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MARKET DESIGN AND INVESTMENT INCENTIVES*

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The purpose of this study was to understand how market design affects market performance through its impact on investment incentives. For this purpose, we model capacity choices by two *ex ante* identical firms which compete in the product market. We analyse a number of different market design elements, including (*i*) two commonly used auction formats, the uniform-price and discriminatory auctions, (*ii*) price caps and (*iii*) bid duration. We find that although the discriminatory auction tends to lower prices, this does not imply that investment incentives at the margin are poorer; indeed, aggregate capacity is the same under both auction formats.

While the importance of issues related to market structure and market design has been addressed by economists for a long time, the interaction between the two has remained, by and large, unexplored. This is also true for utility industries (such as electricity, gas and telecommunications) in which regulators can indeed modify the 'rules of the game' but where the debate has mostly focused on the short-run effects of market design. However, market structure and market design cannot be analysed in isolation; on the one hand, market rules affect firms' incentives in ways that ultimately shape market structure (e.g. through entry, mergers or investment); on the other hand, the relative performance of alternative market rules depends on market structure, especially in markets characterised by imperfect competition.

The reform of the British electricity market in 2001, which was followed by a sharp price reduction, illustrates the importance of understanding the interaction between market structure and market design.[1] While some authors credited the fall in prices to the new market rules (Evans and Green, 2002), others attributed it to a simultaneous fall in concentration, which was driven by assets divestitures and capacity expansions (Newbery, 2003). An obvious question is whether and how these factors interacted: would concentration have fallen without the change in market rules? And, did the change in concentration impact on the relative performance of the new rules?

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[1] The New Electricity Trading Arrangements (NETA) replaced the Pool with a series of forward markets and a short-term 'balancing market'. Furthermore, in contrast to the formerly used uniform-price auction format, the auction format initially used in the balancing market was of the discriminatory or 'pay-your bid' type. The British regulatory authority, Ofgem, reported that the month-ahead base-load prices fell by 40% from the time Government accepted the reforms in 1998 up to March 2002, that is, 1 year after the 'go-live' of NETA.

The purpose of this study was to explicitly address the interaction between market design and market structure. For concreteness, and because these issues have received particular attention in the electricity industry, we frame our analysis within this industry. Specifically, we consider a single-technology duopoly model with stochastic demand that extends Fabra *et al.*'s (2006) analysis by allowing firms to make investment decisions prior to competing in the market. We analyse and compare different market design elements, including the two commonly considered pricing formats associated with the uniform-price and discriminatory (or pay-as-bid) auction, respectively, market reserve prices or price caps, and bid duration. Furthermore, we explore the effects of long-run price-responsiveness of demand on investment incentives.

A notable feature of equilibrium outcomes is that capacities are asymmetric across firms even though firms are fully symmetric *ex ante*.[2] Asymmetric outcomes arise because capacity choices affect the nature and intensity of price competition: on the one hand, by choosing a smaller capacity than its rival, a firm can ensure a higher frequency of market outcomes at which not only is price competition softer, but it is itself despatched at full capacity; on the other hand, a firm facing a relatively small rival has incentive to expand capacity so as to take advantage of higher prices in periods of high demand. This holds true regardless of market design choices, which nevertheless affect the degree of capacity asymmetry among firms.

Another insight is that there need not be a negative relationship between intensity of price competition and incentives to invest. For investment decisions, what matters is not firms' absolute (expected) profit level but rather the profitability of capacity additions. In particular, we find that while on average returns to investment are lower with a discriminatory format, at the margin investment incentives are not necessarily weaker; indeed, under reasonable assumptions aggregate capacity is the same regardless of pricing rule. The intuition for this result follows from two observations: (*i*) at the margin, capacity is always determined by a firm that in effect acts as a monopolist with respect to residual demand and (*ii*) the marginal unit is despatched when capacity is fully utilised, in which case it receives the market reserve price under both pricing rules.[3]

The relative supremacy of the discriminatory format as far as prices are concerned tends to be preserved even when we allow for endogenous capacities.[4] The dominant effect is the one identified by Fabra *et al.* (2006), that, when demand is high, competition is fiercer in the discriminatory format than in the uniform-price format. Allowing for endogenous capacity choice does however introduce two new effects. First, a larger total capacity generally reduces prices, especially when demand is close to full capacity; when the discriminatory auction leads to higher investment, this effect enhances the supremacy of that format. Secondly, more asymmetry between firms (which, for a given

[2] Such 'symmetry-breaking', or heterogeneity-generating process, has arisen also in other models in applied microeconomics, including the capacity choice games analysed by Hviid (1990) and Reynolds and Wilson (2000); see also Amir *et al.* (2010).

[3] The importance of marginal returns, as opposed to absolute profit levels, has also been emphasised in studies of exclusive dealing (Segal and Whinston, 2000; Fumagalli *et al.*, 2009), buying power (Inderst and Wey, forthcoming) and public versus for-profit intermediation in two-sided markets (Belleflamme and Peitz, 2010).

[4] The overall assessment of the two pricing formats may depend on concerns that are not represented in our model; in particular, on productive inefficiencies. For a discussion, see Fabra *et al.* (2006).

aggregate capacity, means higher market concentration) tends to raise prices; when the discriminatory auction leads to more asymmetry, this effect reduces the supremacy of that format. The determinants of these additional effects are complex and the comparison depends on underlying market characteristics. However, with price-inelastic demand, while total capacity is the same and the asymmetry is greater with the discriminatory format, prices are nevertheless lower.

The relationship between the market reserve price and market performance gets richer and probably more realistic once capacities are endogenised. Reserve prices have two countervailing effects on consumer welfare. On the one hand, for given capacities, lowering the price cap reduces equilibrium prices, thereby benefitting consumers; however, a lower price cap also decreases firms' incentives to expand capacity, leading to a greater likelihood of demand rationing. It turns out that consumers may be made better off with a price cap, so long as this is neither too lenient (i.e. close to consumers' willingness to pay) nor too stringent (i.e. close to firms' costs). The level of the optimal price cap also depends on the pricing rule in place, and this in turn affects the relative performance of the two pricing rules. At least when demand is uniformly distributed, the fact that the optimal price cap is higher under the discriminatory format implies that aggregate investment and, hence, total welfare, is greater than under the uniform-price format.

Whether price-responsiveness tends to stimulate or discourage investments depends on whether capacity expansions translate into lower or higher prices and, hence, into more or less demand. This link is not symmetric across pricing formats: while capacity expansions tend to reduce prices under the discriminatory format, the opposite is true under the uniform-price format. Hence, the discriminatory format delivers an aggregate capacity level that is closer to the first best also under price-responsive demand.

Last, on the issue of whether bids in the wholesale market should have long or short duration, our analysis also leads to clear results. With endogenous capacities, prices tend to be higher when bids are long-lived (i.e. remain fixed while demand varies), while total investment is unaffected, compared to when bids are short-lived. Given that under long-lived bids the discriminatory auction also outperforms the uniform-price format, we can conclude that in our setting a combination of short-lived bids and the discriminatory format produces the most favourable outcome.

Our analysis complements and extends two strands of the literature: the comparison across the uniform-price and discriminatory formats (Federico and Rahman, 2003; Fabra *et al.*, 2006), and the literature on capacity investment under demand uncertainty (Hviid, 1990; Reynolds and Wilson, 2000). Whereas the first set of papers concentrates on price formation in the short-run, that is, for given capacities, the second set of papers concentrates on capacity investments in the long-run, that is, for a given market design. By modelling endogenous investment decisions within alternative market designs, we are able to explore the interactions between the two.

