Investments in Electricity Generation Capacity under Different Market Structures

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Abstract

Investments in Generation Capacities by a social planner, by a monopolist and by two competing firms are compared when electricity demand is uncertain but price responsive. A unit price auction determines the electricity price when firms compete. Firms know the level of demand when they bid their capacities. With simultaneous capacity choices total capacities are always larger than with a monopoly if a subgame perfect equilibrium in pure strategies exists. With sequential capacity choices existence is always ensured and the aggregate capacity is smaller in the duopoly than with a monopolist if capacity costs are very low. Capacities always fall short of the socially efficient level.

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1 Introduction

In many industrialised countries the market for electricity has been liberalised. Until the end of the eighties there was usually no competition among electricity suppliers. The market was characterised by regional monopolies that were either private enterprises which had to stick to some kind of price regulations or public utilities. The Electricity Pool of England and Wales and the so-called North Pool of the Scandinavian countries were the first attempts to organise a market for electricity and to introduce competition in the electricity industry. Other countries followed and each country chose a different organization of its newly formed electricity market.

England and Wales as well as the Scandinavian countries never suffered major crises since they liberalised their markets. Although there is a debate whether the Pool prices in England and Wales reflect market power by the two main suppliers, England and Wales as well as the Scandinavian countries seem to be rather successful by having introduced competition into their electricity markets.[1] Contrary to them California and New Zealand experienced explosions of their wholesale prices for electricity and/or black-outs after their markets had been liberalised.[2]

Especially the Californian experience received a lot of attention from professional economists who pointed out many deficiencies in the way the Californian electricity market has been liberalised.[3] Most of the observers, however, also agree that California does not have enough generation and transmission capacity. The lack of capacity might be due to the uncertainty in the deregulation phase and to the very strict environmental regulations in California.

Given the special characteristics of the electricity industry, one can also imagine that competition between generators of electricity reduces their incentive to build capacity. Generators are, for instance, interested in congested transmission lines because this insulates them from competition of more efficient electricity suppliers and preserves their market power.[4] Since transmission lines could be built also by outside firms without any interest in the generation business, this problem should be solvable in the long run. Therefore this paper focusses on the comparison of investment incentives into generation capacity with and without competition.[5]

[1]See Wolfram (1999) for empirical evidence for market power in the British electricity industry

[2]See e.g. *The Economist* from March 7, 1998, p. 46., and from February 10, 2001, and for the latest crisis in New Zealand *Modern Power Systems* from August 2001, p. 11.

[3]See Joskow (2001), Borenstein *et al.* (2001), Borenstein (2002) and Wilson (2002).

[4]See e.g. Borenstein *et al.* (2000), Joskow and Tirole (2000) and Léautier (2001) for theoretical results that point into this direction.

There are some hints that competing generators invest too little in their generation capacity. If generators behave competitively, the market price for electricity equals marginal costs. For this case von der Fehr and Harbord (1997) as well as Castro-Rodriguez *et al.* (2001) show that from a social welfare point of view firms would build suboptimal low levels of generation capacity. They also prove that firms invest more in their generation capacity, if the spot market price exceeds marginal costs at a fixed margin. In addition von der Fehr and Harbord (1997) endogenise the spot market price of electricity for an inelastic demand that is ex ante uncertain in the capacity decision stage, and known, when the firms bid in the auction for the supply of electricity. The auction is a unit price auction à la von der Fehr and Harbord (1993). They conclude that the firms underinvest in capacity as long as the distribution of the uncertain inelastic demand is concave, meaning skewed to the lower end of the distribution.

Neither of the two papers, however, does address the question whether investment in capacity is more efficient under a monopolistic market structure than under competition. On the one hand, the monopoly has the advantage that all the externalities are internalised. The externalities are due to the joint use of the same network where aggregate demand has to be balanced with aggregate supply at each point in time. Thus, if the monopolist builds a large generation capacity only he gains from the possibility to sell high amounts of electricity in the rare occasion of a high demand. In case of competition the revenues that can be earned on an additional unit of capacity are much lower and therefore one would expect lower levels of investments in generation capacity. On the other hand, the monopoly tends to produce less than is socially efficient and would therefore need and build fewer generation capacity. In this paper the levels of investments in generation capacity by a duopoly are compared to the ones installed in a monopoly market.

We assume that consumers have an elastic demand for electricity and can instantaneously adapt their demand to price signals from the market. The spot market is modelled in the same way as in von der Fehr and Harbord (1997) and von der Fehr and Harbord (1993).[6] Firms invest in the first stage of the game. Then nature chooses the levels of the demand shocks and after observing the realised shocks firms bid in the spot market.

[5]The incentives to invest in generation capacity might not be independent of the available transmission capacity, if the latter is scarce. This case is however not considered here. See Wilson (2002) for interesting insights into this problem.

[6]An alternative approach has been suggested by Green and Newbery (1992). It is based on Klemperer and Meyer (1989). They assume that firms bid differentiable supply functions whereas von der Fehr and Harbord (1997) and von der Fehr and Harbord (1993) assume that they bid step functions.

This scenario is inspired by the proponents of a better metering technology. They argue that such a technology would result in much more elastic demands, reduce peak demands and improve the performance of liberalised electricity markets (Borenstein, 2002; Faruqui *et al.*, 2001). Nowadays most of the consumers still lack the technology necessary to adapt their demands to a fluctuating wholesale price because this technology is still too expensive. In practice their demand does not respond to changes in the wholesale price for electricity because most of the consumers buy electricity at a retail price that is fixed before the uncertainty whether the demand will be high or low is resolved. Competition among electricity suppliers that fix retail prices despite uncertain demand will be analysed in a companion paper.

The investments in generation capacity under two competitive scenarios are compared to the investment decisions of a monopoly and to the first best level of investments installed by a social planner. In the first scenario both firms choose their capacities simultaneously, whereas in the second a sequential choice of capacities is assumed. It turns out that the investment in generation capacity is too low in each of the competitive scenarios as well as in the monopoly setting from a social welfare point of view. Investment levels are, however, almost always higher in the competitive scenario than with a monopoly. Only with very low capacity costs and sequential capacity choice does the monopolist invest more than the two competing firms. Nevertheless, social welfare is always higher under competition than under monopoly, but an underinvestment problem remains.

2 The Model

There are two generators of electricity $j = A, B$, and one representative consumer of electricity who suffers from demand shocks. The representative consumer has a quasilinear utility function. Let his surplus function be given by

$$V(x; \varepsilon, p) = U(x, \varepsilon) - px = x - \varepsilon - \frac{(x-\varepsilon)^2}{2} - px \tag{1}$$

where x is the consumed electricity, p is the price paid per unit of electricity, and ε is the consumer's demand shock. The demand shock is uniformly distributed on the interval $[0, 1]$. The demand for electricity can be derived from maximising $V(x; \varepsilon, p)$ with respect to x and results in

$$x(p) = 1 + \varepsilon - p. \tag{2}$$

The variable costs of generating electricity is assumed to be constant and, for the sake of simplicity, equal to zero for both firms. Thus the costs of firm j consist only of the costs of capacity which are assumed to be:

$$C(k_j) = zk_j \tag{3}$$

where z is a constant unit cost of capacity and k_j the generation capacity installed by firm j. Firms decide on their capacities before they know the level of demand. When they bid their capacity in the electricity spot market, the demand shocks of the two consumer groups are already realised and market demand is known for sure.

The spot market price of electricity is determined in an auction of the type introduced by von der Fehr and Harbord (1993) and von der Fehr and Harbord (1997) after the firms and the auctioneer already know the realisations of the demand shocks. Firms have to bid a price p_j at which they are willing to supply their whole generating capacity. For the sake of simplicity the firms cannot bid other quantities.[7] The auctioneer must secure the balance of supply and demand on the grid. Therefore he orders the bids according to their prices and determines the marginal bid that is just necessary to equal supply and demand. The price of the marginal bid is the spot market price that is payed to all the generators for each unit that is dispatched on the grid no matter whether they bid a lower price.[8] The capacity of the supplier that has bid a price below the marginal price is dispatched completely, whereas the marginal supplier is only allowed to deliver that amount of electricity necessary to balance supply and demand. If the supplied capacity at a certain bid price is insufficient to satisfy demand but would be more than sufficient to satisfy demand at the next highest bid price, then the auctioneer sets the price inbetween the two bid prices at that level that ensures the balance.[9]

Two duopoly scenarios are considered here where the consumers receive real time price signals to which they can adapt their demand instantaneously. In the first analysed scenario the game proceeds as follows:

1. The two generating firms choose their respective capacities k_A and k_B simultaneously.

[7] Thus, we do not consider the problem of strategic withholding of capacity in order to raise the spot market price.

