Capacity Mechanisms and Effects on Market Structure

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Abstract

This article studies the effects of capacity mechanisms and price caps on market structure in electricity markets with dominant firms and a competitive fringe. While strict price caps mitigate the impact of market power for fixed capacities, we find a counter-veiling dynamic effect. Given endogenous investments within capacity mechanisms, lower price caps increase market concentration and thus lead to more frequent capacity withholding in spot markets, yielding higher total profits for the dominant firms. The results robustly hold for different capacity mechanisms, including capacity auctions, direct subsidies and strategic reserves.

Keywords:

Electricity Markets; Market Design; Market Structure; Capacity Mechanisms; Competitive Fringe

JEL classification: L11, L51, L94, D47

1. Introduction

The need for and the design of capacity mechanisms have been controversially discussed during recent years. Researchers as well as policymakers are concerned that there may not be sufficient investment incentives for adequate generation capacity on the wholesale market.[1] As the European Commission (2012) summarizes, "ensuring generation adequacy in electricity markets has become an increasingly visible topic in the policy discussion".

The reason for the concerns and the subsequent debate about capacity mechanisms is often based on the following line of argument: Electricity markets are characterized by a fluctuating price-inelastic demand and limited storage possibilities, which can cause high price volatility and facilitate the exercise of market power.[2] Therefore, price caps or related measures are often proposed or are already implemented to reduce the potential of market power in the spot market. However, binding price caps reduce spot market revenues and may therefore lead to a lack of investments in the long term. This problem is often referred to as the "missing money" problem and is intensively discussed in economic literature, e.g., by Hogan (2005), Cramton and Stoft (2006) or Joskow (2008). For this reason, capacity mechanisms have been introduced or are currently being debated in many liberalized electricity markets. Typically, capacity mechanisms consist of some form of capacity payments and come along with price caps or similar measures to address the missing money and the market power problems.

The purpose of this paper is to analyze the effects of capacity mechanisms on the market structure. In many electricity markets, the market structure is given by a small group of large incumbent firms (or a single large firm) which competes with many small competitive firms. We investigate such markets using a model with fluctuating price-inelastic electricity demand, in which dominant firms face a competitive fringe of small firms that can freely enter the market and act as price takers. Investments take place in the first stage, followed by firms selling electricity on the spot market. We analyze how the level of price caps and capacity mechanisms affect the market structure, specified by the resulting market shares, the profits of the dominant and competitive firms as well as the frequency of capacity withholding on the spot market.[3] Focus is centered on three common forms of capacity mechanisms: capacity auctions, subsidies and strategic reserve.[4]

We find the following main result, which holds robustly for different forms of capacity mechanisms: If the price cap decreases, the market share and profits of the dominant firms increase and the frequency of capacity withholding in the spot market also increases. This means that even though lower price caps reduce the potential for static market power exertion, there is a robust counter-veiling force such that a reduction of price caps increases market concentration as long as total capacity is fixed by a capacity mechanism. The main intuition is as follows: When fixing a target level of total capacity, a lower price cap means that spot market revenues decrease and a larger fraction of firm revenues must come from the capacity mechanism. This shift in revenue streams benefits the dominant firms relative to the competitive fringe for the following reason: In order to raise spot market profits, dominant firms hold back capacity to increase spot market prices, thus having a lower capacity utilization in peak price periods. As a consequence the average revenue per capacity on the spot market of the dominant firms is lower than that of the competitive firms. On the other hand, a dominant firm and a competitive firm benefit equally from the capacity payments.

The effects of price caps on investments, market outcomes and market power have been studied by Zoettl (2011) and Fabra et al. (2011). Zoettl (2011) analyzes the impact of reduced scarcity prices on investment decisions of strategic firms in base-load and peak-load technologies. He shows that an appropriately set price cap can increase investments in peak-load capacity without reducing base-load investments. Fabra et al. (2011) extend the analysis of Fabra et al. (2006) by analyzing strategic investment incentives in electricity markets in a duopoly model. They compare the impact of uniform-price vs. discriminatory auction formats and price caps on investment incentives. They find that although prices are lower in discriminatory auctions, the aggregated capacity is the same for both auction formats. Grimm and Zoettl (2013) analyze strategic investment decisions and compare different spot market designs. They find that investment incentives decrease if spot markets are designed in a more competitive fashion. Our main contribution to this literature is that we explicitly consider capacity mechanisms and their effects on the market structure.

The remainder of this paper is structured as follows: In Section 2, we describe the model defined by a single dominant firm and a competitive fringe and discuss the main results for a capacity auction. Section 3 illustrates robustness of the results for different capacity mechanisms. Section 4 shows that the results also apply for multiple dominant firms. Section 5 concludes. Proofs are relegated to the Appendix.

2. The Model

We consider a model with a strategic dominant firm m and a competitive fringe f consisting of many small firms that act as price takers. There are two stages: In the first stage, firms perform long-term capacity investments. In the second stage, firms compete in the electricity spot market, which is characterized by fluctuating price-inelastic electricity demand.

During the investment stage, the dominant firm and fringe firms build up their capacities $x_m \in [0,1]$ and $x_f \in [0,1]$, respectively. The structure of the investment game varies between the different capacity mechanisms described below. The fixed costs per unit of capacity (including investment and fixed operation costs) are denoted by k_m and k_f. We allow the dominant firm to have a fixed cost advantage due to expert knowledge or economies of scale, i.e., $k_m \leq k_f$.[5] Variable per unit costs of electricity generation are identical for all firms and denoted by c.

2.1. Spot Market Behavior

We first describe the spot market and characterize its outcome. Electricity demand is given by a non-negative random variable D with distribution function G and a continuously differentiable density function g. There is a maximum level of demand, which we normalize to 1. We assume that $g(D)$ is strictly positive for all $D \in [0,1]$. One can interpret G as the distribution of demand over a large number of hours in which spot market competition with given capacities takes place.

After observing realized demand, the dominant firm chooses an output level q_m with $q_m \leq x_m$.[6] If the sum of the fringe capacity and the dominant firm's chosen output exceeds total demand D, competition by fringe firms will drive the spot market price down to the variable costs c. Otherwise, electricity is scarce and a maximal price $\bar{P} > c$ is reached.[7] $\bar{P}$ corresponds either to a price cap determined by the regulation or to the value of lost load (VOLL), which indicates the amount that customers are willing to pay to avoid a power outage. Written compactly, the spot market prices satisfy

$$P\left(q_m, x_f, D\right) = \begin{cases} \bar{P} & \text{if } D \geq q_m + x_f \\ c & \text{if } D < q_m + x_f. \end{cases} \tag{1}$$

When demand is below the total capacity of the competitive fringe x_f, the spot market price always equals the variable generation costs c. The dominant firm then cannot influence the price level. When demand exceeds the fringe capacity, the dominant firm always has an incentive to withhold just enough capacity that scarcity drives the price up to $\bar{P}$, i.e. it then optimally chooses

$$q_m = min\left\{D - x_f, x_m\right\}.$$

For fixed x_f, the equilibrium prices on the spot market are therefore independent of the dominat firm's capacity x_m and given by

$$P = \begin{cases} \bar{P} & \text{if } D > x_f \\ c & \text{if } D \leq x_f. \end{cases} \tag{2}$$

Positive spot market profits are only achieved in periods with a peak price $P = \bar{P}$. To avoid uninteresting case distinctions, we restrict attention to the case that $x_f + x_m \leq 1$.[8] The expected variable spot market profits per capacity unit of the dominant firm and the competitive fringe are given by

$$\pi_m^s = \left(\bar{P} - c\right) \left((1 - G(x_f + x_m)) + \int_{x_f}^{x_f + x_m} \frac{D - x_f}{x_m} g(D) \, dD \right) \quad (3)$$

$$\pi_f^s = \left(\bar{P} - c\right) (1 - G(x_f)) . \quad (4)$$

To avoid uninteresting case distinctions, we henceforth make

Assumption 1. *The maximum spot market markup $\bar{P} - c$ is strictly larger than the fringe firm's fixed cost of capacity k_f.*