Some studies have specifically focused on the electricity industry. One of the first analyses of this topic was provided by von der Fehr and Harbord (1998), who analysed a model closely related to ours but limited to the case in which firms bid in a uniform-price auction. They found that capacity might fall below or exceed the first best, depending upon parameter values. We confirm von der Fehr and Harbord's (1998) result that overinvestment is a theoretical possibility but point out (in what appears to be the most relevant formulation) that underinvestment is more likely.

Some recent studies have also compared investment incentives in uniform-price and discriminatory auctions. Cramton and Stoft (2007) provide an informal discussion of the long-run effects of these two auction choices. Based on the premise that prices are typically lower with a discriminatory format, they argue that incentives to invest are weaker with this format. However, as pointed out above, our analysis demonstrates that one cannot associate profitability with greater incentives to invest. Assuming fixed and elastic demand, Úbeda (2007) finds that both auction formats result in firms choosing capacities equal to the Cournot outputs, leading to pay-off equivalence.[5]

The rest of the article is organised as follows. In Section 1, we describe the model, and characterise and compare equilibrium outcomes across auction formats. In Section 2, we extend the model in several directions: we discuss entry issues, compare equilibrium outcomes with short-lived and long-lived bids, explore equilibrium selection issues under the uniform-price auction, and introduce long-run price-responsiveness of demand. Section 3 concludes.

1. The Model

We consider a homogeneous-goods, single-technology duopoly model in which firm i, $i = 1, 2$, can supply q_i at no cost up to capacity k_i, that is, $0 \leq q_i \leq k_i$. Demand θ is a random variable, independent of price. It is distributed on the unit interval according to the cumulative distribution function G with continuously differentiable density g, positive everywhere on (0, 1).

At the beginning of the game, before demand is realised, firms simultaneously invest in capacity at unit cost $c > 0$ (capacity-investment stage). Next, demand is realised and firms simultaneously submit bids specifying the minimum price at which they are willing to supply the whole of their capacity (pricing stage).[6] On the basis of the bid profile $\mathbf{b} \equiv (b_1, b_2)$, where $b_i \leq P$ is the bid of firm i and $P > c$ is the 'market reserve price' (possibly determined by regulation), an auctioneer despatches the lower-bidding firm's capacity first and the higher-bidding firm's capacity to serve any residual or remaining demand (if bids are identical, firms are ranked first with equal probability). Formally, the output allocated to firm i is

$$q_i(\theta; \mathbf{b}) = \begin{cases} \min(\theta, k_i) & \text{if} \quad b_i > b_j \\ \frac{1}{2}\min(\theta, k_i) + \frac{1}{2}\min[\max(0, \theta - k_j), k_i] & \text{if} \quad b_i = b_j \\ \min[\max(0, \theta - k_j), k_i] & \text{if} \quad b_i > b_j. \end{cases}$$

[5] However, this conclusion relies on demand being fixed and certain at the investment stage, an assumption which is at odds with features of most markets. Le Coq (2002) and Crampes and Creti (2005) analyse a similar model but restrict attention to the uniform-price auction with inelastic demand.

[6] Fabra *et al.* (2006) demonstrate that (pure-strategy) *equilibrium outcomes* – but not *pricing strategies* – are essentially independent of the number of admissible steps in each firm's bid function (and whether 'step sizes' are choice variables). This implies that constraining firms to submit a single bid for their entire capacity is without loss of generality in this setting. However, as shown by Anwar (2006), this result does not necessarily extend to the case in which firms face demand uncertainty at the pricing stage.

While outputs are solely functions of demand and the bid profile, payments depend upon the auction format: in the *discriminatory auction*, the price received by firm i is equal to its own offer price; in the *uniform-price auction*, the price received is equal to the highest accepted bid. Firms are risk neutral and maximise expected profits.

Let v denote consumers' gross utility per unit consumed – or willingness to pay – and $K = k_1 + k_2$ aggregate capacity. Defining total welfare W as the sum of consumer and producer surplus, it follows that

$$W = v\left[\int_0^K \theta\, \mathrm{d}G(\theta) + \int_K^1 K\, \mathrm{d}G(\theta)\right] - cK, \tag{1}$$

which is a function of K only. Maximisation of (1) with respect to K implies that optimal or first-best capacity is given by:

$$K^{\mathrm{FB}} = G^{-1}\left(1 - \frac{c}{v}\right).$$

1.1. *Discriminatory Auction*

We first consider the discriminatory auction, in which the price received by a firm equals its own bid. We start by characterising equilibrium bidding behaviour for every possible demand realisation and then move to analysing the capacity-investment stage.

Equilibrium bidding behaviour depends on the relationship between capacities and demand. When both firms have enough capacity to serve total demand (Low Demand Region) competition drives prices to marginal cost. When demand exceeds aggregate capacity (Very High Demand Region), there is no effective competition among firms, so that in equilibrium all production is paid at the market reserve price, P. In contrast, when no single firm has enough capacity to satisfy all demand alone but there is excess capacity overall (High Demand Region) an equilibrium in which all production is paid at P cannot exist, given that both firms would have incentives to undercut P. For these realisations, the unique equilibrium is in mixed strategies, and it is such that the large firm makes the same profits as if it offered to sell residual demand at P; the small firm makes more profits per capacity unit as it is more frequently despatched at full capacity.

Let $k^- = \min(k_1, k_2) \leq k^+ = \max(k_1, k_2)$ and denote the firm with capacity k^- 'the small firm' and the firm with capacity k^+ 'the large firm'.

Proposition 1. (*Fabra et al., 2006*) *In the discriminatory auction, for given capacities and a given demand realisation, equilibrium bidding behaviour and equilibrium outcomes are characterised as follows:*

(*i*) *(Low Demand) If $\theta \leq k^-$, there exists a unique pure-strategy equilibrium in which both firms bid at marginal cost and make zero profits.*

(*ii*) *(High Demand) If $\theta \geq k^-$, a pure-strategy equilibrium does not exist. In the unique mixed-strategy equilibrium expected prices exceed marginal costs. Equilibrium bidding behaviour and equilibrium outcomes depend on which of the following regions θ belongs to:*

(Region I) If $k^- \leq \theta \leq k^+$, the small firm makes expected profits $P(k^-/\theta)(\theta - k^-)$ whereas the large makes expected profits $P(\theta - k^-)$.

(Region II) If $k^+ \leq \theta < K$, the small firm makes expected profits $P(k^-/k^+)(\theta - k^-)$ whereas the large makes expected profits $P(\theta - k^-)$.