[8] This differs the analysis here from simple Bertrand competition as in Kreps and Scheinkman (1983) where the undercutting firm receives only its own price per unit sold even if its capacity is too low to serve all the customers and some of them have to pay the price of the competitor with the next highest price.

[9] According to Wilson (2002) we assume an integrated system because participation in the auction is compulsory if a generating firm wants to sell electricity.

2. Nature determines the demand shock ε.
3. Both firms bid a price p_j for their whole capacity k_j in the spot market.
4. The auctioneer determines the spot market price p and which generator is allowed to deliver which amount of electricity to the grid.
5. Consumers have to pay p per unit demanded and the suppliers are payed according to their dispatched quantities.

Here both firms compete on an equal footing. Most liberalised electricity markets are, however, characterised by incumbents that were the regional monopolists before competition was introduced. Often, these incumbents can be regarded as the leaders in the capacity stage and therefore we also consider a game with a sequential choice of capacity where the timing of decision is:

1. Firm A chooses its capacity k_A.
2. Firm B chooses its capacity k_B.
3. Nature determines the demand shock ε.
4. Both firms bid a price p_j for their whole capacity k_j in the spot market.
5. The auctioneer determines the spot market price p and which generator is allowed to deliver which amount of electricity to the grid.
6. Consumers have to pay p per unit demanded and the suppliers are payed according to their dispatched quantities.

3 Benchmark Cases

Here the price and capacity choice of a social planner is derived for the market sketched in the last section. In addition a monopoly is analysed which determines its capacity before, and its price after the observation of demand. The consumers receive instantaneous price signals and adapt their demand accordingly.

3.1 First Best Capacity Choice

We assume that the social planner sets prices after and capacities before the observation of demand. Given that the marginal cost of electricity generation is zero a social planner prefers a price of zero as long as there is no need to ration demand because capacity is scarce. Thus, first best prices are:

$$p^*(k;\varepsilon) = \begin{cases} 0 & \text{for } k \geq 1+\varepsilon \\ 1+\varepsilon-k & \text{for } 0 < k < 1+\varepsilon \end{cases}$$

where k is the level of generation capacity installed in the market. The price is zero for small demand shocks ($\varepsilon \leq k-1$) and balances supply and demand for larger ones ($\varepsilon > k-1$).

Taking (1) and (2) and the uniform distribution of the demand shocks into account a social planner maximises the following social welfare function with respect to k:

$$W(k) = \begin{cases} \int_0^1 \left[k-\varepsilon-\frac{(k-\varepsilon)^2}{2}\right] d\varepsilon - zk & \text{for } 0 \leq k \leq 1 \\ \int_0^{k-1} \frac{1}{2} d\varepsilon + \int_{k-1}^1 \left[k-\varepsilon-\frac{(k-\varepsilon)^2}{2}\right] d\varepsilon - zk & \text{for } 1 < k \leq 2 \\ \int_0^1 \frac{1}{2} d\varepsilon - zk & \text{for } k > 2 \end{cases} \quad (4)$$

The optimal first best capacity level that results from this maximisation is characterised in the following Proposition.

Proposition 1 *The first best generation capacity is given by:*

$$k^*(z) = \begin{cases} 2-\sqrt{2z} & \text{for } 0 < z \leq \frac{1}{2} \\ \frac{3}{2}-z & \text{for } \frac{1}{2} < z \leq \frac{3}{2} \\ 0 & \text{for } z > \frac{3}{2} \end{cases}.$$

Proof: See Appendix A. ■

As one would expect the first best capacity level decreases in the capacity costs z. As the capacity cost z approaches 0 the optimal capacity approaches 2 the maximum possible demand if the electricity price is zero. If the capacity cost exceeds the expected maximum willingness to pay of 3/2 no capacity should be installed.

3.2 Capacity Choice of a Monopolist with Flexible Prices

If a monopolist has not fixed a certain price before the demand uncertainty is revealed, he sets his profit maximising price according to the relevant demand after the observation of the demand shock of ε. The price coincides with the usual monopoly price if his capacity is large enough to satisfy demand at this price. If the monopolist's capacity falls short of the demand at the monopoly price the monopolist sets a price above the monopoly level in order to ensure that demand equals the capacity. Therefore his price is represented by:

$$\tilde{p}_m(k;\varepsilon) = \begin{cases} \frac{1+\varepsilon}{2} & \text{for } k \geq \frac{1+\varepsilon}{2} \\ 1+\varepsilon-k & \text{for } 0 \leq k < \frac{1+\varepsilon}{2} \end{cases}$$

Thus, the monopolist sets the usual monopoly price for low demand shocks ($\varepsilon \leq 2k-1$) and a price that reduces the demand to the available capacity for high demand shocks ($\varepsilon > 2k-1$).

When the monopolist chooses his capacity, he anticipates $\tilde{p}_m$ and maximises his expected profits given by:

$$\tilde{\Pi}_m(k) = \begin{cases} \int_0^1 k(1+\varepsilon-k)d\varepsilon - zk & \text{for } 0 \leq k \leq \frac{1}{2} \\ \int_0^{2k-1} \frac{(1+\varepsilon)^2}{4} d\varepsilon + \int_{2k-1}^1 k(1+\varepsilon-k)d\varepsilon - zk & \text{for } \frac{1}{2} < k \leq 1 \\ \int_0^1 \frac{(1+\varepsilon)^2}{4} d\varepsilon - zk & \text{for } k > 2 \end{cases} \quad (5)$$

From the analysis of the monopolist's expected profit function given in (5) the monopolist's capacity choice can be derived.

Proposition 2 *If the monopolist does not need to fix a price before he can observe the realisation of demand, he chooses the capacity* $\tilde{k}_m$ *with*

$$\tilde{k}_m(z) = \begin{cases} 1-\sqrt{\frac{z}{2}} & \textit{for } 0 \leq z \leq \frac{1}{2} \\ \frac{3-2z}{4} & \textit{for } \frac{1}{2} < z \leq \frac{3}{2} \\ 0 & \textit{for } z > \frac{3}{2} \end{cases}.$$

Proof: See Appendix B. ■

Note that $\tilde{k}_m(z)$ decreases in the capacity cost z. In addition $\tilde{k}_m(z) = 1/2k^*(z)$. Thus, it is always smaller than the first-best level of capacity investment $k^*(z)$, given in Proposition 1.

4 Investments in Generation Capacity with a Duopoly and Flexible Prices

We consider the case where the consumers receive instantaneous price signals and can directly take part in the auction. The auctioneer sets the price after the demand shocks have been realised.

4.1 The Auction Price with Flexible Prices

When firm j has to determine its bid price p_j in the auction the two firms have already fixed their generation capacities k_j and k_h, $j, h = A, B$ and $h \neq j$. In addition the demand, given in (2), is already revealed.

Suppose for the moment that firm j bids $p_j \leq p_h$. Then the bids of the two firms result in the following auction price:

$$p(p_j, p_h) = \begin{cases} p_j & \text{for } p_j \geq 1 + \varepsilon - k_j \\ 1 + \varepsilon - k_j & \text{for } p_j < 1 + \varepsilon - k_j \leq p_h \\ p_h & \text{for } 1 + \varepsilon - k_j - k_h \leq p_h < 1 + \varepsilon - k_j \\ 1 + \varepsilon - k_j - k_h & \text{for } p_h < 1 + \varepsilon - k_j - k_h \end{cases} \tag{6}$$

It coincides with the lower price if the firm's capacity that bids the lower price is sufficiently large to satisfy demand at this price and only part of the low bidding firm's capacity is dispatched by the auctioneer. The auction price is fixed at the level that balances demand with the capacity of the firm that bids a price below the other firm, if demand would exceed the capacity of the low bidding firm at the low bid price, but would fall short of the low bidding firm's capacity at the higher bid price. In this case the low bidding firm's capacity is dispatched completely and the high bidding firm cannot sell any electricity. The auction price coincides with the higher price if both capacities together are large enough to satisfy demand at the higher price, but if the low bidding firm's capacity is too small to satisfy demand at this price. Here the low bidding firm's capacity is again totally dispatched whereas the high bidding firm can only sell the amount of electricity that is needed on top of the lower bidder's capacity to balance supply and demand. And finally, the auction price would be the price that balances demand with the aggregated capacities of the two firms, if even the higher bid price is too small to balance demand with the maximum supply of both firms' capacities. Then both firms can sell their total capacity.