From Assumption 1 and equation (4), it follows that the competitive fringe builds a positive capacity $x_f > 0$. We denote the average capacity utilization (capacity factor) of the dominant firm in periods with peak price by:

$$\phi_m = \mathbb{E}_D \left[\frac{q_m}{x_m} \middle| D > x_f \right] .$$

We can then compactly write its expected spot market profits as

$$\pi_m^s = \left(\bar{P} - c\right) (1 - G(x_f)) \, \phi_m . \quad (5)$$

If fringe capacity is below the maximum demand, there are always some demand realizations in which capacity withholding is optimal for the dominant firm, which implies

$$\phi_m < 1.$$

In contrast, the fringe firms always utilize their whole capacity in peak price periods. Hence, while the dominant firm benefits from capacity withholding on the spot market, a fringe firm benefits even more. We therefore directly find

Proposition 1. *If $x_m > 0$ and $x_f < 1$, the dominant firm's expected spot market profits per capacity unit are strictly below those of a fringe firm and satisfy*

$$0 < \pi_m^s = \phi_m \pi_f^s.$$

2.2. Investments and Capacity Auctions

We assume that the regulator imposes a spot market price cap $\bar{P}$ but at the same time wants to ensure a reliability level ρ, which measures the probability that no blackout takes place due to insufficient supply, i.e.,

$$\rho \equiv \mathbb{P}(D \leq x_m + x_f).$$

In our model, fixing a reliability level is equivalent to fixing a total capacity

$$x_T \equiv x_m + x_f.$$

We investigate a market design in which the desired capacity x_T is procured in an auction that yields a uniform capacity payment to each firm that is willing to provide capacity. Capacity auctions exist in many electricity markets in the USA as well as in Central and South America. Examples include the Forward Capacity Market (ISO New England) and the Colombia Firm Energy Market (see, e.g., Cramton (2006) or Cramton (2007)). We consider a multi-unit descending bid auction. Ausubel and Cramton (2006) discuss this auction type and its application for capacity procurement. The auctioneer starts by announcing a high initial capacity payment (auction price) that is offered for each unit of capacity. At each price level, firms simultaneously announce the capacities that they are willing to build. The price is continuously decreased as long as the offered supply of capacity exceeds the demand for capacity x_T. At any given price, firms can at most offer the same amount of capacity that they had previously offered at a higher price, i.e., offered capacity levels must weakly decrease during the auction. The resulting uniform capacity payment will be the infimum of those auction prices at which the capacity offered was at least as high as capacity demand; in case of excess supply at this price, capacity is randomly allocated. Consider an auction outcome with capacities x_m, x_f and capacity payments z. A fringe firm's expected profits per capacity unit, including spot market profits, fixed cost and capacity payments, are then given by

$$\pi^f = \left(\bar{P} - c\right)\left(1 - G\left(x_f\right)\right) - k_f + z.$$

Hence, fringe profits are zero whenever fringe capacity and capacity payments satisfy the following relationship

$$z = k_f - \left(\bar{P} - c\right)\left(1 - G\left(x_f\right)\right). \tag{6}$$

Consistent with the assumption that fringe firms act as price takers and there is free entry, we assume that for any offered capacity payment z during the auction, total fringe supply is such that the zero profit condition (6) exactly holds. As capacity payments decrease during the auction, the offered fringe capacity also decreases. Figure 1 illustrates this zero profit curve as a fringe supply curve for different capacity payments.

If the dominant firm bids in all rounds some constant capacity $x_m \in [0, 1]$, we have the following auction outcome: the dominant firm receives the capacity x_m, the fringe capacity is $x_f = x_T - x_m$ and the capacity payments z are determined by the zero profit curve (6). Given the competitive bidding of the fringe firms, the dominant firm has no alternative bidding strategies that could lead to different auction outcomes than the simple strategy of bidding a constant x_m. This means that the dominant firm influences the auction outcome and the resulting capacity payments in its choice of x_m. However, its ability to exert market power in the auction is limited by the competitive behavior of the fringe who determines the auction price corresponding to each choice of x_m. By substituting the values for z and

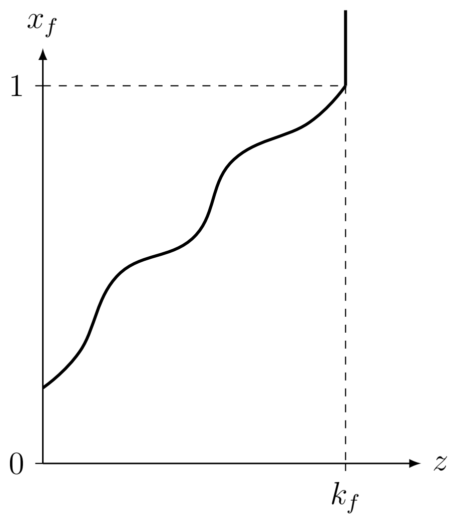

Figure 1: Illustration of the fringe capacity as function of capacity payment derived from the fringe's zero profit curve

x_f, the dominant firm's expected total profits

$$\begin{aligned}\Pi^m &= \left(\pi^s_m + z - k_m\right) x_m \\ &= \Big(\left(\phi_m\left(x_m\right) - 1\right)\left(\bar{P} - c\right)\left(1 - G\left(x_T - x_m\right)\right) + k_f - k_m\Big) x_m\end{aligned} \tag{7}$$

can be written as a function of the desired level of x_m. The dominant firm simply maximizes these profits over x_m. Without imposing further (quite strong) assumptions on the demand distribution G, the dominant firm's profit function is not concave in general. This means that the first order condition of zero marginal profits is not sufficient for an optimal capacity choice, and we cannot rely on the implicit function theorem for comparative statics. Nevertheless, using methods of monotone comparative statics (Milgrom (2004)), we can establish the following general result.

Proposition 2. *If a fixed total capacity x_T is procured in a multi-unit descending bid auction, the dominant firm's total profits Π^m, its capacity x_m and market share, as well as the frequency of capacity withholding in the spot market decrease if the price cap $\bar{P}$ increases.*

Main intuition for why the dominant firm's profits decrease in the price cap $\bar{P}$: Even though at first thought it may seem counter-intuitive that the dominant firm's expected profits are decreasing in the price cap, there is a nice economic intuition for this result. Ceteris-paribus, i.e., holding capacities x_m and x_f fixed, an increase in the price cap $\bar{P}$ increases the spot market profits of both the fringe firms and the dominant firm. Since the capacity payment z in the auction is determined by the fringe firm's zero profit, it adjusts downwards accordingly. This means that an increase in the price cap $\bar{P}$ induces a shift in the revenues from the capacity market to the spot market that is profit-neutral for fringe firms. Recall that the dominant firm makes lower expected spot market profits per capacity unit than the competitive fringe since, due to capacity withholding, the dominant firm has a lower capacity utilization $\phi_m < 1$ in times of peak prices than fringe firms. On the other hand, the dominant firm benefits as much per capacity unit from the capacity payment z as a fringe firm. Hence, a revenue shift from capacity market to spot market that is profit neutral for fringe firms reduces expected total profits of the dominant firm. Reversely, a reduction of the spot market price cap $\bar{P}$ causes a revenue shift from spot markets to capacity markets that benefits the dominant firm. This intuition is quite robust: Even if we had elastic electricity demand, the dominant firm would make lower average profits on the spot market than a fringe firm and therefore prefer revenue shifts from the spot market to the capacity market.