(*iii*) *(Very High Demand) If $\theta \geq K$, both firms sell all of their capacity at P.*

We next analyse the capacity-investment stage in order to characterise the equilibrium of the overall game. At this stage, since expected profits depend on whether the firm is small or large, expected profits of firm i, $i = 1,2$, $i \neq j$, become

$$\pi_i^d(k_i, k_j) = \begin{cases} \pi_i^{d-} & \text{if } k_i = k^- \leq k_j = k^+ \\ \pi_i^{d+} & \text{if } k_i = k^+ \geq k_j = k^-, \end{cases}$$

where

$$\pi_i^{d-} = P\left[\int_{k^-}^{K} \frac{k^-}{\min(\theta, k^+)}(\theta - k^-)\,\mathrm{d}G(\theta) + \int_{K}^{1} k^-\,\mathrm{d}G(\theta)\right] - ck^-,$$

$$\pi_i^{d+} = P\left[\int_{k^-}^{K} (\theta - k^-)\,\mathrm{d}G(\theta) + \int_{K}^{1} k^+\,\mathrm{d}G(\theta)\right] - ck^+.$$

First-order derivatives are

$$\frac{\partial \pi_i^{d-}}{\partial k_i} = P\left[\int_{k^-}^{k^- + k^+} \frac{\theta - 2k^-}{\min(\theta, k^+)}\,\mathrm{d}G(\theta) + 1 - G(k^- + k^+)\right] - c, \tag{2}$$

$$\frac{\partial \pi_i^{d+}}{\partial k_i} = P[1 - G(k^- + k^+)] - c. \tag{3}$$

The expected profit of firm i is a piecewise continuous function made up of the continuous and differentiable functions π_i^{d-} and π_i^{d+}. The latter is a strictly concave function in k^+. Furthermore, since $\pi_i^{d-} = \pi_i^{d+}$ at $k^- = k^+$, the expected profit function is everywhere continuous. However, it is not everywhere differentiable given that the partial derivative of the expected profit for firm i with respect to its own capacity 'jumps up' at the point where capacities are identical, that is,

$$\frac{\partial \pi_i^{d+}(k,k)}{\partial k_i} - \frac{\partial \pi_i^{d-}(k,k)}{\partial k_i} = \int_k^{2k} \frac{2k - \theta}{k}\,\mathrm{d}G(\theta) > 0. \tag{4}$$

This non-differentiability results from differences in marginal returns to investment for large and small firms. More specifically, the large firm benefits from capacity investments only for Very High Demand, since when demand is High it just serves residual demand. In contrast, an increase in the small firm's capacity also affects its profits for High Demand realisations: on the one hand, a higher capacity allows the small firm to expand output when it prices below the rival; on the other hand, as this makes the large firm more aggressive, the probability that the small firm sells at capacity is reduced. The overall impact on the small firm's profits from these effects may be positive or negative depending on their relative strength.

The 'jump' in firms' marginal profit at symmetric capacity pairs rules out existence of a symmetric equilibrium in capacity choices. Hence, at equilibrium, capacity choices must be asymmetric. Since at equilibrium one firm will be smaller than its rival, the large firm must be setting its capacity optimally. More specifically, since π_i^{d+} is strictly concave in k^+, the first-order condition of the large firm has to be satisfied at equilibrium, which implies $K = G^{-1}[1-(c/P)]$. These results are summarised in the following Proposition.

PROPOSITION 2. *In the discriminatory auction, there does not exist a symmetric equilibrium in capacity choices. Hence, at any candidate equilibrium, firms choose different capacities, and aggregate capacity K is characterised by the condition*

$$K^d = k^{d-} + k^{d+} = G^{-1}\left(1 - \frac{c}{P}\right) \in (0, 1) \quad \text{with } k^{d-} < k^{d+}.$$

Inspection of π_i^{d+} and π_i^{d-} reveals that the large firm's marginal returns to investment are decreasing in the small firm's capacity, that is, the second-order cross derivative is negative, but it is in general not possible to sign the small firm's second-order cross derivative. However, we can guarantee that the small firm's second-order cross derivative is also negative by assuming that $\theta g(\theta)$ is increasing.[7] Whenever both firms' marginal returns to investment are decreasing in the rival's capacity, capacity choices are strategic substitutes. Then equilibrium existence can be demonstrated by appealing to the theory of submodular games. Indeed, there exist exactly two asymmetric equilibria in capacity choices, both of which result in the same level of aggregate capacity. These results are summarised in the following Proposition.

PROPOSITION 3. *In the discriminatory auction, for any G for which $\theta g(\theta)$ is increasing, the simultaneous capacity choice game has exactly two subgame perfect pure-strategy equilibria in capacity choices, one with $(k_1, k_2) = (k^{d-}, k^{d+})$ and the other with $(k_1, k_2) = (k^{d+}, k^{d-})$, $k^{d-} < k^{d+}$.*

Equilibrium profits of the small and the large firm are given by

$$\pi_i^{d-} = P \int_{k^-}^{K} \frac{k^-}{\min(\theta, k^+)} (\theta - k^-)\,\mathrm{d}G(\theta),$$

$$\pi_i^{d+} = P \int_{k^-}^{K} (\theta - k^-)\,\mathrm{d}G(\theta).$$

Note that while the large firm earns higher profits than the small firm, the difference is relatively smaller than the difference in capacities; the reason is that the small firm tends to be despatched at full capacity more often than the large firm. Nevertheless, if given a choice, either firm would prefer to be large.

[7] Any convex distribution function satisfies this assumption; moreover, it also holds for a range of concave distributions, such as the power $G(\theta) = \theta^a$ or the exponential $G(\theta) = (1 - e^{-a\theta})/(1 - e^{-a})$, with $0 \leq a \leq 1$.

1.2. *Uniform-price Auction*

We now consider the uniform-price auction, in which the price received by firms equals the highest accepted bid. Equilibrium outcomes are the same as in the discriminatory auction when demand is either Low or Very High. In contrast, for High Demand realisations, competition in the uniform-price auction is less vigorous than in the discriminatory auction. More specifically, there exist multiple equilibria in all of which total supply is paid at the market reserve price, P. When only the small firm is unable to serve total demand (Region I), the large firm maximises profits by serving residual demand at P; when both firms are needed to cover demand (Region II), there also exist equilibria in which the small firm bids high and therefore sells below capacity if there is excess capacity overall.

PROPOSITION 4. *(Fabra et al., 2006) In the uniform-price auction, for given capacities and a given demand realisation, equilibrium bidding behaviour and equilibrium outcomes are characterised as follows:*

(*i*) *(Low Demand) If $\theta \leq k^-$, there exists a unique pure-strategy equilibrium in which both firms bid at marginal cost and make zero profits.*

(*ii*) *(High Demand) If $\theta \geq k^-$, there exist multiple pure-strategy equilibria in all of which the highest accepted bid is P. Equilibrium bidding behaviour and equilibrium outcomes depend on which of the following regions θ belongs to:*
(Region I) If $k^- \leq \theta \leq k^+$, the large firm bids at P and the small firm bids a sufficiently low price to make undercutting unprofitable. The small firm supplies all capacity k^- at P, whereas the large firm serves residual demand $\theta - k^-$ at P.
(Region II) If $k^+ \leq \theta < K$, either one of the two firms bids at P and the other firm bids a sufficiently low price to make undercutting unprofitable. The low-bidding firm sells all capacity at P, whereas the high-bidding firm serves residual demand at P.