Thus, the profit of firm j $\tilde{\pi}_j(p_j, p_h)$ for all price bids $p_j < p_h$ is represented by:

$$\underline{\pi}_j(p_j, p_h) = \begin{cases} p_j(1+\varepsilon-p_j) & \text{for } p_h > p_j \geq 1+\varepsilon-k_j, \\ \min\{1+\varepsilon-k_j, p_h\}\, k_j & \text{for } \min\{1+\varepsilon-k_j, p_h\} \\ & > \max\{p_j, 1+\varepsilon-k_j-k_h\} \\ (1+\varepsilon-k_j-k_h)k_j & \text{for } 1+\varepsilon-k_j-k_h > p_h \\ & > p_j \geq 0. \end{cases} \quad (7)$$

Note that if the firm undercuts its competitor it either sells its capacity at the competitor's bidding price or it serves the whole market alone or it sells its capacity at the market clearing price set by the auctioneer. The first scenario occurs, if the firm's capacity and the competitors price is low enough that both firms' capacities are needed to serve the demand, but also not that low that the auctioneer must set a market clearing price beyond the two firms' bidding prices. If the competitor's price is rather high or the undercutting firm's capacity rather large, then the firm that undercuts can serve the market alone.

The profit of firm j $\tilde{\pi}_j(p_j, p_h)$ for all price bids $p_j > p_h$ is given by:

$$\bar{\pi}_j(p_j, p_h) = \begin{cases} 0 & \text{for } p_j > \max\{1+\varepsilon-k_h, ph\}, \\ p_j(1+\varepsilon-p_j-k_h) & \text{for } 1+\varepsilon-k_h \geq p_j > \\ & \max\{1+\varepsilon-k_h-k_j, p_h\}, \\ (1+\varepsilon-k_h-k_j)k_j & \text{for } 1+\varepsilon-k_h-k_j > p_j > p_h. \end{cases} \quad (8)$$

If the considered firm sets a higher price than its competitor, it can only sell if its own price is low enough and the competitor's capacity small enough. If the two firms bid identical prices $p_j = p_h$ firm j's profit is $\tilde{\pi}_j(p_j, p_h) = \frac{1}{2}\underline{\pi}_j(p_j, p_h) + \frac{1}{2}\bar{\pi}_j(p_j, p_h)$ because the auctioneer treats firm j with probability one half like the low price bidder and with probability one half like the high price bidder.

From the analysis of $\tilde{\pi}_j(p_j, p_h)$ firm j's best response in bid prices and all possible Nash equilibria can be derived. They depend on the generation capacities installed by the two firms and are characterised in Lemma 1.

Set	Definition
$\mathcal{A}$	$k_A \leq \min\{(1+\varepsilon-k_B)/2, 1+\varepsilon-2k_B\}$
$\mathcal{B}$	$\max\{1+\varepsilon-2k_B, 0\} \leq k_A \leq \min\{1+\varepsilon_2-\sqrt{2k_B(1+\varepsilon-k_B)}, 1+\varepsilon\}$
$\mathcal{B}'$	$\max\{1+\varepsilon-2k_A, 0\} \leq k_B \leq \min\{1+\varepsilon_2-\sqrt{2k_A(1+\varepsilon-k_A)}, 1+\varepsilon\}$
$\mathcal{C}$	$\max\left\{-\sqrt{2k_B(1+\varepsilon-k_B)}+1+\varepsilon, \left(1+\varepsilon-\sqrt{2k_B[2(1+\varepsilon)-k_B]-(1+\varepsilon)^2}\right)/2\right\} \leq k_A \leq \left(1+\varepsilon+\sqrt{2k_B[2(1+\varepsilon)-k_B]-(1+\varepsilon)^2}\right)/2$
$\mathcal{D}$	$k_A \geq 1+\varepsilon$ and $k_b \geq 1+\varepsilon$

Table 1: The Definitions of the capacity sets in Lemma 1

Lemma 1 *The bidding strategies p_A and p_B of the two firms that form a Nash equilibrium in pure strategies and the resulting auction price p is:*

1. $p_A, p_B \leq 1+\varepsilon-k_A-k_B = p$ *if* $(k_A, k_B) \in \mathcal{A}$.
2. $p_B = (1+\varepsilon-k_A)/2 = p$ *and* $p_A < (1+\varepsilon-k_A)^2/(4k_B)$ *if* $(k_A, k_B) \in \mathcal{B}$.
3. $p_A = (1+\varepsilon-k_B)/2 = p$ *and* $p_B < (1+\varepsilon-k_B)^2/(4k_A)$ *if* $(k_A, k_B) \in \mathcal{B}'$.
4. *either* $p_A = (1+\varepsilon-k_B)/2 = p$ *and* $p_B < (1+\varepsilon-k_B)^2/(4k_A)$ *or* $p_B = (1+\varepsilon-k_A)/2 = p$ *and* $p_A < (1+\varepsilon-k_A)^2/(4k_B)$ *if* $(k_A, k_B) \in \mathcal{C}$.
5. $p_A = p_B = p = 0$ *if* $(k_A, k_B) \in \mathcal{D}$.

The capacity sets $\mathcal{A}$, $\mathcal{B}$, $\mathcal{B}'$, $\mathcal{C}$ and $\mathcal{D}$ are defined in Table 1.

Proof: The best responses in bid prices are given in Appendix C. From these best responses the Nash equilibria, given in Lemma 1, can directly be derived. ■

Lemma 1 is illustrated in Figure 1. The areas labeled $\mathcal{A}$, $\mathcal{B}$, $\mathcal{B}'$, $\mathcal{C}$, and $\mathcal{D}$ coincide with the capacity sets defined in Table 1. In area $\mathcal{A}$ both firms have

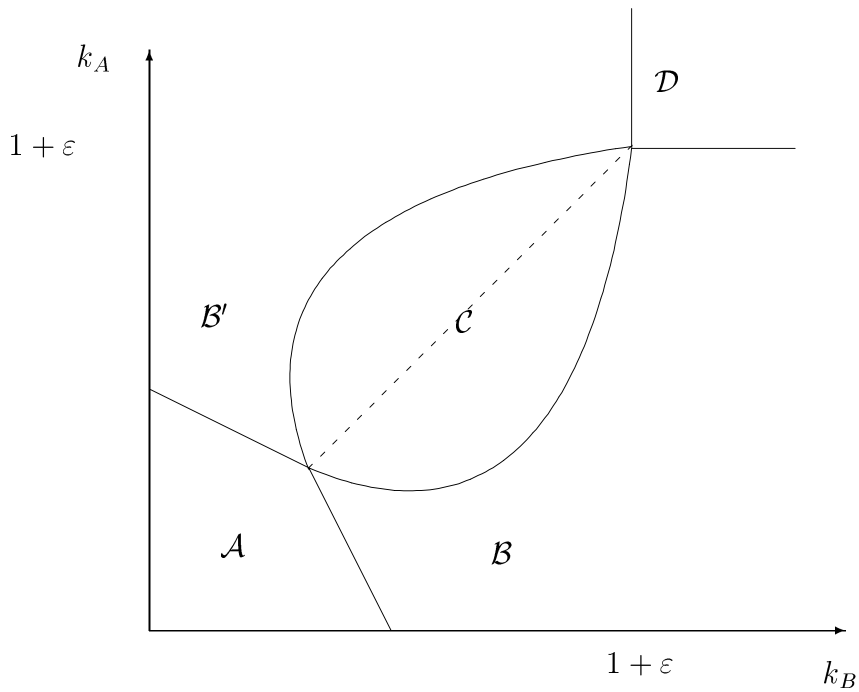

Figure 1: The Sets of (k_A, k_B) that Induce Different Bidding Equilibria

such a low capacity that the best thing to do for both of them is to choose a low price in equilibrium that forces the auctioneer to set a price that balances demand with the total available capacity $k_A + k_B$. Both firms sell their entire capacity at this price. In area $\mathcal{B}$ firm B with the larger capacity bids the monopoly price on the demand that cannot be served by the small provider A. The bid of the small provider is low enough that the large provider has no incentive to undercut him. The small provider sells his complete capacity at the equilibrium price whereas the large provider's capacity is only partially dispatched in equilibrium. In area $\mathcal{B}'$ the roles of firm A and firm B are just interchanged compared to area $\mathcal{B}$. Otherwise, the large provider A and the small provider B act in the same way as the large and small provider in area $\mathcal{B}$. In area $\mathcal{C}$ the difference in the two firms' capacities is relatively small compared to area $\mathcal{B}$ or $\mathcal{B}'$. Thus, there are two Nash equilibria in pure strategies here, one where the large firm sets the monopoly price on the demand that cannot be served by its opponent and one where the small firm does the same. As in $\mathcal{B}$ and $\mathcal{B}'$ the other firm bids a price that is low enough that the high bidding firm has no incentive to undercut. In area $\mathcal{D}$