More detailed intuition: To gain a deeper intuition of Proposition 2, consider the derivative of the dominant firm's total profits (7) with respect to its constant auction bid x_m, taking all effects into account. It can be compactly written as[9]

$$\frac{\partial \Pi^m}{\partial x_m} = (k_f - k_m) - g(x_T - x_m)(\bar{P} - c)x_m. \tag{8}$$

To interpret this marginal profit function, consider Figure 2. Each box illustrates a

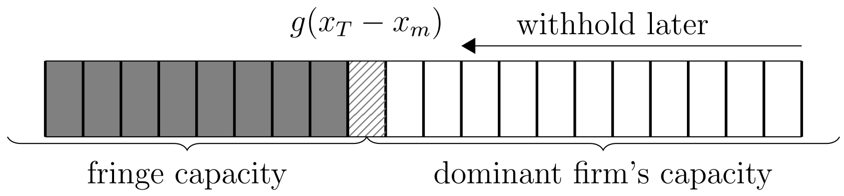

Figure 2: Illustrating the effect of a marginal capacity expansion of the dominant firm

small capacity unit, with the shaded box indicating the unit which has transferred from the fringe to the dominant firm in the event the dominant firm marginally increases its capacity x_m. If the dominant firm performs capacity withholding on the spot market, we assume w.l.o.g. that it first withholds capacity units that are more to the right in Figure 2. Since the newly acquired capacity unit is the last unit that is withheld, the dominant firm earns approximately the same expected spot market profit from this unit as the competitive fringe. Given that the fringe firms' profits from the last capacity unit are internalized in the capacity payment z, the dominant firm has a gross benefit from this extra unit equal to its fixed cost advantage $k_f - k_m$, which appears as the first term in the marginal profit function.

A marginal increase in the dominant firm's capacity x_m marginally decreases the fringe capacity x_f and therefore increases expected spot market revenues, which causes capacity payments to fall. This shift from capacity market revenues to spot market revenues decreases the dominant firm's total profits due to the intuition explained above.

This negative impact is captured by the term $-g(x_T - x_m)(\bar{P} - c)x_m$ in the marginal profit function. To understand this term, consider the case in which realized spot market demand is just slightly above the new fringe capacity, so that the dominant firm withholds all its capacity including the newly acquired capacity unit. The density $g(x_T - x_m)$ can be interpreted as a measure for the "probability" of this event occurring. The fringe firms then earn a spot market profit of $(\bar{P} - c)$ per unit, which they would not have made if the dominant firm had not expanded its capacity. This increase in fringe firms' expected spot market profits translates into a lower auction price, which reduces the capacity payments for all x_m inframarginal capacity units of the dominant firm.

This negative effect in the marginal profit function is ceteris paribus increasing in the price cap $\bar{P}$. Intuitively, this is because a higher price cap means that an increase in the dominant firm's capacity causes a stronger revenue shift from capacity markets to spot markets. For this reason the dominant firm's equilibrium capacity is decreasing in the price cap $\bar{P}$.

Necessity of fixed cost advantage for market power: We also see from (8) that it can only be profitable for the dominant firm to build a positive capacity if it has a fixed cost advantage, i.e. $k_m < k_f$. Given that a firm with market power gains fewer spot market profits than a competitive firm, it is clear that market power can only arise if the dominant firm has a cost advantage.

Welfare

Proposition 2 has the following implication on total welfare:

Corollary 1. *Given completely inelastic demand, total welfare is decreasing in the price cap* $\bar{P}$.

To understand the result, note that in our model with capacity markets, a higher market share of the dominant firm corresponds to a larger welfare level. This is because of the following reasons:

i) The total capacity x_T, and thus the frequency of blackouts, is exogenously fixed.

ii) The dominant firm has a positive capacity $x_m > 0$ if and only if it has a cost advantage over the competitive fringe. This means a higher market share of the dominant firm implies lower total costs of electricity production.

iii) Due to the perfectly inelastic electricity demand, there are no deadweight losses from the capacity withholding of a dominant firm.

On the other hand, our assumption of perfectly inelastic electricity demand is a simplification rather than an exact description of reality. In reality, some deadweight losses from capacity withholding are very plausible, which would lead to ambiguous welfare results. Ambiguous welfare results could also result if we maintain the assumption of perfectly inelastic demand but extend the model to account for uncertainty in predicted electricity demand. If the dominant firm underestimates demand, capacity withholding may cause blackouts or require excessive procurement of balancing energy from network operators. Corollary 1 illustrates, however, that an increase in market concentration is not necessarily connected to a reduction in welfare.

3. Alternative Capacity Mechanisms

This section studies the robustness of our results by considering two alternative capacity mechanisms: subsidies and strategic reserves.

3.1. Subsidies

Assume that before investments take place, the regulator fixes a uniform capacity subsidy s to encourage sufficient capacity levels. The regulator fixes a price cap $\bar{P}$ and chooses the subsidy such that the resulting equilibrium capacity x_f^* and x_m^* add up to a target level of total capacity x_T.

The total profits per unit of capacity for a fringe firm are given by

$$\pi_f = \pi_f^s - k_f + s. \tag{9}$$

We assume that fringe firms enter the market until profits are driven down to zero. This zero profit condition can be written as

$$s = k_f - \left(\bar{P} - c\right)\left(1 - G\left(x_f^*\right)\right). \tag{10}$$

For $s < k_f$, this condition uniquely determines the fringe capacity x_f^*, which is increasing in the per unit subsidies s. The fringe's equilibrium capacity does not depend on the dominant firm's capacity x_m. This is because the dominant firm always withholds sufficient capacity to drive prices up to $\bar{P}$ when $D > x_f^*$. Therefore the frequency of high prices ($P = \bar{P}$) only depends on the fringe's capacity and the distribution of demand. Consequently, it does not matter whether the dominant firm invests before, at the same time or after the competitive fringe: the resulting equilibrium capacities are the same. The dominant firm's expected profits are given by

$$\Pi^m = \left(\pi_m^s + s - k_m\right) x_m. \tag{11}$$

The dominant firm's equilibrium capacity x_m^* maximizes total profits Π^m, given the fringe's equilibrium capacity x_f^* and the previously fixed subsidy s. In contrast to the auction, the capacity payments are no longer a function of the dominant firm's capacity choice. The dominant firm's first order condition for an interior solution is given by

$$\frac{\partial \Pi^m}{\partial x_m}\left(x_m^*\right) = \left(\bar{P} - c\right)\left(1 - G\left(x_f^* + x_m^*\right)\right) - \left(k_m - s\right) = 0. \tag{12}$$

The term $k_m - s$ simply describes the net cost of an additional capacity unit. The term $\left(\bar{P} - c\right)\left(1 - G\left(x_f^* + x_m^*\right)\right)$ captures the effect of a marginal capacity expansion on spot market profits. In situations in which demand exceeds the total capacity, the additional marginal unit is sold with a markup of $\bar{P} - c$.

Independent of the form of the demand distribution G, the dominant firm's expected profits are strictly concave in x_m. Hence, the fringe's zero profit condition and the dominant firm's first order condition uniquely determine equilibrium investments for any given pair of subsidies s and price cap $\bar{P}$. It follows from (12) that for any fixed total capacity $x_T < 1$, the subsidies s must increase if the price cap $\bar{P}$ decreases. In the special case of a 100% reliability level, i.e., $x_T = 1$, subsidies must always be equal to the dominant firm's fixed cost k_m.[10]

Even though the dominant firm's first order condition is quite distinct from the one in the auction case, we find qualitatively the same comparative static results with respect to the price cap.

Proposition 3. *If the regulator uses subsidies s to fix a reliability level $\rho \in [0, 1]$, the dominant firm's total profits Π^m, its capacity x_m and market share, as well as the frequency of capacity withholding in the spot market decrease if the price cap $\bar{P}$ increases.*

The intuition for this result is similar to that in the auction case. The regulator must compensate a reduction in the price cap by a higher subsidy level. The dominant firm benefits from the shift in spot market revenues to capacity subsidies since it has a lower capacity utilization at peak prices than fringe firms.

Comparison of dominant firm's profit under capacity subsidies and capacity auctions

While the competitive fringe's zero profit conditions for the auction and subsidy case are basically identical, the dominant firm's first order conditions differ. We can generally establish

Proposition 4. *For a given price cap $\bar{P}$ and desired total output x_T, the dominant firm earns weakly higher profits under a capacity auction than under capacity subsidies.*

The intuition is as follows: The dominant firm can replicate the profits by simply bidding the equilibrium quantity under capacity subsidies in the auction. However, since its first order conditions differ, it generally has more profits under the capacity auction.