(*iii*) *(Very High Demand) If $\theta \geq K$, there exist multiple pure-strategy equilibria in all of which at least one firm bids at P and both firms sell all capacity at P.*

Note that, for a given demand realisation, equilibrium outcomes are unique, except for High Demand realisations in Region II, in which either firm may bid at P. In what follows, we concentrate attention on the equilibrium at which the large firm bids at P for High Demand realisations in Region II (when firms have identical capacities we assume they are equally likely to bid at P).[8] Not only is this a natural focal point, but, as we show next, it is the only robust equilibrium outcome to introducing (slight) demand uncertainty.[9]

PROPOSITION 5. *Suppose there is demand uncertainty (or demand variation) at the pricing stage over the full demand support. In the uniform-price auction, there is a unique equilibrium in mixed strategies. If the demand distribution converges to the Dirac Delta distribution that puts all the mass on a High Demand realisation in Region II, the unique mixed-strategy equilibrium*

[8] Nevertheless, the qualitative nature of outcomes is essentially the same in all continuation equilibria, as we demonstrate in Section 3.2.
[9] Other equilibria with uncertain demand require bounding of the support of the demand distribution.

converges to the equilibrium strategy profile of the game with certain (or fixed) demand at which the small firm bids low and the large firm bids at P.[10]

Accordingly, at the capacity-investment stage, expected profits of firm i, $i = 1,2$, $i \neq j$, become

$$\pi_i^u(k_i, k_j) = \begin{cases} \pi_i^{u-} & \text{if} \quad k_i = k^- < k_j = k^+ \\ \pi_i^{u=} & \text{if} \quad k_i = k_j = k \\ \pi_i^{u+} & \text{if} \quad k_i = k^+ > k_j = k^-, \end{cases}$$

where

$$\pi_i^{u-} = P \int_{k^-}^{1} k^- \, \mathrm{d}G(\theta) - ck^-,$$

$$\pi_i^{u=} = P \int_{k}^{K} \left[\frac{1}{2}(\theta - k) + \frac{1}{2}k\right] \mathrm{d}G(\theta) + P \int_{K}^{1} k \, \mathrm{d}G(\theta) - ck,$$

$$\pi_i^{u+} = P \int_{k^-}^{K} (\theta - k^-) \, \mathrm{d}G(\theta) + P \int_{K}^{1} k^+ \, \mathrm{d}G(\theta) - ck^+.$$

Expected profits are not continuous at symmetric capacities, implying non-existence of a pure-strategy equilibrium in capacity choices.[11] Beginning from a symmetric profile of capacities, since there is an advantage to being slightly smaller than the rival, firms would wish repeatedly to undercut each other, leading to low capacities; eventually, these capacities would be so low that one firm would deviate upwards to a large capacity and then the sequence of best-reply undercuts would begin again. This logic rules out pure-strategy equilibria.

It turns out that this problem may be solved by a slight amendment to the model. Instead of considering a single stage of simultaneous capacity choices, consider a multi-stage game where capacities are first built and then each firm is given the opportunity to sequentially reduce (or mothball) capacity, with the small firm moving first. The implicit assumption in the simultaneous-move formulation is that suppliers commit to their capacities in the long run. Given that expanding capacity takes time, and given that the pricing game (or the auction) takes place at regular short-term intervals, it makes sense to assume that a supplier is unable to increase its capacity in the short run. However, there is no reason why firms should not be allowed to destroy (or mothball) capacity. Therefore, allowing for an interim mothballing stage not only solves the problem of non-existence, as we show next, but also adds realism to the model.[12]

[10] For all other demand regions, the unique mixed-strategy equilibrium with demand uncertainty converges to the unique equilibrium strategy profile with certain demand.

[11] An equilibrium in mixed strategies fails to exist as well. Formal proofs of these statements can be made available from the authors upon request.

[12] As already noted, in the discriminatory auction, both firms prefer to be the large one, both before as well as after investment costs are sunk; hence, the possibility of mothballing has no effect.

Proposition 6. *Suppose that, after investment has been made but before demand is realised and prices are set, first the small firm and subsequently the large firm are allowed to dispose of some of their capacity. Assume further that at the pricing stage the large firm bids high for all High Demand realisations.*

(*i*) *Then, in the uniform-price auction, any equilibrium in capacity choices is a pair* (k^{u-}, k^{u+}), $k^{u-} < k^{u+}$ *that solves*

$$P[1 - G(k^{u-} + k^{u+})] = c, \tag{5}$$

$$k^{u-}[1 - G(k^{u-})] = \int_{k^{u-}}^{k^{u-}+k^{u+}} (\theta - k^{u-})\mathrm{d}G(\theta) + k^{u+}[1 - G(k^{u-} + k^{u+})]. \tag{6}$$

(*ii*) *Such an equilibrium always exists.*

Equation (5) corresponds to the first-order condition for the large firm's capacity choice, reflecting the fact that the marginal unit of capacity will only be used when demand exceeds aggregate capacity. Equation (6) equates net revenues for the small and the large firm and ensures that, given capacities, firms are indifferent between playing either role. The former condition implies that equilibrium aggregate capacity is $G^{-1}[1-(c/P)]$, whereas the latter condition implies that, at equilibrium, the small firm makes higher profits than the large firm as it incurs lower investment costs.

To see why the intermediate stage in which firms are allowed to dispose of capacity ensures existence of an equilibrium, consider a candidate equilibrium of the model without this stage such that the large firm bids high for all High Demand realisations. Then the capacity of the small firm would have to be (almost) as large as that of the large firm, given the high returns to capacity resulting from the price umbrella erected by the large firm's high bid when demand is high. However, given that the small firm has such a large capacity, the rival would not want to play the role of large firm, but would rather choose a smaller capacity in order to obtain the advantage of acting as the small firm.

The option to dispose of capacity deters the small firm from investing too much, thereby ensuring that the rival is willing to maintain its large capacity; that is, the small firm chooses a capacity such that its rival is just indifferent between playing the role of the large firm and disposing of sufficient capacity to obtain the role of the small firm. Foreseeing that it will not want to dispose of any of its capacity, the large firm invests so as to maximise expected profits conditionally on being large.[13]

1.3. *Comparison across Auctions*

Having characterised equilibria for the two auction formats, we turn to a comparison of equilibrium outcomes.

[13] The crucial amendment to the model is thus the ability of the large firm to reduce its capacity after observing the capacity choice of its smaller rival (the small firm's opportunity to dispose of capacity is therefore not strictly necessary). It would seem that any generalisation of the model with this feature – for example, a sequential move structure with an arbitrary order of moves – would lead to the same result. While such generalisations would tend to make the model more realistic – in the sense that it is typically possible, at any time, to reduce available capacity, for example by mothballing – we choose here to concentrate attention on a simpler set up with the desired feature.

Both auction formats result in the same level of aggregate investment, as determined by the first-order condition of the large firm, which is identical in the two auctions. Unless the market reserve price P is set equal to consumers' per unit gross utility v, the marginal return to extra capacity is below the marginal social benefit; hence, there is under-investment with respect to the first best.

PROPOSITION 7. *Aggregate capacity equals* $G^{-1}[1-(c/P)]$ *in both auctions. Hence, unless* $P = v$, *both auction formats result in under-investment relative to the first best.*

In other words, ignoring price levels – which only represent a transfer between consumers and producers – total welfare is the same under both formats. However, if the reward to capacity at the margin is less than consumers' willingness to pay, that is, $P < v$, welfare is below the first-best level.

Since capacity may be allocated differently between the two firms, prices – and hence the distribution of surplus between consumers and producers – may differ across auction formats. To get further insights into these issues, in the remainder of this Section we concentrate attention on uniformly distributed demand.

PROPOSITION 8. *Suppose demand is uniformly distributed. Then*

(*i*) *the discriminatory auction results in more capacity asymmetry than the uniform-price auction,*
(*ii*) *expected prices are higher in the uniform-price auction than in the discriminatory auction and*
(*iii*) *consumer surplus is thus greater in the discriminatory auction.*

While the resulting market structure is more concentrated in the discriminatory than in the uniform-price auction, prices are nevertheless higher in the latter auction. Since the small firm is smaller with the discriminatory auction, the incidence of Low Demand realisations is lower; taken in isolation, this implies that prices tend to be higher in the discriminatory auction. However, for High Demand realisations competition is fiercer and prices lower in the discriminatory action. With uniformly distributed demand, the latter effect outweighs the former and hence expected prices are lower with the discriminatory than with the uniform-price format. Since output is identical in the two auctions in all contingencies, it follows that consumer surplus is higher in the discriminatory auction. As the difference in expected prices is increasing in the market reserve price P, the gain to consumers from moving from the uniform-price to the discriminatory format is increasing in P.