both firms can serve the whole market even if the price is zero. Since the capacity constraint is never binding, both firms have always an incentive to undercut each other. The only possible strategy combination in equilibrium is that both firms bid a price of zero.

Except for area $\mathcal{D}$ the Nash equilibrium in pure bidding strategies is never unique. In areas $\mathcal{A}$, $\mathcal{B}$, and $\mathcal{B}'$ of Figure 1 the auction price is, however, identical for all possible Nash equilibria. If the generation capacities k_A and k_B satisfy the conditions of area $\mathcal{C}$ there are multiple equilibria of two types. One type coincides with the family of Nash equilibria and the auction price of area $\mathcal{B}$, and the other type of Nash equilibria coincides with the ones of area $\mathcal{B}'$. Neither type of Nash equilibria is Pareto dominated by the other. Firm A realises higher profits, if a Nash equilibrium of the type played in $\mathcal{B}'$ is also played in area $\mathcal{C}$, whereas firm B has higher profits, if the two firms co-ordinate on a Nash equilibrium of the type induced in $\mathcal{B}$. The following assumption is made in order to handle the problem of multiple Nash equilibria that result in different auction prices.

Assumption 1 *In the case of two types of Nash equilibria that result in different auction prices the two firms co-ordinate on a Nash equilibrium that is preferred by the firm with the larger generation capacity. If $k_A = k_B$ holds, the firms co-ordinate with probability one half on a Nash equilibrium preferred by firm A and with probability one half on one that is preferred by firm B.*

The motivation for Assumption 1 is that if both firms play the strategy of their most preferred type of equilibrium the outcome would always be an auction price that coincides with the type of equilibrium preferred by the larger provider. Thus, Assumption 1 ensures that in area $\mathcal{C}$ the firms select a Nash equilibrium where the firm with the larger capacity bids the monopoly price on the demand that cannot be served by the firm with the smaller capacity. The firm with the smaller capacity chooses its price small enough that the other firms has no incentive to undercut. Thus, for all combinations of k_A and k_B above the dashed line in area $\mathcal{C}$ of Figure 1 firms play in the same way as in $\mathcal{B}'$. Below the dashed line firms play as in area $\mathcal{B}$.

4.2 Simultaneous Capacity Choices with Flexible Prices

When the two firms decide on their investments in generation capacity they anticipate the auction price, given in Lemma 1, that results from their respective capacity choices. Taking into account Assumption 1, the profit of firm j in terms of the firms' chosen capacities $\tilde{\Pi}_j(k_j, k_h)$, given that $k_j > k_h$, is represented by :

$$\bar{\Pi}_j(k_j,k_h) = \begin{cases} \int_0^1 kj(1+\varepsilon-k_j-k_h)d\varepsilon - zk_j & \text{for } 0 < k_j \\ & \leq \frac{1-k_h}{2}, \\ \int_0^{2k_j+k_h-1} \frac{(1+\varepsilon-k_h)^2}{4} d\varepsilon + & \\ \int_{2k_j+k_h-1}^1 kj(1+\varepsilon-k_j-k_h)d\varepsilon - zk_j & \text{for } \frac{1-k_h}{2} < k_j \\ & \leq \frac{2-k_h}{2}, \\ \int_0^1 \frac{(1+\varepsilon-k_h)^2}{4} d\varepsilon - zk_j & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } k_h \leq 1, \\ \int_{k_h-1}^1 \frac{(1+\varepsilon-k_h)^2}{4} d\varepsilon - zk_j & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } 1 < k_h \leq 2, \\ -zkj & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } k_h > 2. \end{cases} \tag{9}$$

The profit of firm j in terms of the firms' chosen capacities $\tilde{\Pi}_j(k_j, k_h)$, given that $k_j < k_h$, is equivalent to:

$$\underline{\Pi}_j(k_j,k_h) = \begin{cases} \int_0^1 kj(1+\varepsilon-k_j-k_h)d\varepsilon - zk_j & \text{for } 0 < k_j \\ & \leq 1-2k_h, \\ \int_0^{2k_h+k_j-1} \frac{1+\varepsilon-k_j}{2} k_j d\varepsilon + & \\ \int_{2k_h+k_j-1}^1 kj(1+\varepsilon-k_j-k_h)d\varepsilon - zk_j & \text{for } 1-2k_h < k_j \\ & \leq 2-2k_h, \\ \int_0^1 \frac{1+\varepsilon-k_j}{2} k_j d\varepsilon - zk_j & \text{for } 2-2k_h < k_j \\ & \leq 1, \\ \int_{k_j-1}^1 \frac{1+\varepsilon-k_j}{2} k_j d\varepsilon - zk_j & \text{for } 1 < k_j \leq 2, \\ -zkj & \text{for } k_j > 2. \end{cases} \tag{10}$$

If $k_j = k_h$ firm j's profit in terms of the firms' chosen capacities is given by $\tilde{\Pi}_j(k_j, k_h) = \frac{1}{2}\bar{\Pi}_j(k_j, k_h) + \frac{1}{2}\underline{\Pi}_j(k_j, k_h)$. From the expected profit functions in (9) and (10) one can derive the best response functions $k_A(k_B)$ and $k_B(k_A)$

of the two firms.[10] The analysis of the best response functions yields:

Proposition 3 *If the two firms do not have to fix a price before they can observe the realisation of demand and choose their generation capacity simultaneously, no subgame perfect Nash equilibrium in pure strategies exists, if $z < \frac{1}{2}$. For $z \geq \frac{1}{2}$ there is a unique subgame perfect Nash equilibrium in pure strategies where both firms choose the same level of capacity $\tilde{k}_j(z)$ with*

$$\tilde{k}_j(z) = \max\left\{\frac{1}{2} - \frac{z}{3}, 0\right\}.$$

Proof: The overall best response of a firm $j = A, B$ in capacity for a given capacity of its rival k_h with $h = A, B$ and $h \neq j$ is represented by one of the equations (15)-(15′) or (16)-(16″) in Appendix D depending on the capacity costs z. The best responses $k_A(k_B)$ and $[k_B(k_A)]^{-1}$ cut exactly once if $k_A(k_B)$ and $k_B(k_A)$ are represented by (16), (16′) or (16″) meaning that $z \geq \frac{1}{2}$. At the cutting point $k_A = k_B = \tilde{k}_j(z)$ holds. If $z < \frac{1}{2}$ the best responses $k_A(k_B)$ and $k_B(k_A)$ coincide either with (15) or with (15′). In both cases the best responses are discontinuous and do not intersect at any point. ■

The condition $z \geq \frac{1}{2}$ must be satisfied in order to ensure the existence of an equilibrium in pure strategies because only in this case will the equilibrium price always be determined by the scarcity of the capacity. The auctioneer sets $p = 1 + \varepsilon - k_A - k_B$ no matter which demand shock $\varepsilon \in [0, 1]$ is chosen by nature. If $z < \frac{1}{2}$ holds, the firms might also play those bidding equilibria that occur in area $\mathcal{B}$, $\mathcal{B}'$ or $\mathcal{C}$ of Figure 1 for some $\varepsilon \in [0, 1]$ meaning that only the smaller supplier uses his total capacity whereas the supplier with the larger capacity uses only part of it. Given symmetric capacities both firms prefer to reduce their capacity in this situation.