While we can generally rank the two mechanisms based on the the dominant firm's expected profits, ranking based on the dominant firm's market share and the frequency of capacity withholding is subject to the distribution of demand and the total capacity level. For the special case of uniformly distributed demand, the outcomes under an auction and subsidies are equivalent, as we will discuss in Subsection 3.3.

3.2. Strategic Reserves

Strategic reserves are generation capacity controlled by a regulator and are only used in the case of a supply shortage or when spot market prices rise above a previously determined trigger price. In some liberalized electricity markets, strategic reserves exist in addition to the wholesale market. The strategic reserves can be used to implement a desired reliability level without using capacity payments. Assume the trigger price of the strategic reserve is equal to the price cap $\bar{P}$ and the regulator procures a strategic reserve of size x_r that satisfies $x_r + x_f^* + x_m^* = x_T$ for a specified total capacity level. The strategic reserve is only used in the case of shortage and does not push prices below the cap $\bar{P}$, i.e.,

$$q_r = \min\left\{x_r, \max\left\{0, D - x_f - qm_m\right\}\right\}.$$

Given this usage policy, the strategic reserve then has no influence over the distribution of spot market prices. Correspondingly, the equilibrium investments and profits of the dominant firm and the competitive fringe are independent of the size of the strategic reserve. The equilibrium capacities x_m^* and x_f^* are given by the solution of the zero profit condition (10) and the first order condition (12) of the previous subsection for the case of a zero subsidy $s = 0$. In particular, the fringe firms' capacity does not depend on the dominant firm's capacity. We find the following limit result for changes in the price cap.

Proposition 5. *Consider an electricity market with strategic reserves and the limit $\bar{P} \to \infty$. The equilibrium capacities of the dominant firm and the competitive fringe then satisfy $x_f \to 1$ and $x_m \to 0$.*

The intuition for this proposition is as follows: The frequency of high prices $P = \bar{P}$ only depends on the fringe's capacity and on the distribution of demand. Therefore, the higher the maximal price $\bar{P}$, the higher the expected spot market profits of the fringe firms and the higher the equilibrium capacity x_f^*. The dominant firm faces countervailing effects: On the one hand, a higher maximal price $\bar{P}$ leads to higher spot market profits if demand exceeds the fringe's capacity. On the other hand, the fringe's capacity is increasing in $\bar{P}$ and therefore reduces the frequency of high prices and the dominant firm's average share in production if prices are high. In contrast to the previously discussed capacity mechanisms, there is no shift in revenues from the spot market to a capacity market if $\bar{P}$ decreases. Hence, it is not clear as to whether the dominant firm's expected spot market profits as well as its equilibrium capacity are increasing or decreasing in $\bar{P}$. However, the limit result holds true since the fringe's capacity is strictly increasing in $\bar{P}$ and there is no incentive to build capacity greater than the maximal demand (i.e., $x_f^* + x_m^* \leq 1$).

3.3. Equivalent Equilibrium Outcomes under Uniformly Distributed Demand

Interestingly, for the special case of uniformly distributed demand, fixed total capacity x_T and price cap $\bar{P}$, we find that the dominant firm's equilibrium capacity and expected profits are the same under all three capacity mechanisms:

$$x_m^* = \frac{k_f - k_m}{\bar{P} - c} \quad \text{and} \quad \Pi^m\left(x_m^*\right) = \frac{\left(k_f - k_m\right)^2}{2\left(\bar{P} - c\right)}. \tag{13}$$

The dominant firm's equilibrium capacity is then independent of the total capacity x_T and simply given by the ratio of the fixed cost advantage to the difference in price cap and variable costs. Furthermore, fringe capacity and the distribution of spot market prices are the same for capacity auctions and subsidies. Under strategic reserves, fringe capacity is generally lower, however, and replaced by reserve capacity. Consequently, under strategic reserves, there is a larger fraction of periods in which the spot price peaks. This result does not necessarily extend to more general demand functions, however.

Entry Barriers

Free entry by competitive firms substantially limits the dominant firm's scope of market power. The dominant firm may attempt to restrict the competitive pressure by building entry barriers. In this subsection, we analyze how the dominant firm's incentive to build entry barriers by raising the fringe firms' fixed costs depends on the spot market price cap. See Salop and Scheffman (1983) and Salop and Scheffman (1987) for a classical treatment on raising rivals' costs. Assume that at an initial stage, the dominant firm can pick an intensity level $b \in \left[0, \bar{b}\right]$ of anti-competitive practices and the resulting fringe firm's fixed costs are given by

$$k_f = k_m + \Delta + b.$$

The parameter Δ measures a natural fixed cost benefit of the dominant firm. For simplicity, we assume that demand is uniformly distributed and that the dominant firm has quadratic costs of anti-competitive practices

$$\psi(b) = \gamma b^2.$$

The dominant firm's total expected profits as a function of the sabotage intensity then satisfy

$$\Pi^m(x_m^*) = \left(\frac{(\Delta + b)^2}{2\left(\bar{P} - c\right)} - \gamma b^2\right).$$

By solving for the optimal level of b, we directly find the following result:

Proposition 6. *In equilibrium, the intensity of anti-competitive practices b to build entry* *barriers is decreasing in the price cap; i.e., the incentive to build entry barriers is reduced.*

The intuition is as follows: A higher price cap causes a revenue shift from the capacity market to the spot market, reducing the expected profits that the dominant firm can reap from a fixed cost advantage. Therefore, the dominant firm has less incentive to gain such a cost advantage by raising rivals cost.

4. Multiple Dominant Firms and a Competitive Fringe

In this section, we analyze the robustness of our insights for the case with n dominant firms, indexed by $i = 1, ..., n$, and a competitive fringe f. Again, all firms face the same variable cost c per unit of capacity and the dominant firms have weakly lower per unit fixed costs than the fringe firms, i.e., $k_m \leq k_f$. In this extension, we restrict attention to the case in which electricity demand D is uniformly distributed on $[0, 1]$. We establish that for the case of uniform demand, the joint market shares and profits of all dominant firms, capacity payments and distribution of market prices are independent of the number of dominant firms n. This means that our comparatively static results of the main model carry over to the case of multiple dominant firms.

4.1. Spot Market Behavior

In the first step, we analyze the production choices on the spot market for a given vector of capacities $x = (x_1, .., x_n, x_f)$ and realized demand D. Since the maximal demand level is normalized to 1, we restrict our analysis to the interesting case that $x_f + X_d \leq 1$, with $X_d := \sum_{j=1}^{n} x_j$. In order to simplify the exposition, we assume w.l.o.g. that dominant firms are sorted increasingly in their capacities, i.e., $x_1 \leq x_2 \leq ... \leq x_n$. All dominant firms simultaneously choose their spot market outputs $q_i \in [0, x_i]$ and fringe firms act as price takers. We denote the resulting output vector by $q = (q_1, ..., q_n, q_f)$, the output of all dominant firms by $Q_d := \sum_{i=1}^{n} q_i$ and the total output by $Q := Q_d + q_f$. As before, the spot market price as a function of Q and D is given by

$$P(Q, D) = \begin{cases} \bar{P} & \text{if } Q \leq D \\ c & \text{otherwise.} \end{cases}$$

If the demand is below the total capacity of the fringe firms, i.e., $D \leq x_f$, the perfect competition of the fringe drives down prices to marginal cost c. Consider the case $D > x_f$. Since demand is perfectly inelastic, each dominant firm would always find it profitable to unilaterally reduce its output q_i such that total output satisfies $Q = D$ and spot market prices jump to the price cap $\bar{P}$. Consequently, there remains a unique equilibrium spot market price that is determined in the same fashion as for a single dominant firm (see equation 2). However, there is a multitude of spot market equilibria that differ by the distribution of capacity withholding among dominant firms: If demand exceeds the fringe's capacity, $D > x_f$, then all (and only those) feasible output vectors $q = (q_1, ..., q_n, x_f)$ for which dominant firms' total output satisfies $Q_d = min\{D - x_f, X_d\} \equiv Q_d^*$ constitute a spot market equilibrium.