We conclude this Section by comparing outcomes when the market reserve price has been set so as to maximise consumer surplus.

PROPOSITION 9. *Suppose demand is uniformly distributed. Then the market reserve prices that maximise consumer surplus satisfy*

$$c < P^u < P^d < v.$$

At these market reserve prices,

$$K^u < K^d < K^{\mathrm{FB}} \quad \textit{and} \quad W^u < W^d < W^{\mathrm{FB}}.$$

From consumers' perspective, optimal market reserve prices exceed the unit cost of capacity c and are below consumers' maximum willingness to pay v. As, for a given P, profits and prices are higher in the uniform-price than in the discriminatory auction, the market reserve price that maximises consumer welfare is lower in the former than in the latter. It follows that, at such reserve prices, capacity is larger in the discriminatory auction, and so is total welfare.

2. Extensions and Variations

The model developed in the previous Section is intentionally kept simple so as to highlight the economic mechanisms driving the main results. One of these simplifications concerns the number of competing firms, which is fixed at two. An extension to more than two firms is straightforward (albeit somewhat cumbersome); in particular, Fabra *et al.* (2006) demonstrate that, with suitable redefinition of terms, outcomes of the pricing stage can be characterised in essentially the same way independently of the number of firms, while von der Fehr and Harbord (1998) demonstrate (for the uniform-price auction) that the essential features of the overall capacity game (such as asymmetric capacity choices) carry over from duopoly to oligopoly. Since, in the basic model, inefficient investment is due to the price cap and not to market power, total installed capacity is independent of the number of firms. Hence, the number of firms (and auction format) only affect the distribution of a given capacity among firms. Indeed, the analysis would remain valid even with an endogenous number of firms, so long as this number was limited (say, due to fixed costs or government regulations).

If one were to allow for entry at any scale and a complete fragmentation of the industry, prices would be driven to marginal cost except when capacity were fully utilised. This would collapse the set of demand realisations to Low Demand and Very High Demand only, therefore eliminating the impact of pricing rules and the asymmetric nature of capacity choices.

In practice, most developed electricity industries seem trapped in a concentrated structure even after markets have been opened up; for instance, the England and Wales electricity industry retained its duopoly nature for more than a decade, even in the presence of entry and capacity adjustments. We therefore believe the assumption of a concentrated market structure does have some relevance and so below we maintain the duopoly assumption while considering alternative formulations in other dimensions.

2.1. *Long-lived Bids*

So far it has been assumed that price competition takes place after demand is realised and observed. The assumption that firms know demand when they set prices is a reasonable approximation for markets in which prices are set for short periods of time, say for hourly or half-hourly periods; given the relatively high persistence of demand and the very high accuracy with which demand can be forecasted, market players will in effect be able to foresee the level of demand when they prepare their bids. Nevertheless, even in such circumstances some variation or uncertainty around expected values remains; moreover, in markets in which prices are set for longer periods of time, demand will typically vary considerably over the pricing period and then the assumption that demand is fixed and known is not appropriate.

In this Section we relax the assumption that demand is fixed and known when prices are set. We demonstrate that the fundamental insights of our earlier analysis carry over to settings with demand uncertainty (or demand variation) at the pricing stage.

Assume that, after investment has been made but before prices are set, firms observe a public signal *s*. Conditional upon *s*, demand θ is distributed according to the distribution G_s on $[\underline{\theta}_s, \bar{\theta}_s] \subset [0, 1]$. Such a formulation accommodates the two main sources of demand variation in electricity markets: first, demand varies across time in a systematic manner due to time-of-day, week and year (seasonal) effects and secondly, demand at each point in time is subject to random shocks due, say, to changes in weather conditions. The extent of variation (or resolution of uncertainty) at the pricing stage depends both on the duration of bids and their lead-time: for example, with 'real-time' bidding for half hours up to an hour before operation, there will be little or no relevant variation in demand; however, with day-ahead bids that remain good for a whole day, demand will vary considerably over the pricing period.

From the analysis in von der Fehr and Harbord (1993), it follows that the extension to demand uncertainty at the pricing stage does not affect the nature of equilibrium so long as the demand support falls entirely within one of the regions defined in Propositions 1 and 4. Equilibrium is only affected if the demand support extends over more than one of these regions and, more specifically, when demand may be both below and above the capacity of the small firm, in which case no pure-strategy equilibrium exists. Therefore, rather than attempting a full generalisation we consider the extreme opposite case of the one analysed above: instead of assuming that demand is known and fixed at the pricing stage, that is, $\underline{\theta}_s = \bar{\theta}_s = \theta$, we now assume that no information is revealed between the two stages, that is, $\bar{\theta}_s = 0$, $\bar{\theta}_s = 1$ and $G_s(\theta) = G(\theta)$.[14] As we shall see, while outcomes for this 'long-lived bids' formulation differ quantitatively from those of the 'short-lived bids' formulation, the qualitative conclusions remain unchanged.

Equilibrium at the pricing stage differs from the case in which bids are short-lived. In particular, two forces destroy any candidate pure-strategy equilibrium: on the one hand, a higher price translates into higher profits if demand turns out to exceed aggregate capacity; on the other hand, pricing high reduces a firm's expected sales (von der Fehr and Harbord, 1993). Therefore, the only equilibrium is in mixed strategies, and it is characterised next.

Proposition 10. *Suppose bids are long-lived. Under both auction formats, for given capacities $k_i \leq k_j \leq 1$, a pure-strategy equilibrium does not exist. In the unique mixed-strategy equilibrium, firms choose prices from a common support, with a lower bound strictly above (zero) marginal costs and an upper bound equal to P. If $k_i \neq k_j$, the firm with the larger capacity bids less aggressively (i.e. plays prices below any threshold with lower probability) than the firm with the smaller capacity; in particular, the firm with the larger capacity plays P with positive probability.*

At the unique equilibrium, the large firm plays a mass point at *P*, so that it receives the same profits as if it served residual demand at *P* with probability one; in expected terms, these profits are the same as with short-lived bids. The small firm's profits differ

[14] Note that this amounts to assuming that the variation in demand over the pricing period corresponds to that over the lifetime of investment.

from the profits it makes with short-lived bids. Nevertheless, it preserves features that account for the non-existence of a symmetric equilibrium in capacity choices; in particular, the small firm's returns to investment are lower than those of the large firm since the small firm takes into account that an increase in its capacity would affect the aggressiveness of the pricing behaviour of its rival.

Although a number of the results do generalise, for tractability in what follows we limit attention to the case in which G is uniform. Equilibrium capacity choices under the two auction formats may be characterised as follows.

Proposition 11. *Suppose that bids are long-lived and demand is uniformly distributed. Under each auction format, exactly two pure-strategy equilibria in capacity choices exist, one with* $(k_1, k_2) = (k^{a+}, k^{a-})$ *and the other with* $(k_1, k_2) = (k^{a-}, k^{a+})$, *where* $k^{a-} < k^{a+}$, *and* $a = d,u$ *denotes discriminatory and uniform-price format, respectively. At equilibrium, aggregate capacity is* $K^a = 1-(c/P)$, $a = d,u$.

The next Proposition compares equilibrium outcomes across auction formats.