The non-existence of pure strategy equilibria for relatively low capacity costs has its analogue in the literature on two stage games with an uncertain demand where firms set capacities in the first stage and prices in the second and where consumers are allocated to the cheaper supplier according to an efficient rationing rule in those cases where the capacities are not totally used. For a demand with an additive demand shock Reynolds and Wilson (2000) show that a symmetric subgame perfect Nash equilibrium fails to exist if the minimum shift parameter of the demand is smaller than the expected value of the shift parameter minus the constant capacity costs. This translates for the uncertain demand assumed here to $1 < E(1 + \varepsilon) - z \Leftrightarrow z < \frac{1}{2}$. Note that prices are determined in a different way here than in Reynolds

[10] See Appendix D.

and Wilson (2000), because different bids in the auction do not result in different prices on the market but in one market clearing price. Nevertheless our result points to an equivalence between the two models because in our setting the symmetric subgame perfect Nash equilibrium in pure strategies is destroyed at the same level of z as would be predicted by Reynolds and Wilson (2000).[11]

Given a subgame perfect Nash equilibrium exists, then the total investment in capacity by the two firms $\tilde{k}_d(z) = \tilde{k}_A(z) + \tilde{k}_B(z)$ is still too low from the point of view of a social planner because $\tilde{k}_d(z) = \frac{2}{3}k^*(z)$ holds for all capacity costs z that ensure positive investments.

Comparing the investments in generation capacity by the monopolist if he sets a price after observing demand, with the total investment in the duopoly setting where the firms bid prices also after observing demand and choose their capacities simultaneously reveals the following:

Corollary 1 *If $\frac{1}{2} \leq z < \frac{3}{2}$, then the monopolist chooses always a lower capacity than the two firms in the duopoly together, meaning $\tilde{k}_d(z) > \tilde{k}_m(z)$, given that in both cases consumer prices are determined after the observation of the uncertain demand. If $z \geq \frac{3}{2}$ investments in capacity are zero under both market structures.*

The incentive of a monopolist to supply too small quantities leads to smaller generation capacities than in the duopoly setting for those cases where a subgame perfect equilibrium in pure strategies exists. If consumers can receive real time price signals, the balancing of supply and demand is not such a big problem. Black-outs never occur, no matter whether a monopolist sets a consumer price or whether the consumer price is determined in an auction where two firms bid prices. The necessary balancing of supply and demand does not create an externality here. Therefore the monopolist cannot be more efficient than the duopoly.

4.3 Sequential Capacity Choices with Flexible Prices

If the capacities are chosen sequentially the follower firm B observes the capacity choice of the leader firm A. For given capacities k_A its profits is given either by $\bar{\Pi}_B(k_B, k_A)$ from (9) if $k_B > k_A$ or by $\underline{\Pi}_B(k_B, k_A)$ from (10) if $k_B < k_A$ or by $\frac{1}{2}\bar{\Pi}_B(k_B, k_A) + \frac{1}{2}\underline{\Pi}_B(k_B, k_A)$ if $k_B = k_A$ holds. Therefore firm B chooses its capacity according to the relevant best response $k_B(k_A)$

[11] See their Corollary on p.129.

that is given either in one of the equations (15)-(15′) or in (16)-(16″) in Appendix D depending on the level of the capacity costs z. Firm B's capacity choice is anticipated by the leader, firm A. Firm A chooses its capacity k_A such that it maximises its profits $\Pi_A(k_A, k_B(k_A))$.[12] The analysis of the leaders profit function $\Pi_A(k_A, k_B(k_A))$ yields Proposition 4 where we use the following definitions:

$$\begin{aligned}\hat{k}_A &= \frac{1}{18}\left[\frac{\sqrt[3]{16}(5-18z)}{\sqrt[3]{11+54z-108\sqrt{2z^3}+\sqrt{(11+54z-108\sqrt{2z^3})^2-4(18z-5)^3}}}\right. \\ &\quad +1-\sqrt[3]{4}\Big(11+54z-108\sqrt{2z^3} \qquad (11) \\ &\quad \left.+\sqrt{(11+54z-108\sqrt{2z^3})^2-4(18z-5)^3}\Big)^{\frac{1}{3}}\right].\end{aligned}$$

$$\begin{aligned}\breve{k}_A &= \left\{k_A \in \left(\frac{1}{3}(2-\sqrt{\frac{12z-1}{5}}), \frac{5+4z}{8}\right]\middle| -3043-2688z+708z^2\right. \qquad (12) \\ &\quad +784z^3+(14544+8784z-864z^2)k_A-(23796+8112z+528z^2)k_A^2 \\ &\quad \left.+(16416+3264z)k_A^3-(5056+256z)k_A^4+512k_A^5\right\}\end{aligned}$$

Proposition 4 *If the two firms do not have to fix a price before they can observe the uncertain demand and choose their generation capacity sequentially, a subgame perfect Nash equilibrium in pure strategies always exists and is unique. The capacity choices are for* $0 \leq z < 0.4432$*:*

$$\tilde{k}_A^l = \hat{k}_A \text{ and } \tilde{k}_B^f = \hat{k}_A - \mu \text{ with } \mu \to 0$$

being the smallest unit of capacity that can be installed, for $0.4432 \leq z < 0.6580$*:*

$$\tilde{k}_A^l = \breve{k}_A \text{ and } \tilde{k}_B^f = \frac{1}{3}\left[6-4\breve{k}_A-\sqrt{3(5+4z)-4(6-\breve{k}_A)\breve{k}_A}\right],$$

for $0.6580 \leq z < \frac{7}{10}$*:*

$$\tilde{k}_A^l = \frac{1+2z}{6} \text{ and } \tilde{k}_B^f = \frac{2}{3}(1-z),$$

[12]See Appendix E for the profit function $\Pi_A(k_A, k_B(k_A))$.

for $\frac{7}{10} \leq z < \frac{3}{2}$*:*

$$\tilde{k}_A^l = \frac{3}{4} - \frac{z}{2} \text{ and } \tilde{k}_B^f = \frac{1}{2}\left[\frac{3}{4} - \frac{z}{2}\right]$$

and for $z \geq \frac{3}{2}$*:*

$$\tilde{k}_A^l = 0 = \tilde{k}_B^f$$

where $\hat{k}_A$ *and* $\breve{k}_A$ *are given in (11) and implicitly in (12).*

Proof: See Appendix E for the derivation of the leader's optimal capacity choice. Firm B's capacity choice results from substituting firm A's optimal capacity in the relevant best response of firm B given in Appendix D. ■

Thus, the leader always ensures that he installs a larger generation capacity than his follower. Given that in our setting the larger provider can play the more profitable role in the auction, this does not come as a surprise. If the capacity cost is sufficiently small the difference between the two suppliers becomes, however, pretty small, whenever the leader plays the capacity where the followers best response is discontinuous.

Let us define the aggregate capacity in the sequential duopoly as $\tilde{k}_d^s(z) = \tilde{k}_A^l(z) + \tilde{k}_B^f(z)$. If we compare it with the aggregate capacity $k_d(z)$ when firms choose their capacities simultaneously, it turns out that the total capacity is larger, if firms choose their capacity sequentially in all those cases where a subgame perfect Nash equilibrium exists in the simultaneous case. This result corresponds to the usual result obtained from Cournot competition where the aggregate supply with sequential moves is higher than with simultaneous moves. If we compare the total investment in capacity by the two firms $\tilde{k}_d^s(z)$ when they choose capacities sequentially with the efficient level of capacity $k^*(z)$ given in Proposition 1, it turns out, however, that the total capacity is still too low from the point of view of a social planner.