Since we consider our perfectly inelastic demand function as an approximation only for very inelastic demand functions, it seems sensible to pick equilibrium quantities that correspond to the limit of equilibria quantities from a sequence of elastic demand functions converging to our inelastic demand function. We define the capacity-constrained, symmetric distribution of the dominant firms' total output $Q_d^* > 0$ as the unique vector $q_d^* = (q_1^*, ..., q_n^*)$ that satisfies the following conditions. The first $l \in \{1, ..., n\}$ dominant firms that are capacity constrained produce

$$q_i^* = x_i \text{ for } i = 1, ..., l.$$

The remaining firms that are not capacity-constrained split the remaining excess demand equally, i.e.,

$$q_i^* = \frac{D - x_f - \sum_{j=1}^{l} x_j}{n-l} \text{ for } i = l+1, ..., n.$$

In Cournot models with a smooth and (possibly just slightly) elastic inverse demand function and common constant marginal cost, equilibrium outputs usually distribute total output in such a symmetric fashion; see, e.g. Zoettl (2011).[11] Correspondingly, we find the following result:

Lemma 1. *Fix $D > x_f$ and consider any sequence of continuously differentiable concave inverse demand functions $\left(P^l(Q)\right)_{l\in\mathbb{N}}$ that converges to our inelastic inverse demand function. Then the corresponding sequence $\left(q_d^l\right)_{l\in\mathbb{N}}$ of dominant firms' equilibrium output vectors converges to the symmetric output vector q_d^*.*

In light of this result, we base the subsequent analysis on the following assumption:

Assumption 2. *If $D > x_f$, the spot market equilibrium with the capacity-constrained symmetric output vector $q^* = (q_1^*, ..., q_n^*, x_f)$ is selected.*

4.2. Investments in Capacity

In this subsection, we prove that our comparative static results of the main model carry over to the case of multiple dominant firms.

4.2.1. Capacity Auctions

Assume the regulator procures the total capacity $x^T = X_d + x_f$ in a multi-unit descending bid auction. Let x_m^* be the equilibrium capacity of a monopolistic firm and let z^* be the resulting capacity payment. The bidding function $x_f(z)$ of the fringe is determined by its zero profit condition

$$z = k_f - \left(\bar{P} - c\right)(1 - x_f). \tag{14}$$

Let z_0 be the lowest capacity payment at which it would still be profitable for a monopolist to offer a capacity of $x_T - x_f(z)$ instead of stopping to bid and letting the auction fail.

Consider the following symmetric bidding strategy of the n dominant firms in the descending bid auction:

$$\mathbf{x}^*(z) = \begin{cases} \frac{1}{n}x_m^* & \text{if } z \geq z^* \\ \frac{1}{n}\left(x_T - x_f(z)\right) & \text{if } z_0 \leq z \leq z^* \\ 0 & \text{if } z < z_0 \end{cases}$$

The first line states that all firms start bidding one n'th of the equilibrium quantity of a monopolistic firm, causing the auction to end with a resulting auction price of z^* and a total capacity of the dominant firms of $nx^*(z^*) = x_m^*$. The other two lines are mainly important to correctly specify the behavior of off the equilibrium path in order to have a subgame perfect equilibrium in the descending bid auction: If an auction price $z < z^*$ were to be reached in the descending bid auction, firms would immediately finish the auction by offering the total capacity $nx^*(z) = x_T - x_f(z)$. Even if an auction price below z_0 were to be reached, the dominant firms would stop bidding and the auction would fail.

Proposition 7. *The symmetric bidding strategies* $\mathbf{x}^*(z)$ *form a symmetric subgame perfect equilibrium in the descending bid auction with multiple dominant firms. The equilibrium auction price* z^**, the total capacity and the total profits of all dominant firms are independent of the number of dominant firms* n *and equal to the results for a monopolistic firm.*

A rough intuition for this result is that the completely inelastic demand causes the oligopolistic dominant firms to act in the same fashion as a monopolistic dominant firm. For a more detailed insight, we refer the reader to the proof in the Appendix.

4.2.2. Subsidies and Strategic Reserve

Assume the regulator fixes a uniform capacity subsidy s such that the resulting equilibrium capacities $X_d^* = \sum_{i=1}^n x_i^*$ and x_f^* add up to the target level x^T. The fringe's capacities do not depend on the dominant firms' capacity because spot market prices rise up to $\bar{P}$ whenever $D > x_f^*$. For $s < k_f$, the fringe's equilibrium capacities x_f^* are therefore uniquely determined by the zero profit condition:

$$s = k_f - \left(\bar{P} - c\right)\left(1 - x_f^*\right).$$

The dominant firms choose their equilibrium capacities $x_d^* = (x_1^*, ..., x_n^*)$ to maximize their profits for given fringe capacities x_f^* and previously fixed subsidies s. We find the following proposition.

Proposition 8. *For fixed capacity subsidies s, the total equilibrium capacities as well as the total profits of all dominant firms are independent of the number of dominant firms and equal to the equilibrium capacities x_m^* and profits $\Pi^m\left(x_m^*\right)$ for a monopolistic dominant firm. Furthermore, the equilibrium capacities and profits of the dominant firms are symmetric.*

Let us consider a market in which the regulator procures a strategic reserve to obtain the total capacity level $x^T = x_r + X_d^* + x_f^*$. As in subsection 3.2, the strategic reserve is only used in times of shortage and does not influence the distribution of spot market prices. This means that the equilibrium capacities of the dominant firms and the competitive fringe are the same as in the previously considered market but with zero subsidies, i.e., $s = 0$. Since the dominant firms' equilibrium capacities are independent of the total capacity x_T (and s) see subsection 3.3, we directly find

Corollary 2. *If the regulator procures a strategic reserve to obtain the total capacity level x^T, the total equilibrium capacities as well as the total profits of all dominant firms are independent of the number of dominant firms and equal to the equilibrium capacities and profits for a monopolistic dominant firm. Furthermore, the equilibrium capacities and profits of the dominant firms are symmetric.*

5. Conclusion

It has been the purpose of this study to understand the effects of price caps and capacity mechanisms on the market structure. For our analysis, we have chosen a model with fluctuating price-inelastic electricity demand in which a dominant firm faces competitive firms that can freely enter the market and act as price takers. Firms invest in capacity in the first stage and afterwards sell electricity on the spot market. We have found the following main result: A higher price cap reduces the profits and the market share of the dominant firm, as well as the frequency of capacity withholding in equilibrium. This result is very robust and we have shown that it holds true for different types of capacity mechanisms as well as for multiple dominant firms.

The intuition is as follows: Fringe firms make higher average spot market profits per capacity unit than a dominant firm since a dominant firm has (on average) a lower capacity utilization in peak price periods due to the fact that it holds back capacity to increase spot market prices. In contrast, a dominant firm and a competitive firm benefit equally from capacity payments. When fixing a target level of total capacity, a lower price cap means that wholesale market revenues decrease and a larger fraction of firms' revenues must come from the capacity mechanism. This shift in revenue streams benefits the dominant firm relative to the competitive fringe.

The result is quite robust and its intuition has more general implications: First, dominant firms benefit from policy measures that reduce spot market revenues if capacity mechanisms exist. A lower price cap is one such measure, although we would see similar effects with alternative policy interventions. For example, a dominant firm would also benefit from a law that explicitly forbids capacity withholding on the spot market. Second, even if we had an elastic electricity demand, a dominant firm would have lower spot market profits per capacity unit than a fringe firm and therefore prefer revenue shifts from the spot market to the capacity market.

Especially in light of the present debate surrounding the future design of electricity markets, price caps and capacity mechanisms, the results we established are quite interesting. In this discussion, one should take into account that a reduction of price caps and the resulting shift in revenues from the spot market to the capacity market could lead to an increasing market share for the large incumbent electricity generators. The actual purpose of reducing price caps to reduce the exercise of market power may fail.

