uniform auctions and inelastic demand, there is multiplicity of equilibria in terms of capacities, though uniqueness of Cournot equilibrium price which is just the monopoly price, that is $\widehat{p}$. However, it is impossible to eliminate the subgame equilibria using a Pareto dominance argument. Certainly, the set $K_a^* + K_b^* = D$ (with or without $K_i^* \leq \overline{K}_i$) is very attractive for the generators. The range of capacities allows for the possibility of using finite horizon trigger strategies to condition the subgame equilibrium selection on the capacities chosen. This may possibly allow for collusion to be enforced in equilibrium (see Decheneaux and Kovenock, 2004). However,

[14] One can easily see that, when both firms have symmetric unit costs equal to c, in the price game, Betrand equilibria arise only when the demand is low. For medium and high demand regimes, two symmetric subsets of pure strategy equilibria with one firm bidding high and the competitor bidding low exist (the "medium-like" demand regime does not exist). The mixed strategy equilibrium gives the same expected profit for both firms, and the support of the prices over which firms randomize is $[c, \widehat{p}]$. In the capacity game, firms' reaction functions become symmetric and both switch at capacity values equal to D.

the characterization of those equilibria goes beyond the scope of this paper.

Finally, it appears that capacity bids are always sufficient to match the demand: there is no incentive to organize voluntary power shortage. Actually, the results of Proposition 1 to 3 are independent of the values of $\widetilde{p}$ and S. Even in the case of a zero penalty, that is with $\widetilde{p} = \widehat{p}$ and $S = 0$, neither firm has the incentive to create the excess demand regime. We conclude that power shortage can only occur due to unexpected variation of demand or costs, or to strategic long-term reasons (e.g. lack of investment) that are beyond the scope of this paper.

5 Capacity competition and uniform auctions

That competition between capacity constrained firms generally yields a market price above marginal cost and therefore positive profits is not surprising: decreasing returns to scale soften price competition, as Bertrand-Edgeworth (henceforth, B-E) models have shown. This is not the place to review systematically these models (for a very interesting synthesis, see Vives, 1999, chapter 5). We simply recall here all the elements that can be useful in comparing the results of our model to this literature.

The B-E models describe price competition, under the hypothesis that 1) the scale of the firm is given, as production decisions adjust to demand; 2) each firm takes into account that the competitor will not sell more than its competitive profit-maximizing supply at the announces price. Therefore, when one firm puts a price lower than the competitor's, she gets all the consumers that can buy at the set price; if she names a price higher than the competitor's, she can face a positive residual demand, since the competitor sells the minimum between its residual demand and its competitive supply (unlike the Bertrand competition model, where all consumers are served by the low-price firm). The residual demand is then allocated according to a rationing rule.

The B-E models predict that in those markets where firms have high capacities relative to demand, there is a unique pure strategy market equilibrium, the competitive price, whereas when firms are relatively small, there exists only a mixed strategy equilibrium where high prices (stochastically) prevail.[15][16] These models also predict that large firms will tend to set low prices. These predictions could have been obtained also from Cournot

[15] The existence of mixed strategy equilibria is guaranteed under relatively weak assumptions (demand continuous and equal to zero for large prices, strictly convex costs, see Maskin, 1986, Allen and Hellwig, 1986).

[16] Moreno and Ubeda (2004) introduce a simple model of oligopolistic competition where firms first build capacity, and then choose a reservation price at which they are willing to supply their capacities.They show that in this new model every pure strategy equilibrium yields the Cournot outcome, and that the Cournot outcome can be sustained by a pure strategy subgame perfect equilibrium.

games, in particular from the Kreps-Scheinkmann (1983) model, a two-stage game where firms decide first their scale and then compete in prices to their supply limits.

To which extent the predictions of our model coincide with those of the capacity constrained literature?