Comparing the investments in generation capacity by the monopolist if he sets prices after demand can be observed with the total investment in the duopoly setting where the firms bid prices after they observe the demand and choose capacities sequentially reveals the following:

Corollary 2 *If* $0 \leq z < 0.0056$*, then the monopolist chooses a higher capacity than the two duopolists together in the sequential duopoly setting. For* $0.0056 \leq z < \frac{3}{2}$*, the monopolist chooses always a lower capacity than the two firms together. If* $z \geq \frac{3}{2}$*, investments in capacity are zero under both market structures.*

Note that for $z < \frac{1}{2}$ it was not possible to derive a subgame perfect equilibrium in pure strategies for the simultaneous move game. In these cases the leader always chooses capacities where he, as the provider with the larger capacity, will for some low levels of demand shocks not use his total capacity at the resulting auction price. This weakens his incentive to invest in capacity. The monopolist also does not always use his total capacity at these low levels of capacity costs. Nevertheless, he invests more than the two duopolists together with very low capacity costs because the possibility to realise a full monopoly profit for a wider range of demand shocks more than compensates him for the additional capacity costs. With these very low capacity costs the leader in the sequential duopoly game chooses the smallest capacity that ensures him a larger capacity than his rival. He does not want to increase his capacity beyond this point because he cannot earn the full monopoly profit but only the monopoly profit on the residual demand that is not served by the smaller follower. Given that the follower's best response is upward sloping for all larger capacities, an increase in his capacity also increases the rival's capacity and reduces the residual demand on which he can earn a monopoly profit. Thus, installing a larger capacity does, on the one hand, result in a wider range of demand shocks where the leader earns a monopoly profit on the residual demand. On the other hand, this profit becomes always smaller and additional capacity costs must be born by the leader. Therefore the leader has a smaller incentive to install capacity than the monopolist and the additional capacity of the follower is not sufficient to weigh out this effect.

Comparing the social welfare realised in the sequential duopoly setting with the social welfare in the monopoly case reveals the following:

Corollary 3 *The social welfare with two competing firms that choose their capacities sequentially is always higher than the social welfare with a monopolist.*

The realised social welfare with a monopolist is always lower than with two competing firms, despite the higher capacity level installed by the monopolist for very low capacity costs. This is due to the fact that the monopolist sets a much higher price than would be preferred by the social planner. Although his capacity investment is closer to the efficient level for small capacity costs, he underuses his capacity.

5 Conclusions

The analysis pursued here confirms the intuition of the proponents of a better metering technology. If consumers can instantaneously respond to price signals and can therefore directly take part in the electricity auction, then competition does not destroy the incentive to invest in generation capacity. In almost all cases for which we can derive subgame perfect equilibria in pure strategies is the level of investment with two competing firms closer to the efficient level than with a monopolist.

Only for very small capacity costs does the monopolist invest more than the two duopolists together with sequential capacity choices. The social welfare level is, however, also in these cases lower with a monopolist than with two competing firms despite the monopolist's capacity investment that is closer to the efficient level. The reason for this result is that the monopolist does not obey the first best pricing rule. Even if he invests more in capacity he underuses this capacity and does therefore not generate as much social welfare as the two duopolists with a smaller aggregate level of investment.

Since demand responds to the price signals of the auctioneer it is no problem for him to find prices that balance demand and supply. No black-outs occur. Therefore the externalities in the network are not that important, and the better ability of a monopolist to internalize externalities does not compensate for his tendency to reduce his output. Nevertheless, is the level of investment never socially efficient, because we have underinvestment also in all the analysed duopoly cases. Given the demand that responds to price signals instantaneously, we would expect, however, that more competition improves the incentive to invest in generation capacity.

In a companion paper we will analyse a situation where demand cannot respond instantaneously on price signals and where the firms compete in retail price before the uncertainty of demand is revealed.

Appendix

A Derivation of the First Best Capacity

Integrating (4) results in the following social welfare function:

$$W(k) = \begin{cases} \frac{(3-k)k}{2} - \frac{2}{3} - kz & \text{for } 0 \leq k \leq 1, \\ \frac{4k-1}{2} + \frac{k^3-2}{6} - k^2 - kz & \text{for } 1 < k \leq 2 \\ \frac{1}{2} - kz & \text{for } k > 2 \end{cases} . \tag{13}$$

Maximising (13) with respect to k yields the first best capacity k^* given in Proposition 1.

B The Unconstrained Monopolist's Capacity Choice

Integrating (5) results in the following expected profit function for the monopolist:

$$\tilde{\Pi}_m(k) = \begin{cases} \left(\frac{3}{2} - k\right) k - zk & \text{for } 0 \leq k \leq \frac{1}{2} \\ 2k(1-k) + \frac{1}{12}(8k^3 - 1) - zk & \text{for } \frac{1}{2} < k \leq 1 \\ \frac{7}{12} - zk & \text{for } k > 1 \end{cases} \tag{14}$$

Maximising (14) with respect to k yields the capacity choice $\tilde{k}_m$ of an uncommitted monopolist given in Proposition 2.

C The Best Responses in Bid Prices

From the analysis of (7) and (8) the best response in bid prices can be derived for firm j. The best response for $k_j \geq 1 + \varepsilon$ in prices is given by:

$$p_j = \begin{cases} \frac{1+\varepsilon-k_h}{2} & \text{for } p_h \leq \frac{1+\varepsilon-\sqrt{k_h(2+\varepsilon-k_h)}}{2}, \\ \min\left\{p_h - \varrho, \frac{1+\varepsilon}{2}\right\} & \text{for } p_h > \frac{1+\varepsilon-\sqrt{k_h(2+\varepsilon-k_h)}}{4} \end{cases}$$

if $k_h < 1+\varepsilon$ and

$$p_j = \min\left\{p_h - \varrho, \frac{1+\varepsilon}{2}\right\}$$

if $k_h \geq 1+\varepsilon$ where $\varrho \to 0$ is the smallest unit in which prices can be announced to the auctioneer.

The best response for $1+\varepsilon > k_j \geq (1+\varepsilon)/2$ in bid prices is given by:

$$p_j \begin{cases} = \frac{1+\varepsilon-k_h}{2} & \text{for } p_h \leq \frac{(1+\varepsilon-k_h)^2}{4k_j}, \\ < p_h & \text{for } \frac{(1+\varepsilon-k_h)^2}{4k_j} < p_h \leq 1+\varepsilon-k_j, \\ = \min\left\{p_h - \varrho, \frac{1+\varepsilon}{2}\right\} & \text{for } p_h > 1+\varepsilon-k_j, \end{cases}$$

if $k_h < 1+\varepsilon$ and

$$p_j \begin{cases} < p_h & \text{for } p_h \leq 1+\varepsilon-k_j, \\ = \min\left\{p_h - \varrho, \frac{1+\varepsilon}{2}\right\} & \text{for } p_h > 1+\varepsilon-k_j, \end{cases}$$

if $k_h \geq 1+\varepsilon$.

The best response for $(1+\varepsilon)/2 > k_j \geq (1+\varepsilon-k_h)/2$ in bid prices is given by:

$$p_j \begin{cases} = \frac{1+\varepsilon-k_h}{2} & \text{for } p_h \leq \frac{(1+\varepsilon-k_h)^2}{4k_j}, \\ < \min\{p_h, 1+\varepsilon-k_j\} & \text{for } p_h > \frac{(1+\varepsilon-k_h)^2}{4k_j}, \end{cases}$$

if $k_h < 1+\varepsilon$ and

$$p_j < \min\{p_h, 1+\varepsilon-k_j\}$$

if $k_h \geq 1+\varepsilon$.

The best response for $k_j < (1+\varepsilon-k_h)/2$ in prices is given by:

$$p_j \begin{cases} \leq 1+\varepsilon-k_j-k_h & \text{for } p_h \leq 1+\varepsilon-k_h-k_j, \\ < \min\{p_h, 1+\varepsilon-k_j\} & \text{for } p_h > 1+\varepsilon-k_j-k_h, \end{cases}$$

if $k_h < 1+\varepsilon$ and

$$p_j < \min\{p_h, 1+\varepsilon-k_j\}$$

if $k_h \geq 1+\varepsilon$.