In our analysis, we have focused on the effects of changes in price caps and capacity payments on the market structure. We only briefly discussed the differences between the capacity mechanisms with regard to the dominant firms' market share and the frequency of capacity withholding in Section 3.3. Further research could address these differences, requiring stronger assumptions on demand. Furthermore, the model could be extended by adding base-load and peak-load technologies to investigate whether capacity mechanisms yield efficiency losses or gains in the generation mix.

Appendix

The appendix contains all proofs of the paper. Note that by the assumptions on G and g, and by the assumption that $x_m + x_f \leq 1$, the profit function $\Pi^m \left(x_m, \bar{P}\right)$ is twice continuously differentiable in x_m and $\bar{P}$. The same applies for the profit functions Π^l that we use in the proofs of propositions 7 and 8.

Proof of Proposition 2.

We prove this proposition in two steps: In part (i), we show that the dominant firm's profits are a decreasing function of the price cap. In part (ii), we prove that the dominant firm's equilibrium capacities are a decreasing function of the price cap. From (ii) it follows immediately that capacity withholding is also decreasing in the price cap since the total capacity is fixed and therefore the fringe's equilibrium capacity is increasing in the price cap.

(i) Profits. By the assumption that the total supply of the competitive fringe for each capacity payment z is such that its total profits π_f are zero, the equilibrium capacity payment z^* has to fulfill the following condition:

$$z^* = -\pi_f^s + k_f.$$

The dominant firm's profits are therefore given by

$$\begin{aligned}
\Pi^m &= \left(\pi_m^s + z^* - k_m\right) x_m \\
&= \left(\pi_m^s - \pi_f^s + k_f - k_m\right) x_m \qquad (15)\\
&= \left(-\left(\bar{P} - c\right)\left(1 - G\left(x_T - x_m\right)\right)\left(1 - \phi_m\right) + k_f - k_m\right) x_m.
\end{aligned}$$

Taking the first derivative of equation (15) with respect to $\bar{P}$ directly leads to the following lemma:

Lemma. *If the dominant firm's capacity x_m is fixed, Π^m is strictly decreasing in $\bar{P}$.*

This lemma does not state that the dominant firm's total profits are decreasing in the price cap since generally x_m depends on $\bar{P}$. We consider two different price caps $\bar{P}_L$ and $\bar{P}_H$, $\bar{P}_L < \bar{P}_H$. Let

$$x_m^L \in argmax_{x_m} \Pi^m \left(\bar{P}_L, x_m\right)$$
$$x_m^H \in argmax_{x_m} \Pi^m \left(\bar{P}_H, x_m\right)$$

denote optimal capacity selections of the dominant firm given $\bar{P}_L$ and $\bar{P}_H$, respectively. By optimality of x_m and the lemma above, the following inequalities hold:

$$\Pi^m \left(\bar{P}_L, x_m^L\right) \geq \Pi^m \left(\bar{P}_L, x_m^H\right) > \Pi^m \left(\bar{P}_H, x_m^H\right).$$

We have therefore shown that the dominant firm's total profits Π^m are strictly decreasing in the price cap $\bar{P}$.

(ii) Capacities. We show that x_m^* is a decreasing function of $\bar{P}$. The dominant firm's profit function is given by

$$\begin{aligned}\Pi^m &= \left(\pi_m^s + z^* - k_m\right) x_m \\ &= \left(\bar{P} - c\right) \left(x_m \left(1 - G\left(x_T\right)\right) + \int_{x_T - x_m}^{x_T} \left(D - x_T + x_m\right) g(D) dD\right) \\ &\quad + z^* x_m - k_m x_m.\end{aligned} \tag{16}$$

The auction price is determined by the fringe's zero profit condition. Plugging $z^* = k_f - \left(\bar{P} - c\right)\left(1 - G(x_T - x_m)\right)$ into equation (16) leads to

$$\begin{aligned}\Pi^m \;\; = \;\; & \left(\bar{P} - c\right) \left(x_m \left(1 - G\left(x_T\right)\right) + \int_{x_T - x_m}^{x_T} \left(D - x_T + x_m\right) g(D) dD\right) \\ & + \left(k_f - \left(1 - G\left(x_T - x_m\right)\right)\left(\bar{P} - c\right)\right) x_m - k_m x_m.\end{aligned}$$

The first derivative with respect to x_m is then given by

$$\frac{\partial \Pi^m}{\partial x_m} = k_f - k_m - g\left(x_T - x_m\right)\left(\bar{P} - c\right) x_m.$$

By taking the derivative with respect to $\bar{P}$, we get

$$\frac{\partial \partial \Pi^m}{\partial x_m \partial \bar{P}}\left(x\right) = -g\left(x_T - x_m\right) x_m < 0$$

since $g > 0$. We can apply an analogue of the "Monotone Selection Theorem" to show that x_m^* is a strictly decreasing function of the price cap $\bar{P}$. For the Monotone Selection Theorem, see Milgrom (2004), p.102.

Theorem. *(Analogue of the Monotone Selection Theorem) Assume that the function* Π^m *has strictly decreasing differences (SDD). Every optimal selection* $x_m^*\left(\bar{P}\right) \in argmax_{x_m} \Pi^m\left(x_m, \bar{P}\right)$ *is then strictly decreasing in* $\bar{P} \in [0, \infty)$.

Proof. Since $\Pi^m\left(\cdot, \cdot\right)$ is sufficiently smooth, SDD is equivalent to $\frac{\partial \partial \Pi^m}{\partial x_m \partial \bar{P}} < 0$ for all $\left(x_m, \bar{P}\right) \in [0, 1] \times [0, \infty)$. Let us fix arbitrary $\bar{P}_L, \bar{P}_H \in [0, \infty)$ satisfying $\bar{P}_L < \bar{P}_H$. Let us again denote optimal selections by

$$x_m^L \in argmax_{x_m} \Pi^m\left(\bar{P}_L, x_m\right)$$
$$x_m^H \in argmax_{x_m} \Pi^m\left(\bar{P}_H, x_m\right)$$

Let us assume that $x_m^L \leq x_m^H$. We bring this assumption to a contradiction. By definition of x_m^H and x_m^L, it holds that

$$\Pi^m\left(x_m^L, \bar{P}_L\right) \geq \Pi^m\left(x_m^H, \bar{P}_L\right) \text{ and } \Pi^m\left(x_m^H, \bar{P}_H\right) \geq \Pi^m\left(x_m^L, \bar{P}_H\right).$$

This implies that

$$\Pi^m\left(x_m^L, \bar{P}_L\right) + \Pi^m\left(x_m^H, \bar{P}_H\right) \geq \Pi^m\left(x_m^H, \bar{P}_L\right) + \Pi^m\left(x_m^L, \bar{P}_H\right),$$

which is equivalent to

$$\Pi^m\left(x_m^L, \bar{P}_L\right) - \Pi^m\left(x_m^L, \bar{P}_H\right) \geq \Pi^m\left(x_m^H, \bar{P}_L\right) - \Pi^m\left(x_m^H, \bar{P}_H\right). \tag{17}$$

However, by assumption $x_m^L \leq x_m^H$, the SDD property of Π^m yields a contradiction to (17). Hence, $x_m^L > x_m^H$, i.e., x_m^* is strictly decreasing in $\bar{P}$.

Proof of Proposition 3.

We prove this proposition in two steps: In part (i), we show that the dominant firm's profits are a decreasing function of the price cap. In part (ii), we prove that the dominant firm's equilibrium capacities are a decreasing function of the price cap. From (ii), it follows immediately that capacity withholding is also decreasing in the price cap since the total capacity is fixed and therefore the fringe's equilibrium capacity is increasing in the price cap.

(i) Profits. Due to the competitive fringe's zero profit condition, subsidies have to satisfy the following condition:

$$s^* = k_f - \pi_f^s.$$

The dominant firm's profits are therefore given by

$$\Pi^m = \left(\pi_m^s + s^* - k_m\right) x_m = \left(\pi_m^s - \pi_f^s + k_f - k_m\right) x_m.$$

For the rest of the proof, we refer to part (i) of the proof of Proposition 2.