Proposition 12. *Suppose demand is uniformly distributed. With long-lived bids, the discriminatory auction generates the same aggregate capacity, it induces a more skewed capacity distribution and it results in lower expected prices than the uniform-price auction.*

The comparison across auction formats therefore corresponds to that with short-lived bids (Propositions 7 and 8). However, the fact that the discriminatory auction performs better than the uniform-price auction contrasts with results for the case in which capacities are taken as given. With *ex ante* symmetric firms, fixed capacities and long-lived bids, the uniform-price and the discriminatory auctions yield equal expected prices (Fabra *et al.*, 2006); when capacities are endogenous, this is no longer the case.

Comparing equilibrium outcomes across bid and auction formats allows us to conclude the following:

Proposition 13. *Suppose demand is uniformly distributed. Aggregate capacity is the same under all four possible combinations of bid and auction formats. However, aggregate profits – and hence expected prices – are the lowest under the discriminatory auction with short-lived bids.*

The degree of resolution of demand uncertainty at the pricing stage – or bid format – has no impact on overall capacity. Given that, for a specific bid format, aggregate capacity is also the same across auction formats (Propositions 7 and 12), it follows that all four possible combinations of bid and auction formats yield the same level of aggregate capacity. Nevertheless, bid and auction formats alter the way in which total capacity is distributed among firms, thereby affecting market concentration. In perhaps the most relevant case, when the market reserve price is not extremely high as compared to capacity costs (specifically, $c/P > 0.093$), the capacity distribution becomes less concentrated under the discriminatory format (where concentration tends to be higher in any case) and more concentrated under the uniform-price format (where concentration is less). Hence, moving from short-lived to long-lived bids tends to reduce the difference between the two auction formats.

For a given bid format, profits – and hence consumer prices – are lower under the discriminatory format than under the uniform-price format (Propositions 8 and 12). Furthermore, since profits in the discriminatory format are higher with long-lived bids than with short-lived bids, it follows that out of the four possible combinations of bid and auction formats, prices are the lowest under the discriminatory auction with short-lived bids. Hence, the combination of a reasonable price cap, short-lived bids and the discriminatory format produces the most favourable outcome from consumers' point of view.

2.2. *Equilibrium Selection*

As stated in Proposition 4, in the uniform-price auction there is a multiplicity of equilibria in the pricing subgame for High Demand realisations in Region II. We concentrated attention on the equilibrium in which the large firm bids high, which may be justified by seeing the model as the limit of a more general set up with demand uncertainty at the pricing stage (Proposition 5). For completeness, we now demonstrate that all continuation equilibria lead to essentially the same qualitative outcomes.

Consider first the class of correlated equilibria, such that in the uniform auction, for High Demand realisations in Region II, the equilibrium in which Firm i bids high will be played with probability ρ_i, with $\rho_1 + \rho_2 = 1.$[15]

PROPOSITION 14. *In the uniform-price auction, if firms play the correlated equilibrium at the pricing stage, a symmetric equilibrium in capacity choices does not exist. Hence, at any candidate equilibrium, firms choose different capacities. Furthermore, aggregate capacity K is characterised by the condition*

$$1 - G(K) + (1 - \rho_i)[G(K) - G(k^+) - k^- g(k^+)] = \frac{c}{P},$$

where $k^+ = k_i > k^- = k_j$.

Here we sketch the main argument supporting Proposition 14. At the capacity-investment stage, expected profits of firm i, $i = 1, 2$, $i \neq j$, now become

$$\pi_i^u(k_i, k_j) = \begin{cases} \pi_i^{u-} & \text{if } k_i \leq k_j \\ \pi_i^{u+} & \text{if } k_i \geq k_j, \end{cases}$$

[15] These equilibria may be justified by assuming that, at the outset of the pricing stage, firms observe the outcome of a public signal, $\tilde{\rho}$, uniformly distributed on [0,1], which allows them to coordinate on either of the two price equilibria; specifically, in High Demand Region II, an equilibrium in which Firm 1 bids high is played whenever $\tilde{\rho} \leq \rho$, where ρ is a constant independent of installed capacity levels. Since both strategy profiles constitute a Nash equilibrium, such a random coordination on each of them is also an equilibrium. This is the idea that underlies the concept of correlated equilibrium proposed by Aumann (1974). A public randomising device expands the set of Nash equilibria, so that any convex combination of the Nash equilibria in the second stage is an equilibrium. This allows firms to achieve any point in the convex hull of the set of continuation payoffs. Furthermore, firms play a continuation game with payoffs on the Pareto frontier of the convex hull.

where

$$\pi_i^{u-} = P\left[\int\limits_{k^-}^{k^+} k^- \mathrm{d}G(\theta) + \int\limits_{k^+}^{K} [(1-\rho_i)k^- + \rho_i(\theta - k^+)]\mathrm{d}G(\theta) + \int\limits_{K}^{1} k^- \mathrm{d}G(\theta)\right] - ck^-,$$

$$\pi_i^{u+} = P\left[\int\limits_{k^-}^{k^+} (\theta - k^-)\mathrm{d}G(\theta) + \int\limits_{k^+}^{K} [(1-\rho_i)k^+ + \rho_i(\theta - k^-)]\mathrm{d}G(\theta) + \int\limits_{K}^{1} k^+ \mathrm{d}G(\theta)\right] - ck^+.$$

Since $\pi_i^{u-} = \pi_i^{u+}$ at symmetric capacity pairs, the expected-profit function is everywhere continuous. Marginal returns to investment differ for large and small firms, thus creating a kink in firms' profit functions; in particular, the partial derivative of the profit function of firm i with respect to its own capacity 'jumps up' at the point where capacities are identical:

$$\lim_{k_i \uparrow k} \frac{\partial \pi_i^{u+}}{\partial k_i} - \lim_{k_i \downarrow k} \frac{\partial \pi_i^{u-}}{\partial k_i} = P(1-\rho_i)kg(k) > 0.$$

As a result, best-replies do not cross the diagonal, implying that there cannot exist a symmetric equilibrium in capacity choices. Finally, aggregate capacity exceeds (falls below) the level $G^{-1}[1-(c/P)]$ when the demand distribution is convex (concave), that is, $G(K) > (<)\, G(k^+) + k^- g(k^+)$.

Further equilibrium characterisation is difficult for general demand distributions G and we therefore turn to the uniform distribution. Without loss of generality, we set $i = 1$ for all $\rho_1 = \rho \leq \frac{1}{2}$, so that the probability with which Firm 2 bids high is $1 - \rho$.

Proposition 15. *In the uniform-price auction, when demand is uniformly distributed,*

(*i*) *there exists* $\hat{\rho} \in (0, \frac{1}{2})$, *such that if* $\rho \in [0, \hat{\rho})$, *there is a unique pure-strategy Nash equilibrium in capacity choices; it has the form* (k_1^{u+}, k_2^{u-}). *Otherwise, if* $\rho \in [\hat{\rho}, \frac{1}{2}]$, *there are exactly two pure-strategy equilibria in capacity choices, one with* (k_1^{u+}, k_2^{u-}) *and the other with* (k_1^{u-}, k_2^{u+}). *In either case,*

$$k_1^{u+} = \frac{2-\rho}{3-\rho}\left(1 - \frac{c}{P}\right) > k_2^{u-} = \frac{1}{3-\rho}\left(1 - \frac{c}{P}\right),$$

$$k_1^{u-} = \frac{1}{2+\rho}\left(1 - \frac{c}{P}\right) < k_2^{u+} = \frac{1+\rho}{2+\rho}\left(1 - \frac{c}{P}\right).$$

(*ii*) *Aggregate equilibrium capacity is* $K^u = 1 - (c/P)$.