First, *all* the subgame perfect equilibria we obtain are characterized by productive inefficiency, in the sense that the price is not the competitive one and does not correctly signal the profit from entry. Though in the price subgame we do obtain a result which is similar to the B-E models (indeed, when demand is low, the equilibrium price is equal to marginal cost), this competitive effect is offset by the capacity game. Moreover, the price subgame exhibits multiple pure strategy equilibria under all the demand regimes, as Fabra and *alii* (2005) have also shown.

Second, regarding allocative efficiency, although the multiplicity of equilibria prevents to conclude in full generality, in all the medium and medium-high demand regimes, the large firm sets high prices, contrary to the findings of B-E models. It implies that when the high-cost/low installed capacity firm b is left without the capacity advantage, she will be called into operation first, which is clearly undesirable. When ex-post high demand regime occurs, allocative efficiency is even more difficult to assess: using the mixed-strategy price equilibrium profits, we know that stochastically, the smaller firms can bid larger prices; when the small firm is the inefficient one, then firm b sells all of her capacity, so compromising allocative efficiency.

Third, although our model predicts a market price well above marginal costs, both firms producing at capacity is only one of the possible outcomes of the game: this equilibrium may arise in the ex-ante high demand regime, that is when total installed capacity is small relative to the market size and generators might not play strategically. This is similar to Kreps-Scheinkman (1983) model.

The roots of these relative differences between our model and the capacity-constrained competition literature have to be found in some crucial hypothesis we have made. First, we model the price-stage game as a uniform auction which has clearly an impact on the equilibrium price; second, and most importantly, inelastic demand creates strong incentives for firms to bid the highest attainable price. These assumptions strongly limit competition for the residual demand and subgame perfect equilibria leave no room at all to marginal cost pricing. Moreover, though in the high demand regime our results on the relationship between large firms and high prices contradict the stochastic dominance obtained in B-E models, this is less crucial in our model, as it impacts allocative efficiency but not the market price (the SMP is the price cap, whatever the bidding behavior of the firms).

Finally, notice that most of the subgame equilibria are not characterized by firms producing at full capacity. In our model, firms decide on capacity availability (which comes at zero costs) and not on their scale (that is, installed capacity) which would involve very high fixed costs. Therefore, there is no discrepancy between the first-period (ex-ante) cost and the second period (ex-post) cost, implying that there is no incentive to dump existing capacity ex-post. Most importantly, in this model with uniform price and inelastic demand, the equilibrium price jumps to the price-cap as soon as at least *one* firm is unable to serve the demand. Therefore, firms withhold capacity to earn scarcity rents. Moreover, the less the firms are "naturally" capacity constrained (that is, in the ex-ante low and ex-ante medium demand regimes), the stronger the incentive to withhold. This explains the main difference between our results, especially in the ex-ante low demand regime, and those of the literature on endogenous capacity choice.

5.1 Cost asymmetry

Cost asymmetry plays a very important role in capacity-constrained competition models. The only model that analyzes Bertrand-Edgeworth duopoly with unit cost asymmetries is Deneckere and Kovenock (1996). As an application of their characterization, they examine the Kreps-Sheinkmann model of capacity choice followed by Bertrand-Edgeworth price competition with elastic demand and efficient rationing. Obtaining closed-form solutions for such a game is not trivial. Deneckere and Kovenock find that if the cost of capacity is negligible, when the high-cost firm's capacity is not too large, the low-cost firm best response coincides with the downward-sloping Cournot best response. When the high cost firm's capacity reaches a critical level (which depends on the unit production costs of both firms), the low-cost firm's best response becomes flat and jumps to a capacity level that would allow her to accommodate all demand and to price its rival out in the price subgame, yielding a more competitive outcome, with capacities above the Cournot level. Therefore, Cournot capacity levels only arise for limited cost pairs/capacity combinations and demand functions: as compared with the symmetric case, the low-cost firm has a greater incentive to price its rival out.[17] As the cost of capacity becomes larger, the range of unit cost up to capacity for which Cournot does not hold becomes smaller.