(ii) Capacities. We show that x_m^* is strictly decreasing in $\bar{P}$. Due to the dominant firm's first-order condition (12), subsidies have to satisfy the following condition

$$s^* = k_m - \left(\bar{P} - c\right)\left(1 - G(x_T)\right).$$

Plugging s^* into the fringe's zero profit condition (10) leads to

$$x_f^* = G^{-1}\left(G(x_T) - \frac{k_f - k_m}{\bar{P} - c}\right).$$

Therefore, by adjusting s such that the reliability level ρ and the total capacity x_T are kept constant, we find that x_f is an increasing function of $\bar{P}$ by taking the first derivative $\frac{\partial x_f^*}{\partial \bar{P}}$. Since $x_T = x_f^* + x_m^*$ is kept constant, x_m^* is a decreasing function of $\bar{P}$.

Proof of Proposition 4.

Let s^* be the subsidy that implements the total output x_T. Let x_f^* and x_m^* be the resulting fringe and dominant firm capacity, respectively. Note that due to the same zero profit condition, x_f^* is also the fringe supply in the capacity auction for an auction price of $z = s^*$. Therefore, the dominant firm can replicate the same outcome in the auction as in the subsidy case by bidding a constant quantity of x_m^* in the auction. The resulting capacity payment is $z = s^*$, the fringe's capacity is x_f^* and the dominant firm's capacity is x_m^*.

Proof of Proposition 5.

The equilibrium capacities in a market with strategic reserves are given by the solution of the zero profit condition (10) and the first order condition (12) for the case of a zero subsidy $s = 0$. For $\bar{P} \to \infty$, it follows from the fringe's zero profit condition that $x_f \to 1$. Since $x_f + x_m \leq 1$ and $x_m \geq 0$, it follows that $x_m \to 0$.

Proof of Proposition 6.

By solving the first order condition

$$\frac{\partial \Pi_m}{\partial b} = \frac{1}{\bar{P} - c} 2 \left(b + \Delta \right) - 2 \gamma b = 0$$

and accounting for corner solutions, we find that the dominant firm's optimal level of anti-competitive practices a^* is by

$$b^* = \begin{cases} \frac{\Delta}{\left(\bar{P}-c\right)\gamma - 1} & \text{if } \left(\bar{P} - c\right) \gamma > 1 \\ \bar{b} & \text{otherwise.} \end{cases}$$

The result follows immediately.

Proof of Lemma 1.

Assume $D \in (x_f, 1)$. We consider any sequence $\left(P^l \left(Q, D\right)\right)_{l \in \mathbb{N}}$ in which each item of the sequence is twice continously differentiable and concave in Q and $P^l \left(Q, D\right) \to \bar{P}$ for $l \to \infty$. For $x_1, ..., x_n \in (0, 1)$, the equilibrium quantities $q_1^{l*}, ..., q_n^{l*}$ are given by

$$q_i^{l*} := argmax_{0 \leq \tilde{q} \leq x_i, \sum_{i=1}^n q_i \leq D - x_f} \left[P^l \left(\tilde{q} + Q^*_{-i} + x_f, D \right) \tilde{q} - c \tilde{q} \right].$$

Since the inverse demand function is given by P^l, which is twice continuously differentiable and concave, the unconstrained Cournot equilibrium is unique and symmetric, i.e., $q_1^{l*} = ... = q_n^{l*}$; see, for example, Vives (2001), pp. 97/98. We consider the case in which all firms are unconstrained. Due to the fact that the equilibrium quantities are symmetric, we have the following constraint: $q_i^{l*} \leq \frac{D - x_f}{n}$.

We choose $\epsilon > 0$ and $N \in \mathbb{N}$ such that $||P^l - \bar{P}|| < \epsilon$ for all $l \geq N$. With $\delta := \bar{P} - c > 0$, it follows that

$$\left(P^l - c\right)\tilde{q} = \begin{cases} \leq & (\delta+\epsilon)\,\tilde{q} \\ \geq & (\delta-\epsilon)\,\tilde{q} \end{cases}$$

for all $l \geq N$ and $\tilde{q} \in [0,1]$. The function for which we consider the argmax is therefore bounded from above by the linear function with the slope $\delta+\epsilon$ and bounded from below by the linear function with the slope $\delta-\epsilon$ for all $\tilde{q} \in \left[0, \frac{D-x_f}{n}\right]$. For ϵ sufficiently small, we have $\delta-\epsilon > 0$ and the function for which we consider the argmax has the maximum in the interval $\left[\frac{\delta-\epsilon}{\delta+\epsilon}\frac{D-x_f}{n}, \frac{D-x_f}{n}\right]$. For $\epsilon > 0$ sufficiently small, the quantity is close to $\frac{D-x_f}{n}$.

If the first $m \in \{1,...,n\}$ firms are capacity constrained, the arguments from above hold true for the remaining $n-m$ unconstrained firms. For the equilibrium quantities q_i^{l*}, $i \in \{n-m,...,n\}$, we then have the following constraint: $q_i^{l*} \leq \frac{D-x_f-\sum_{j=1}^{m} x_j}{n-m}$.

Proof of Proposition 7.

The number of firms that are capacity constrained is weakly increasing in the demand level D. The critical demand level above which the i'th dominant firm becomes capacity constrained on the spot market is given by

$$\tilde{D}_i = x_f + (n-i)\,x_i + \sum_{j=0}^{i} x_j,$$

where we define $x_0 := 0$. The expected variable spot market profits per capacity unit of the competitive fringe and a dominant firm l are then given by:

$$\begin{aligned} \pi_f^s &= \left(\bar{P}-c\right)(1-x_f) \\ \pi_l^s &= \frac{1}{x_l}\left(\bar{P}-c\right)\left(\sum_{i=0}^{l-1}\int_{\tilde{D}_i}^{\tilde{D}_{i+1}} \frac{D-x_f-\sum_{j=0}^{i} x_j}{n-i} dD + \int_{\tilde{D}_l}^{1} x_l dD\right). \end{aligned}$$

Let $x^* = \mathbf{x}^*(z^*) = \frac{1}{n}x_m^*$. Consider first that after some history with price $z > z^*$, firm l

would have a profitable deviation in his bidding function that results at an equilibrium to an auction price $\hat{z} > z^*$. The resulting equilibrium output of firm l is then given by

$$\hat{x} = x_T - x_f(\hat{z}) - (n-1)x^*.$$

Since the fringe firm's supply is increasing in z, we must have $\hat{x} < x^*$. Let

$$\Delta = x^* - \hat{x} \geq 0$$

denote the reduction of the deviating firm's output compared to its equilibrium output. Since other dominant firms offer a constant amount, the fringe output under the deviation satisfies

$$\hat{x}_f = x_f^* + \Delta$$

and the resulting auction price satisfies

$$\hat{z}(\Delta) = k_f - \left(\bar{P} - c\right)\left(1 - \left(x_f^* + \Delta\right)\right).$$

The resulting spot market equilibrium with asymmetric capacities yields the following expected spot market profit for the deviating firm:

$$\begin{aligned} (x^* - \Delta)\hat{\pi}_l^s(\Delta) \quad = \quad & \left(\bar{P} - c\right)\int_{x_f^*+\Delta}^{x_f^*+nx^*-(n-1)\Delta} \frac{D - \left(x_f^* + \Delta\right)}{n} dD \\ & + \left(\bar{P} - c\right)\int_{x_f^*+nx^*-(n-1)\Delta}^{1} \left(x^* - \Delta\right) dD. \end{aligned}$$

Firm l's expected total profits under this deviation are given by

$$\hat{\Pi}^l(\Delta) = (x^* - \Delta)(\hat{z}(\Delta) - k_d) + (x^* - \Delta)\hat{\pi}_l^s(\Delta)$$

Tedious but straightforward algebra shows that

$$\frac{\partial \hat{\Pi}^l}{\partial \Delta} = -\left(\bar{P} - c\right) n\Delta,$$

which is negative for all $\Delta \geq 0$. This means that a deviation that yields an auction price $\hat{z} > z^*$ cannot be profitable after any history.