A pure-strategy Nash equilibrium always exists in which one firm – here called Firm 1 – invests more than its rival. For a range of values of the parameter ρ, this equilibrium is unique. For other parameter values, another pure-strategy equilibrium exists in which the other firm – Firm 2 – invests more.

In any equilibrium, independently of the value of ρ, aggregate capacity equals $1 - (c/P)$ but the degree of capacity asymmetry depends on which equilibrium is played, as well as on the value of ρ. For $\rho = \frac{1}{2}$, the two equilibrium outcomes mirror each other, that is, $k_1^{u+} = k_2^{u+} > k_1^{u-} = k_2^{u-}$. For smaller ρ, Firm 1 is less likely to bid high and hence has a larger probability of being despatched at full capacity; therefore, its incentive to expand capacity is stronger. Consequently, as ρ is reduced, Firm 1 becomes larger, and Firm 2 correspondingly smaller, leading to more asymmetry if (k_1^{u+}, k_2^{u-}) is played but less asymmetry if (k_1^{u-}, k_2^{u+}) is played. When $\rho = 0$ – that is, when firms coordinate on the equilibrium in which Firm 1 never plays high – capacity asymmetry is at its maximum; here Firm 1 is twice as large as Firm 2.

Expected price depends on the size of the small firm only; the larger it is, the higher is the probability that price equals marginal costs rather than the market reserve price P. If the equilibrium (k_1^{u+}, k_2^{u-}) is played, expected price is decreasing in ρ, whereas if (k_1^{u-}, k_2^{u+}) is played it is increasing in ρ. Since, for $\rho = \frac{1}{2}$, expected prices are the same in both equilibria, it follows that when $\rho < \frac{1}{2}$ the (k_1^{u+}, k_2^{u-})-equilibrium results in a higher expected price than the (k_1^{u-}, k_2^{u+})-equilibrium. In other words, prices tend to be higher when it is more likely that an equilibrium is played in which the small firm prices high, because this decreases the incentive of the small firm to expand its capacity, thereby reducing the range of demand realisations at which the price is competed down to marginal cost.

We conclude that aggregate investment and, therefore, total welfare, does not depend on whether firms coordinate on one of the pure-strategy equilibria or whether they play both with positive probability. Market concentration is lower when firms play a correlated equilibrium because such an equilibrium involves weaker incentives for the large firm to expand capacity. The increase in the relative size of the small firm, which implies greater incidence of Low Demand realisations, tends to reduce prices; in particular, prices are at their lowest when both firms are equally likely to bid high, that is, when $\rho = \frac{1}{2}$. Since, even in this case, the uniform-price auction results in higher prices and lower consumer surplus than the discriminatory auction, it follows that this result holds independently of which equilibrium is considered.

If firms play a mixed-strategy equilibrium at the pricing stage for demand realisations in High Demand Region II, the qualitative nature of the equilibrium of the overall game is essentially the same as when we consider pure strategies only. This last result on equilibrium selection is summarised in the following Proposition, where we have again restricted attention to uniformly distributed demand (although the results would seem to generalise):

Proposition 16. *In the uniform-price auction, for High Demand realisations in Region II, mixed-strategy equilibria also exist at the pricing stage. When firms play a mixed-strategy equilibrium for High Demand realisations in Region II, equilibria in the overall game have the same qualitative characteristics as when firms play (correlated) pure strategies. In particular,*

(*i*) *Equilibrium capacities are asymmetric.*
(*ii*) *Aggregate equilibrium capacity is* $K^u = 1 - (c/P)$.
(*iii*) *For a given capacity configuration, industry profits and prices are lower than when firms play (correlated) pure strategies.*
(*iv*) *Industry profits and prices are nevertheless higher than in the discriminatory auction.*

There turns out to be a very close connection between the set of correlated equilibria and the set of mixed-strategy equilibria. In particular, as far as capacity configurations are concerned, each outcome in a correlated equilibrium corresponds to an outcome in a mixed-strategy equilibrium, and *vice versa*. In other words, whether firms randomise over which firm should bid high and which firm should bid low, or whether each firm individually randomises over its choice of bid, is immaterial as far as investment incentives are concerned.[16]

2.3. *Price-responsive Demand*

So far we have restricted attention to the case in which demand is completely price inelastic, both in the short and long run. We now extend the basic model by introducing a long-term demand function that depends on the retail price. For analytical convenience, we assume aggregate demand has the multiplicative form $\theta D(p)$, where D is deterministic and decreasing in the retail price, p, and (as before) θ is a stochastic parameter uniformly distributed on the unit interval and publicly observed before prices are set.

While with a price-inelastic formulation it is not essential to specify the exact form of consumer payments, here we need to be explicit about the determination of the retail price. We assume that the retail price is set so that the market clears in average or expected terms, that is, payments by consumers exactly cover payments to producers:

$$p\left[\int_0^{K/D(p)} \theta D(p)\,\mathrm{d}\theta + \int_{K/D(p)}^{1} K\,\mathrm{d}\theta\right] = \pi_1 + \pi_2 + cK. \tag{7}$$

This formulation may be given several interpretations. For instance, free entry and perfect competition among retailers would drive their profits to zero, so that (7) would hold. Alternatively, a regulated retailer operating under a zero profit condition would also set such retail prices. Note that, for given capacities, an auction format that leads to lower payments to producers will result in lower retail prices, more demand and hence higher welfare.

Consider the impact on the large firm's profit of a marginal increase in its capacity under the discriminatory and uniform-price auctions (recall that the large firm's first order condition for profit maximisation is the same under both auction formats, and it has to be satisfied in equilibrium):[17]

$$\frac{\partial \pi_i^{a+}}{\partial k^+} = P\frac{\partial p}{\partial k^+}\left[\int_{k^-/D(p)}^{K/D(p)} \theta D'(p)\mathrm{d}\theta\right] + P\left[1 - \frac{K}{D(p)}\right] - c, \quad a = d, u. \tag{8}$$

Compared to the case in which demand is price-inelastic, there are two additional effects. First, as captured by the second element on the right-hand side in (8), the probability that the marginal unit of capacity is despatched depends on the level of demand and hence on market price; the lower is price, the higher is the probability

[16] The fact that the mixed-strategy equilibria generate lower profits but the same aggregate capacity as the pure or correlated equilibria provides an additional example of how investment incentives depend on marginal profits rather than profits *per se*.

[17] The derivation of this expression and other results essentially follow those for the model developed in Section 2; see the Technical Appendix S1 for details.

that capacity is fully utilised. To the extent that prices are lower in the discriminatory as compared to the uniform-price format, this effect tends to stimulate investments more in the former than in the latter.

Secondly, as captured by the first element in (8), there is what we may term a 'market-size' effect; that is, capacity affects retail prices and hence demand. Whether this effect stimulates or depresses investment incentives depends on whether increases in the large firm's capacity tend to reduce or increase retail prices; that is, it depends on the sign of $(\partial p)/(\partial k^{+})$. The link between capacities and retail prices is complex: a capacity increase allows for an expansion of consumption (the left-hand side of (7)) but also raises total costs and affects producers' profits (the right-hand side of (7)); the overall impact depends on which of these effects dominates. In the uniform-price auction, an increase in the large firm's capacity unambiguously raises retail prices, implying that overall capacity will be smaller when demand is price-elastic. However, in the discriminatory auction, it is not, in general, possible to sign $(\partial p/\partial k^{+})$. However, at least with a linear demand function, numerical simulations demonstrate that an increase in the large firm's capacity induces a reduction in the retail price. Hence, whereas the market-size effect tends to discourage investments in the uniform-price auction, it has the opposite effect in the discriminatory auction.