The application developed by Deneckere and Kovenock is quite similar to our ex ante low demand regime. Recall that if the capacity made available by the high-cost firm is below a critical value (namely, $K_b \leq D/\zeta$), the low-cost firm best reaction function is any capacity level above the value that avoid shortages, and, for $K_b > D/\zeta$, firm a accommodates *almost* all the demand. The behavior of the high-cost firm is similar, but her reaction function switches at the upper frontier of the Bertrand competition, that is

[17] If the critical capacity level is below the intersection of the Cournot firms reaction functions, there is no equilibrium in pure strategies. Also note that Deneckere and Kovenock make ad hoc assumptions to avoid the high-cost firm having the same incentive to engage in price competition.

at D/ζ.

The shape of the reaction functions in our model is different from Deneckere and Kovenock because of the price subgame, as already stated. But the most crucial point is that for values above the critical capacity of the competitor, firms can avoid serving all the demand, because this would lead to Bertrand competition. By undercutting slightly the demand level, they create the asymmetry in capacity that ensures a high pay-off, since when one firm is unable to serve all demand, the market price is equal to the price cap. If in our model firms were symmetric, this anticompetitive effect would still arise, but in a more limited space, as both firms' reaction function would switch at D.

On a more technical ground, unit-cost asymmetries also modify the support of the mixed strategies. As in Deneckere and Kovenock (1996), we find that the support of mixed strategies is not the same for the two firms. Another analogy can be found with Allen and Hellwig (1993), who find that, given the set of competitive prices at which market demand is equal to aggregate production capacity, in equilibrium asymmetric firms do not charge prices below the highest competitive price. This is similar to our result that the system marginal price does not fall below the cost of the least efficient firm.

5.2 Rationing

In B-E models, the rationing rule[18] used to allocate residual demand can drastically change 1) the region where a pure strategy equilibrium exists[19] and 2) the characterization of mixed strategies.[20] More drastically, the Kreps-Sheinkmann (1983) result is not robust to departures from the efficient rationing rule if the cost of capacity is zero. With proportional rationing, the equilibrium tends to be more competitive, with excess capacity

[18] Edgeworth used proportional rationing, that is the low-price firm serves the maximum between zero and a random sample of the consumer population (rationing is made through a queuing system). Levitan and Shubick (1972) proposed the surplus-maximizing or efficient rule, where the low price firm sells an amount equal to its competitive supply and the high price firm serves the difference between the demand that clears at the high price less the consumers satisfied by the low price firm.

[19] The region where a pure strategy equilibrium exists is restricted under efficient rationing.

[20] For instance, in Kreps and Scheinkman (1983), with elastic demand, efficient rationing, symmetric unit production costs and asymmetric (costly) capacities, firms expected profits are asymmetric. The expected revenue of the largest firm is the reduced form of the Cournot profits: this serves as foundation for Cournot equilibrium in the two stage games. In the mixed-strategy equilibrium, the larger firm charges higher prices in a stochastic sense. Under the same hypothesis, but using efficient rationing, Vives (1999) shows that the expected profits and the upper bound of the support are analogous to those we obtain in the mixed strategy equilibria (except that in our model demand is inelastic, hence the upper bound is the price cap, and that the profit will be net of marginal production costs).

with respect to the Cournot level (Davidson and Deneckere, 1986). If the cost of capacity is small, then the Cournot equilibrium cannot be an equilibrium outcome of the two stage game if the rationing rule is not the efficient one (see Tirole, 1988, Section 5.7).

Our results are independent from the demand rationing assumption. With uniform auctions the market price is unique, and the merit-order procedure only changes the allocation of supply. Allowing the firm that has quoted the lowest price to serve first is equivalent to the efficient rationing allocation. However one can easily verify that, with inelastic demand, efficient and proportional rationing collapse into the same allocation rule. Also notice that the excess demand regime is never an equilibrium outcome, then we do not have to consider rules to ration unserved customers.