D The Best Responses in Generation Capacity

Integrating $\bar{\Pi}_j(k_j, k_h)$ from (9) yields:

$$\bar{\Pi}_j(k_j,k_h) = \begin{cases} k_j(\frac{3}{2} - k_h - k_j) - zk_j & \text{for } 0 < k_j \\ & \leq \frac{1-k_h}{2}, \\ \frac{k_h(1-k_h)}{4} - \frac{1-k_h^3}{12} + \frac{2k_j^3}{3} + \frac{k_j(2-k_h)(2-k_h-2k_j)}{2} - zk_j & \text{for } \frac{1-k_h}{2} < k_j \\ & \leq \frac{2-k_h}{2}, \\ \frac{1}{4}\left[\frac{7}{3} - (3-k_h)k_h\right] - zk_j & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } k_h \leq 1, \\ \frac{(2-k_h)^3}{12} - zk_j & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } 1 < k_h \leq 2, \\ -zkj & \text{for } \frac{2-k_h}{2} < k_j \\ & \text{and } k_h > 2. \end{cases}$$

From Analysing and Differentiating $\bar{\Pi}_j(k_j, k_h)$ with respect to k_j we can derive the best response $\bar{k}_j(k_h)$ from above, meaning the best response of firm j if it is restricted to $k_j \geq k_h$. It is given by:

$$\bar{k}_j(k_h) = \begin{cases} 1 - \frac{k_h}{2} - \sqrt{\frac{z}{2}} & \text{if } k_h \leq \frac{1}{3}\left(2 - \sqrt{2z}\right) \\ k_h & \text{if } k_h > \frac{1}{3}\left(2 - \sqrt{2z}\right) \end{cases}$$

for $0 \leq z < \frac{1}{2}$, by:

$$\bar{k}_j(k_h) = \begin{cases} \frac{3}{4} - \frac{k_h}{2} - \frac{z}{2} & \text{if } k_h \leq \frac{1}{2}\left(1 - \frac{2z}{3}\right) \\ k_h & \text{if } k_h > \frac{1}{2}\left(1 - \frac{2z}{3}\right) \end{cases}$$

for $\frac{1}{2} \leq z < \frac{3}{2}$ and by $\bar{k}_j(k_h) = 0$ for $z \geq \frac{3}{2}$.

Integrating $\underline{\Pi}_j(k_j, k_h)$ from (10) results in:

$$\underline{\Pi}_j(k_j,k_h) = \begin{cases} k_j(\frac{3}{2} - k_h - k_j) - zk_j & \text{for } 0 < k_j \\ & \leq 1 - 2k_h, \\ k_j\left[\frac{7}{4} + k_j^2 - (2-kh)k_h - k_j\left(\frac{3}{2} - k_h\right)\right] - zk_j & \text{for } 1 - 2k_h < k_j \\ & \leq 2 - 2k_h, \\ k_j\frac{3-2k_j}{4} - zk_j & \text{for } 2 - 2k_h < k_j \\ & \leq 1, \\ k_j\frac{(2-k_j)^2}{4} - zk_j & \text{for } 1 < k_j \leq 2, \\ -zkj & \text{for } k_j > 2. \end{cases}$$

By Differentiating $\underline{\Pi}_j(k_j, k_h)$ with respect to k_j we obtain the best response $\underline{k}_j(k_h)$ from below, meaning the best response of firm j if it is restricted to $k_j \leq k_h$. It is given by:

$$\underline{k}_j(k_h) = \begin{cases} k_h & \text{if } 0 \leq k_h \leq \frac{1}{3}, \\ k_h - \mu & \text{if } \frac{1}{3} < k_h \leq \frac{3}{4} - z, \\ \frac{3}{4} - z & \text{if } k_h > \frac{3}{4} - z, \end{cases}$$

for $0 \leq z < \frac{1}{12}$, by:

$$\underline{k}_j(k_h) = \begin{cases} k_h & \text{if } 0 \leq k_h \leq \frac{1}{3}, \\ k_h - \mu & \text{if } \frac{1}{3} < k_h \leq \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right), \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right) < k_h \leq \frac{5+4z}{8} \\ \frac{3}{4} - z & \text{if } k_h > \frac{5+4z}{8}, \end{cases}$$

for $\frac{1}{12} \leq z < \frac{1}{2}$, by:

$$\underline{k}_j(k_h) = \begin{cases} k_h & \text{if } 0 \leq k_h \leq \frac{1}{2} - \frac{z}{3}, \\ \frac{1}{2}\left(\frac{3}{2} - k_h - z\right) & \text{if } \frac{1}{2} - \frac{z}{3} < k_h \leq \frac{1+2z}{6}, \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1+2z}{6} < k_h \leq \frac{5+4z}{8} \\ \frac{3}{4} - z & \text{if } k_h > \frac{5+4z}{8}, \end{cases}$$

for $\frac{1}{2} \leq z < \frac{3}{4}$, by

$$\underline{k}_j(k_h) = \begin{cases} k_h & \text{if } 0 \leq k_h \leq \frac{1}{2} - \frac{z}{3}, \\ \frac{1}{2}\left(\frac{3}{2} - k_h - z\right) & \text{if } \frac{1}{2} - \frac{z}{3} < k_h \leq \frac{1+2z}{6}, \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1+2z}{6} < k_h \leq 1 - \frac{1}{2}\sqrt{4z-3} \\ 0 & \text{if } k_h > 1 - \frac{1}{2}\sqrt{4z-3}, \end{cases}$$

for $\frac{3}{4} \leq z < 1$, by

$$\underline{k}_j(k_h) = \begin{cases} k_h & \text{if } 0 \leq k_h \leq \frac{1}{2} - \frac{z}{3}, \\ \frac{1}{2}\left(\frac{3}{2} - k_h - z\right) & \text{if } \frac{1}{2} - \frac{z}{3} < k_h \leq \frac{3}{2} - z \\ 0 & \text{if } k_h > \frac{3}{2} - z, \end{cases}$$

for $1 \leq z < \frac{3}{2}$, and by $\underline{k}_j(k_h) = 0$ for $z \geq \frac{3}{2}$. Note that if firm j chooses a corner solution for $k_h > \frac{1}{3}$ and $z < 1/2$ its best response from below is $k_j = k_h - \mu$ rather than $k_j = k_h$ where $\mu \to 0$ is the smallest unit of capital that can be installed.

By substituting $\bar{k}_j(k_h)$ in $\bar{\Pi}_j(k_j, k_h)$ and $\underline{k}_j(k_h)$ in $\underline{\Pi}_j(k_j, k_h)$ and by comparing $\bar{\Pi}_j(\bar{k}_j(k_h), k_h)$ with $\underline{\Pi}_j(\underline{k}_j(k_h), k_h)$ one can derive the overall best response $k_j(k_h)$ of firm j. Firm j chooses its best response from above as long as $\bar{\Pi}_j(\bar{k}_j(k_h), k_h) > \underline{\Pi}_j(\underline{k}_j(k_h), k_h)$. Otherwise it chooses its best response from below. The overall best response $k_j(k_h)$ is discontinuous, if $z < \frac{1}{2}$. It is represented by:

$$k_j(k_h) = \begin{cases} 1 - \frac{k_h}{2} - \sqrt{\frac{z}{2}} & \text{if } 0 \leq k_h < \hat{k}_h \\ k_h - \mu & \text{if } \hat{k}_h \leq k_h \leq \frac{3}{4} - z \\ \frac{3}{4} - z & \text{if } k_h > \frac{3}{4} - z \end{cases} \tag{15}$$

for $0 \leq z < \frac{1}{12}$ and by:

$$k_j(k_h) = \begin{cases} 1 - \frac{k_h}{2} - \sqrt{\frac{z}{2}} & \text{if } 0 \leq k_h < \hat{k}_h \\ k_h - \mu & \text{if } \hat{k}_h \leq k_h \leq \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right), \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right) < k_h \leq \frac{5+4z}{8} \\ \frac{3}{4} - z & \text{if } k_h > \frac{5+4z}{8}, \end{cases} \tag{15'}$$

for $\frac{1}{12} \leq z < \frac{1}{2}$ with $\hat{k}_h = \hat{k}_A$ as defined in equation (11). The overall best response $k_j(k_h)$ jumps at $k_h = \hat{k}_h$ from the best response from above to the best response from below.