In sum, both effects point in the same direction, implying that aggregate investments tend to be greater under the discriminatory format when demand is price-responsive in the long run.

3. Conclusions

There is a long-standing debate on the question of whether market performance depends on market structure or on market design. While previous studies have tended to analyse each of these features in isolation, in this article we have tried to shed light on the interaction between the two by analysing how alternative market designs affect investment incentives and hence market structure.

For this purpose, we have extended earlier work by Fabra *et al.* (2006) who demonstrated that, in a model which captures essential features of price setting in deregulated electricity markets, the discriminatory price format consistently leads to lower prices than the uniform-price format. This analysis, which was based on the assumption that installed capacities were given, suggested three sets of issues for future research. First, given that market prices depend on the pricing format, and given that price signals influence investment incentives, how does the choice of auction format affect capacity investment? Second, does allowing for endogenous capacities affect the relative performance of the two market designs? And, third, how do price caps – which mitigate market power but also reduce the profitability of investment – affect overall market performance once the effect on investment incentives is accounted for; in particular, is it still true that consumers are better off the more stringent is the price cap?

On the first set of issues, we have demonstrated that, although the discriminatory auction generally leads to more competitive behaviour and lower prices than the uniform-price auction, incentives to invest are not necessarily weaker; indeed, investment incentives may be greater with the discriminatory format.

On the second set of issues, relating to market performance, the relative supremacy of the discriminatory auction as far as prices are concerned tends to be true even when we allow for endogenous capacities. This is the case even though the discriminatory format consistently induces a more concentrated market structure.

On the third set of issues, our results confirm the widespread conjecture that eliminating price caps suffices for the market to deliver efficient outcomes.[18] However, from a consumer point of view, there is a trade-off between prices and capacity availability: a larger capacity, which allows for greater consumption, comes at the cost of higher prices. Hence, consumers prefer an effective price cap even though it might result in more demand rationing. The introduction of a price cap can therefore benefit consumers; however, it is never optimal to lower the price cap to a level that eliminates all profits. The fact that the discriminatory format results in greater consumer surplus, implies that the optimal price cap is lower there than under the uniform-price format, resulting in more efficient investment and less demand rationing.

Admittedly, our model is highly stylised and we would not want to over-emphasise the empirical relevance of the theoretical results. Nevertheless, some of the insights appear quite robust and seem to point to more fundamental characteristics of the workings of markets in general and deregulated electricity markets in particular. One of these has already been pointed out: lower prices do not necessarily imply poorer investment incentives; profit-maximising firms are not concerned with profit levels *per se* but rather with the effect of capacity choices on the level of profits.

A second apparently robust result is the asymmetry of investment incentives, leading to asymmetrically sized firms. Due to such asymmetries, incumbency size advantages may be maintained also after market-based competition has taken effect. A natural question to analyse next is to which extent different auction formats favour investment by the current market leader, thereby leading to increasing asymmetries in the long-run.[19]

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Additional Supporting information may be found in the online version of this article:

Appendix S1. Proof of Propositions.

Please note: The RES and Wiley-Blackwell are not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the authors of the article.

[18] See Joskow (2007) for a discussion of how price caps create the so-called 'missing money' problem in electricity markets. More generally, Earle *et al.* (2007) show that an increase in the price cap might be welfare improving when firms compete *à la* Cournot under demand uncertainty.

[19] Athey and Schmutzler (2001) analyse a model of oligopolistic competition with ongoing investment and derive conditions under which the leading firms invest more, thereby reinforcing their initial market dominance.

References

Amir, R., García, F. and Knauff, M. (2010). 'Symmetry-breaking in two-player games via strategic substitutes and diagonal nonconcavity: a synthesis', *Journal of Economic Theory*, vol. 145(5), pp. 1968–86.

Anwar, A.W. (2006). 'Single or multiple pricing in electricity pools?', Working Paper, University of Edinburgh.

Athey, S. and Schnutzler, A. (2001). 'Innovation and the emergence of market dominance', *Rand Journal of Economics*, vol. 32(1), pp. 1–26.

Aumann, R. (1974). 'Subjectivity and correlation in randomized strategies', *Journal of Mathematical Economics*, vol. 1(1), pp. 67–96.

Belleflamme, P. and Peitz, M. (2010). 'Platform competition and seller investment incentives', *European Economic Review*, vol. 54(8), pp. 1059–1076.

Bracewell, R. (1999). *The Fourier Transform and Its Applications.* New York: McGraw-Hill.

Crampes, C. and Creti, A. (2005). 'Capacity competition in electricity markets', *Economia delle Fonti di Energia e dell' Ambiente*, vol. 48(2), pp. 59–83.

Cramton, P. and Stoft, S. (2007). 'Why we need to stick with uniform-price auctions in electricity markets', *Electricity Journal*, vol. 20(1), pp. 26–37.

Earle, R., Schmedders, R. and Tatur, T. (2007). 'On price caps under uncertainty', *Review of Economic Studies*, vol. 74(1), pp. 93–111.

Evans, J. and Green, R. (2002). 'Why did British electricity prices fall after 1998 ?', Working Paper, University of Hull.

Fabra, N., von der Fehr, N.-H. and Harbord, D. (2006). 'Designing electricity auctions', *Rand Journal of Economics*, vol. 37(1), pp. 23–46.

Federico, G. and Rahman, D. (2003). 'Bidding in an electricity pay-as-bid auction', *Journal of Regulatory Economics*, vol. 24(2), pp. 175–211.

Fumagalli, C., Motta, M. and Ronde, T. (2009). 'Exclusive dealing: the interaction between foreclosure and investment promotion', Working Paper, CEPR.

Hviid, M. (1990). 'Sequential capacity and price choices in a duopoly model with demand uncertainty', *Journal of Economics*, vol. 51(2), pp. 121–44.

Inderst, R. and Wey, C. (forthcoming). 'Countervailing power and dynamic efficiency', *Journal of European Economic Association.*

Joskow, P. (2007). 'Competitive electricity markets and investment in new generating capacity'. in (D. Helm, ed.), *The New Energy Paradigm*, pp. 76–122, Oxford: Oxford University Press.

Le Coq, C. (2002). 'Strategic use of available capacities in the electricity spot market', Working Paper, Stockholm School of Economics.

Newbery, D. (2003). 'The effect of NETA on wholesale electricity prices', Working Paper, University of Cambridge.

Reynolds, S. and Wilson, B. (2000). 'Bertrand-Edgeworth competition, demand uncertainty, and asymmetric outcomes', *Journal of Economic Theory*, vol. 92(1), pp. 122–41.

Segal, I.R. and Whinston, M.D. (2000). 'Exclusive contracts and the protection of investments', *Rand Journal of Economics*, vol. 31(4), pp. 603–33.

Topkis, D. (1979). 'Equilibrium points in nonzero sum n-person submodular games', *SIAM Journal of Control and Optimization*, vol. 17(3), pp. 773–87.

Úbeda, L. (2007). 'Capacity and market design: discriminatory versus uniform auctions', Working Paper, Universidad de Alicante.

von der Fehr, N.-H. and Harbord, D. (1993). 'Spot market competition in the UK electricity industry', Economic Journal, vol. 103(418), pp. 531–46.

von der Fehr, N.-H. and Harbord, D. (1998). 'Capacity investment and competition in decentralized electricity markets', Working Paper, University of Oslo.