6 Conclusion

Our analysis provides interesting insights into the functioning of electricity spot markets. We have shown that market power enforced by strategic withholding is quite likely when the ISO announces ex-ante low and medium demand regimes. Given that ex-ante there is excess capacity, at least one firm withholds capacity and this opportunistic behavior creates artificially high mark-ups that do not reflect scarcity rents. The uniform pricing rule makes even more appealing the gains from capacity withholding: when firms restrict capacity, the SMP attains its maximum level, and so do scarcity rents. However, this strategic behavior does not result in black-outs.

Market design rules, such as the uniform auction, as well as market characteristics, such as demand inelasticity, can facilitate capacity withholding by generators. To this extent, an interesting extension of the model would be to compare incentives to withhold capacity under alternative auction formats, namely considering a price subgame where firms are paid the price they bid, like in discriminatory auctions. However, the task of analyzing withholding in electricity markets must include the interaction between spot trading and other markets: in particular, one has to consider whether capacity is declared unavailable because of strategic withholding or for technical reason, or with the intent to provide ancillary services, or because it is constrained down due to transmission congestion or environmental output restrictions.

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7 Appendix

7.1 Proof of Lemma 1

Excess demand regime $\mathbf{D}^E$ When total supply is insufficient to serve the market ($D > K_a + K_b$), firms profits are calculate according to the shortage penalty rule (see Section 2.2).

High demand regime $\mathbf{D}^H$

Equilibria in pure strategies Referring to Lemma 1 in Fabra et alii (2005), equilibria in pure strategies are
i) if $K_a \leq \frac{\zeta}{\zeta-1}(D - K_b)$, there exist two symmetric sets of equilibria in pure strategies, where the low cost firm bids the price cap and the competitor bids below a given threshold; one set of equilibria is:

$$B_a^* \in [0, \gamma_a^H], \qquad B_b^* = \widehat{p} \tag{6}$$

$$\pi_a = (\widehat{p} - c_a)K_a, \qquad \pi_b = (\widehat{p} - c_b)(D - K_a). \tag{7}$$

where $\gamma_a^H \overset{def}{=} c_b + (\widehat{p} - c_b)\dfrac{(D - K_a)}{K_b} > c_a$, and the second set is:

$$B_a^* = \widehat{p}, \quad B_b^* \in [0, \gamma_b^H] \tag{8}$$

$$\pi_a = (\widehat{p} - c_a)(D - K_b), \qquad \pi_b = (\widehat{p} - c_b)K_b \tag{9}$$

where $\gamma_b^H \overset{def}{=} c_a + (\hat{p} - c_a)\dfrac{D - K_b}{K_a} > c_b$.
ii) if $K_a > \frac{\zeta}{\zeta-1}(D - K_b)$ there exist one set of equilibria where firm b bids the price cap and firm a bids below a given threshold. For values of $K_a > \frac{\zeta}{\zeta-1}(D - K_b)$, it is easy to check that $\gamma_b^H < c_b$; Therefore, there is only one set of equilibria, described by equations (6) and (7), where firm b bids high.

Equilibria in mixed strategies Equilibria in mixed strategies are derived by Fabra et alii (2005), in the proof of Proposition 1, to which we add two additional results.

Corollary 1 *The system marginal price cannot be lower than the marginal cost of the least-efficient firm.*

Proof. In the high demand regime, the SMP is fixed by the highest bidder. Even if firm b can bid on the interval $[c_a, c_b]$ with a positive probability, the SMP will be above c_b with zero probability, since firm a bids below the marginal cost of the competitor with zero probability. ■

Corollary 2 *$K_a < K_b$ is a sufficient condition for $G_a(B) \leq G_b(B)$ $\forall B$.*

Proof. Straightforward calculations show that $K_a < (>)K_b \iff \delta_a > (<)\delta_b$. Under the hypothesis $c_a < c_b$, it is always true that for $B < \widehat{p}$:

$$\frac{B - c_a}{\widehat{p} - c_a} > \frac{B - c_b}{\widehat{p} - c_b} \tag{10}$$