If $z \geq \frac{1}{2}$ holds the overall best response $k_j(k_h)$ is continuous and coincides with:

$$k_j(k_h) = \begin{cases} \frac{3}{4} - \frac{k_h}{2} - \frac{z}{2} & \text{if } k_h \leq \frac{1+2z}{6} \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1+2z}{6} < k_h \leq \frac{5+4z}{8} \\ \frac{3}{4} - z & \text{if } k_h > \frac{5+4z}{8}, \end{cases} \tag{16}$$

for $\frac{1}{2} \leq z < \frac{3}{4}$, with:

$$k_j(k_h) = \begin{cases} \frac{3}{4} - \frac{k_h}{2} - \frac{z}{2} & \text{if } k_h \leq \frac{1+2z}{6} \\ \frac{6-4k_h-\sqrt{3(5+4z)-4k_h(6-k_h)}}{3} & \text{if } \frac{1+2z}{6} < k_h \leq 1 - \frac{1}{2}\sqrt{4z-3} \\ 0 & \text{if } k_h > 1 - \frac{1}{2}\sqrt{4z-3}, \end{cases} \tag{16'}$$

for $\frac{3}{4} \leq z < 1$, with:

$$k_j(k_h) = \begin{cases} \frac{3}{4} - \frac{k_h}{2} - \frac{z}{2} & \text{if } k_h \leq \frac{3}{2} - z \\ 0 & \text{if } k_h > \frac{3}{2} - z, \end{cases} \tag{16''}$$

for $1 \leq z < \frac{3}{2}$ and with $k_j(k_h) = 0$ for $z \geq \frac{3}{2}$.

E The Leader's Profit Function

Taking into account the follower's best response function that is either given by one of the equations (15)-(15′) or by one of the equations (16)-(16″) in Appendix D one can derive the leader's profit function. It is given by:

$$\Pi_A(k_A, k_B(k_A)) = \begin{cases} \frac{1}{4}k_A(3 - 2k_A - 2z) & \text{if } 0 \leq k_A < \hat{k}_A, \\ \frac{1}{12}\left[3k_A\left(9 - k_A(17 - 9k_A)\right) - 1\right] - zk_A & \text{if } \hat{k}_A \leq k_A \leq \frac{2}{3}, \\ \frac{1}{4}\left[\frac{7}{3} - (3 - k_A)k_A\right] - zk_A & \text{if } \frac{2}{3} < k_A \leq \frac{3}{4} - z, \\ \frac{31}{192} + \frac{3}{8}z + \frac{z^2}{4} - zk_A & \text{if } k_A > \frac{3}{4} - z, \end{cases}$$

for $0 \le z < \frac{1}{12}$ where $\hat{k}_A$ is defined in (11), by:

$$\Pi_A(k_A, k_B(k_A)) = \begin{cases} \frac{1}{4}k_A(3 - 2k_A - 2z) & \text{if } 0 \le k_A < \hat{k}_A, \\ \frac{1}{12}\left[3k_A\left(9 - k_A(17 - 9k_A)\right) - 1\right] - zk_A & \text{if } \hat{k}_A \le k_A \le \\ & \quad \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right), \\ \frac{1}{2} - \frac{13}{18}k_A + \frac{1}{9}k_A^2 + \frac{8}{81}k_A^3 + \frac{z}{3} - \frac{7}{9}k_A z & \\ \quad -\frac{1}{162}\left(21 - 8(6 - k_A) + 6z\right) & \text{if } \frac{1}{3}\left(2 - \sqrt{\frac{12z-1}{5}}\right) \\ \quad \cdot\sqrt{3(5+4z) - 4k_A(6 - k_A)} & \quad < k_A \le \frac{5+4z}{8}, \\ \frac{31}{192} + \frac{3}{8}z + \frac{z^2}{4} - zk_A & \text{if } k_A > \frac{5+4z}{8}, \end{cases}$$

for $\frac{1}{12} \le z < \frac{1}{2}$, by:

$$\Pi_A(k_A, k_B(k_A)) = \begin{cases} \frac{1}{4}k_A(3 - 2k_A - 2z) & \text{if } 0 \le k_A < \frac{1+2z}{6}, \\ \frac{1}{2} - \frac{13}{18}k_A + \frac{1}{9}k_A^2 + \frac{8}{81}k_A^3 + \frac{z}{3} - \frac{7}{9}k_A z & \\ \quad -\frac{1}{162}\left(21 - 8(6 - k_A) + 6z\right) & \text{if } \frac{1+2z}{6} < k_A \\ \quad \cdot\sqrt{3(5+4z) - 4k_A(6 - k_A)} & \quad \le \frac{5+4z}{8}, \\ \frac{31}{192} + \frac{3}{8}z + \frac{z^2}{4} - zk_A & \text{if } k_A > \frac{5+4z}{8}, \end{cases}$$

for $\frac{1}{2} \le z < \frac{3}{4}$, by:

$$\Pi_A(k_A, k_B(k_A)) = \begin{cases} \frac{1}{4}k_A(3 - 2k_A - 2z) & \text{if } 0 \le k_A < \frac{1+2z}{6}, \\ \frac{1}{2} - \frac{13}{18}k_A + \frac{1}{9}k_A^2 + \frac{8}{81}k_A^3 + \frac{z}{3} - \frac{7}{9}k_A z & \\ \quad -\frac{1}{162}\left(21 - 8(6 - k_A) + 6z\right) & \text{if } \frac{1+2z}{6} < k_A \le \\ \quad \cdot\sqrt{3(5+4z) - 4k_A(6 - k_A)} & \quad 1 - \frac{1}{2}\sqrt{4z - 3}, \\ \frac{1}{3}k_A\left(6 - 2(3 - k_A)k_A\right) - \frac{1}{12} - zk_A & \text{if } k_A > \\ & \quad 1 - \frac{1}{2}\sqrt{4z - 3}, \end{cases}$$

for $\frac{3}{4} \le z < 1$ and by:

$$\Pi_A(k_A, k_B(k_A)) = \begin{cases} \frac{1}{4}k_A(3 - 2k_A - 2z) & \text{if } 0 \le k_A < \frac{3}{2} - z, \\ \frac{1}{2}k_A\left(3 - 2k_A\right) - zk_A & \text{if } k_A > \frac{3}{2} - z. \end{cases}$$

For $0 \le z < \frac{1}{2}$ the relevant profit function $\Pi_A(k_A, k_B(k_A))$ is discontinuous at $\hat{k}_A$ defined in (11). Firm A's profit $\Pi_A(k_A, k_B(k_A))$ increases for all $k_A < \hat{k}_A$, jumps up at $k_A = \hat{k}_A$, and decreases for all $k_A > \hat{k}_A$ if $0 \leq z \leq 0.2464$. For $0.2464 < z < \frac{1}{2}$ the profit function $\Pi_A(k_A, k_B(k_A))$ again increases for $k_A < \hat{k}_A$, jumps up at $k_A = \hat{k}_A$, decreases for $\hat{k}_A < k_A \leq \frac{1}{3}(2 - \sqrt{\frac{12z-1}{5}})$, but has a local maximum in the interval $k_A \in \left(\frac{1}{3}(2 - \sqrt{\frac{12z-1}{5}}), \frac{5+4z}{8}\right]$ at $\breve{k}_A$ as defined in (12) and decreases for $k_A > \frac{5+4z}{8}$. Comparing $\Pi_A(\hat{k}_A, k_B(\hat{k}_A))$ with $\Pi_A(\breve{k}_A, k_B(\breve{k}_A))$ yields that the point of discontinuity $\hat{k}_A$ is optimal for $0 \leq z < 0.4432$ whereas $\breve{k}_A$ is optimal for $0.4432 \leq z < \frac{1}{2}$. For $z \geq \frac{1}{2}$ firm B's best response $k_B(k_A)$ as well as firm A's profit function is continuous. For $\frac{1}{2} \leq z < 0.6580$ firm A's profit function $\Pi_A(k_A, k_B(k_A))$ increases for $0 \leq k_A \leq \frac{1+2z}{6}$ has an inner maximum in the interval $k_A \in \left(\frac{1+2z}{6}, \frac{5+4z}{8}\right]$ at $k_A = \breve{k}_A$ from (12) and decreases for $k_A > \frac{5+4z}{8}$. For $0.6580 \leq z < \frac{7}{10}$ firm A's profit function $\Pi_A(k_A, k_B(k_A))$ increases for $0 \leq k_A \leq \frac{1+2z}{6}$ and decreases for $k_A > \frac{1+2z}{6}$. Finally, if $\frac{7}{10} \leq z < \frac{3}{2}$ firm A's profit function $\Pi_A(k_A, k_B(k_A))$ has an interior maximum in the interval $k_A \in \left[0, \min\{\frac{1+2z}{6}, \frac{3}{2} - z\}\right]$ at $k_A = \frac{3}{4} - \frac{z}{2}$.

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