To check that there are no other profitable deviations, let $\pi_m(z)$ denote the profits of a monopolist who offers the amount $x_m(z)$ that leads to an auction price z. This profit function is strictly concave (at least for uniformly distributed demand) and maximized at z^*. Recall that for all $z \in [z_0, z^*]$, the bids of the equilibrium strategies are given by

$$\mathbf{x}^*(z) = \frac{1}{n} x_m(z)$$

and the resulting profits of each dominant firm are given by $\frac{1}{n} x_m(z)$. Also, if firm i performs any deviation $\hat{\boldsymbol{x}}$ at some history with $z \geq z^*$ that yields an auction price $\hat{z} \in [z_0, z^*)$, then firm i's resulting capacity is always $\frac{1}{n} x_m(\hat{z})$ and its equilibrium profits are $\frac{1}{n} \pi_m(\hat{z})$. Yet, given that $\pi_m(z)$ is maximized for $z = z^*$, such a deviation cannot be profitable. Due to the concavity of $\pi_m(z)$, it is also strictly optimal to follow the equilibrium strategy in any continuation equilibrium in which the current auction price is $z \in [z_0, z^*)$, i.e., to immediately stop the auction. By the definition of z_0 as the lowest capacity payment under which a monopolist would be willing to supply $x_T - x_f(z)$, it is also clear that there can never be a profitable deviation that leads to an auction price $z \leq z_0$.

Proof of Proposition 8.

As already discussed in the proof of Proposition 7, the number of firms that are capacity constrained is weakly increasing in the demand level D. The critical demand level above which the i'th dominant firm becomes capacity constrained on the spot market is given by

$$\tilde{D}_i = x_f + (n-i)\, x_i + \sum_{j=0}^{i} x_j,$$

where we define $x_0 := 0$. The expected variable spot market profits per capacity unit of the competitive fringe and a dominant firm l are then given by:

$$\begin{aligned}
\pi_f^s &= \left(\bar{P} - c\right)(1 - x_f) \\
\pi_l^s &= \frac{1}{x_l}\left(\bar{P} - c\right)\left(\sum_{i=0}^{l-1} \int_{\tilde{D}_i}^{\tilde{D}_{i+1}} \frac{D - x_f - \sum_{j=0}^{i} x_j}{n-i} dD + \int_{\tilde{D}_l}^{1} x_l dD\right).
\end{aligned}$$

Hence, the dominant firm l's total profits are given by

$$\Pi^l = \left(\pi_l^s + s - k_m\right) x_l.$$

The first derivative of the dominant firm l's profit function is given by

$$\frac{\partial \Pi^l(x)}{\partial x_l} = \left(\bar{P} - c\right)\left(1 - x_f - (n-l)\, x_l - \sum_{j=0}^{l} x_j\right) - (k_m - s).$$

In part (i), we show that a symmetric equilibrium exists and that the equilibrium capacities are uniquely determined by

$$0 = \left(\bar{P} - c\right)\left(1 - x_f - n x^*\right) - (k_m - s)$$

(which states that x^* is exactly $\frac{1}{n}$'th of x_m^*). In part (ii), we show the uniqueness of this result.

(i) Existence. To show the existence of an equilibrium, it is sufficient to show quasiconcavity of firm l's profits $\Pi^l\left(x_l^*, \tilde{x}_{-l}\right)$, given the symmetric capacities $\tilde{x}$ of the other dominant firms; see, for example, Vives (2001) page 16. If all other dominant firms choose a symmetric capacity $\tilde{x}$, then the derivative of l's profit function is given by

$$\frac{\partial \Pi^l}{\partial x_l} = \begin{cases} \left(\bar{P} - c\right)\left(1 - x_f - n x_l\right) - \left(k_m - s\right) & \text{if } x_l \leq \tilde{x} \\ \left(\bar{P} - c\right)\left(1 - x_f - (n-1)\,\tilde{x} - x_l\right) - \left(k_m - s\right) & \text{if } x_l \geq \tilde{x}. \end{cases}$$

When other firms choose $\tilde{x} = x_l^*$, then this derivative is zero for $x_l = x_l^*$. The derivative $\frac{\partial \Pi^l\left(x_l, \tilde{x}_{-l}\right)}{\partial x_l}$ is differentiable and $\frac{\partial \partial \Pi^l\left(x_l, \tilde{x}_{-l}\right)}{\partial x_l \partial x_l} < 0$. Hence, the profit function is concave in firm l's profits (and thus quasiconcave).

(i) Uniqueness. Due to strict concavity, no other symmetric equilibrium exists. In the following, we show by contradiction that no asymmetric equilibrium exist: Assume an asymmetric equilibrium exists. In this case, we can order the equilibrium capacities $x_1^* \leq ... \leq x_n^*$, where at least one inequality has to hold strictly, i.e., $x_1^* < x_n^*$. The first order condition of firm n is given by

$$\frac{\partial \Pi^n\left(x\right)}{\partial x_n} = \left(\bar{P} - c\right)\left(1 - x_f - \sum_{j=0}^{n} x_j\right) - \left(k_m - s\right).$$

Obviously $\frac{\partial^2 \Pi^n}{\partial x_n^2} < 0$. Therefore firm n's profit function is concave and any asymmetric equilibrium has to fulfill the condition $\frac{\partial \Pi^n}{\partial x_n} = 0$. However, whenever $\frac{\partial \Pi^n}{\partial x_n} = 0$ holds, firm 1's profits are increasing in x_1:

$$\begin{aligned} \frac{\partial \Pi^1\left(x\right)}{\partial x_1} &= \left(\bar{P} - c\right)\left(1 - x_f - n x_1\right) - \left(k_m - s\right) \\ &> \left(\bar{P} - c\right)\left(1 - x_f - \sum_{j=0}^{n} x_j\right) - \left(k_m - s\right) = 0. \end{aligned}$$

The inequality holds due to $x_1 < x_n$. Therefore, any asymmetric equilibrium cannot exist.

Notes

[1]See, for example, Joskow (2008), Cramton and Stoft (2005), Finon and Pignon (2008).

[2]Market power in electricity markets has been studied, for example, by Borenstein et al. (2002) and Wolfram (1999).

[3]Besides price caps, other control methods to reduce market power and price volatility exist, e.g., reliability options or bid caps on the spot market see Cramton and Stoft (2008); Joskow (2008). All three of these methods lead to a reduction of the generators' profits in times of scarcity. For our analysis, only this impact is important; therefore we do not distinguish between the different methods.

[4]Capacity markets with capacity auctions have been introduced in many electricity markets in the US as well as in Central and South America. Examples include the Forward Capacity Market (ISO New England), the Reliability Pricing Model (PJM) and the Colombia Firm Energy Market. Strategic reserves are used in Sweden and Finland. Capacity subsidies are paid in Spain and Portugal.

[5]Expert knowledge and economies of scale are important factors in electricity markets due to the very high investment costs and the corresponding risk that needs to be assessed accordingly, i.e., for large incumbent firms with power plant portfolios or small new entrants. In addition, the locational advantage of incumbent firms is of particular importance: Existing power plants can be extended or replaced by new power plants, which reduces location and infrastructure costs. As shown below, a strict cost advantage is crucial for the existence of market power in our model with free entry.

[6]We would obtain the same results if the dominant firm offered supply functions that specify price-quantity schedules.

[7]We assume that if electricity demand exceeds total supply, there is a partial blackout. The network operator cuts off exactly so many consumers from the electricity supply that total consumption equals the given supply.

[8]In our model, there is no need for a regulator to design a capacity mechanism that yields a total capacity above the maximum demand.

[9]See the Appendix for a derivation.

[10]Yet, for $s = k_m$, the dominant firm is indifferent between all capacity levels. Clearly, an auction is advantageous for targeting a specific capacity goal.

[11]For the unconstrained Cournot equilibrium: If an inverse demand function $P^l(Q, D)$ is twice continuously differentiable in Q and the first and second derivatives are negative, then the unconstrained Cournot equilibrium is unique and symmetric. See, e.g., Vives (2001), pp. 97/98.

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