Hence $K_a < K_b$ is sufficient to determine the first order stochastic dominance $G_a(B) \leq G_b(B)$. ■

Medium demand regime $\mathbf{D}_b^M$ When $K_b \geq D > K_b$, drawing on the Lemma 1 proven by Fabra and alii (2005), we can state that price equilibria of the medium demand regime are $B_b^* = \hat{p}$, $B_a^* \in [0, \gamma_a^M]$, where $\gamma_a^M \overset{def}{=} c_b + (\hat{p} - c_b)\frac{D-K_a}{D} > c_a$. All the price equilibria give the same profits $\pi_a = (\hat{p} - c_a)K_a, \pi_b = (\hat{p} - c_b)(D - K_a)$.

Medium demand regime D_a^M Similarly to the previous case, when $K_a > D > K_b$ and $K_b \leq \frac{D}{\zeta}$, the equilibria are $B_a^* = \hat{p}$, $B_b^* \in [0, \gamma_b^M]$, where $\gamma_b^M \overset{def}{=} c_a + (\hat{p} - c_a)\dfrac{D - K_b}{D} > c_b$. Firms' profits are: $\pi_a = (\hat{p} - c_a)(D - K_b)$, $\pi_b = (\hat{p} - c_b)K_b$.

Low demand regime $\mathbf{D}^L$ In the ex-post low demand situation, as the firms propose a perfectly homogeneous good, we have pure Bertrand competition (see again Fabra et alii, Lemma 1). Recalling that the parameter $\zeta = \frac{\hat{p}-c_a}{\hat{p}-c_b} > 1$ measures firm a's cost advantage, one can easily check that $K_b > \frac{D}{\zeta}$ is equivalent to $(\hat{p} - c_a)(D - K_b) < (c_b - c_a)D$ or $\gamma_b^M < c_b$.Thus when $K_a > D > K_b$ and $K_b > \frac{D}{\zeta}$, given that $\gamma_b^M < c_b$, firm b should bid below her marginal cost to be in the market. Therefore, firm a will not consider this bid as a credible threat. Firm a undercuts the rival's cost by bidding $c_b - \epsilon$ and the equilibrium outcome is the Bertrand equilibrium. Equilibrium bids are $B_a^* = c_b - \varepsilon, B_b^* = c_b$ and profits $\pi_a = (c_b - c_a)D$, $\pi_b = 0$.[21]

7.2 Proof of Lemma 2

Under the low demand regime, the efficient firm does not need to undercut her competitor's bids to obtain the whole demand. Equilibrium profits are the same as in Lemma 1.

Under medium demand regime, for $K_a > D > K_b$, firms' profits are like in (**??**), except for $B_a = B_b$, where we now have:

$$\pi_a^{ER} = (B_a - c_a)D \quad , \quad \pi_b^{ER} = 0 \quad \text{if} \quad B_a = B_b \tag{11}$$

[21] In real markets, ε is the smallest tick below c_b fixed by the rules of the market. Here, we simply assume that it is an arbitrary small number, so that the low-cost firm a wins the whole market and the SMP is c_b. In markets where a tick is enforced, we would have $B_a^* = Max\{c_b - \varepsilon, c_a\} = SMP$. The existence of the tick could sensitively lower generator a's profit, especially when the difference between the marginal costs is not very large.

where ER refers to the efficiency rule. The profits in (11) coincide with those earned by the firms when $B_a < B_b$, hence the price equilibrium is unchanged.

In the high demand regime, when firms play pure strategies, bidding the same price as the competitor is a strongly dominated strategy for generator b and a weakly dominated strategy for generator a (both when $K_a > K_b$ and when $K_a < K_b$). Therefore, we can eliminate it. Finally, adopting the efficiency rule does not affect mixed strategy equilibria when calculated on a continuous support, because the joint probability of ending up on a single point is of zero measure (this is no longer true when there exists a legal tick that constraints the choice of the bids' format).