Strategic Use of Available Capacity in the Electricity Spot Market

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Abstract

The literature on deregulated electricity markets generally assumes available capacities to be given. In contrast, this paper studies a model where firms precommit to capacity levels before competing in a uniform price auction. The analysis sheds light on recent empirical findings that firms use their available capacity to obtain high market prices. There exist two equilibria where at least one firm withholds its available capacity to induce the maximum price. Moreover, in one equilibrium, the inefficient firm obtains a relatively large market share.

Key Words: spot market, capacity game, auction mechanism, electricity.

JEL classification: C72; D43; D44; L13; L94.

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1 Introduction

Many countries have created an electricity spot market in order to deregulate their electricity sector. Spot markets are supposed to provide strong incentives for efficient and least-cost production. However, empirical studies indicate large markups during periods of high demand (e.g. von der Fehr and Harbord (1993), Wolfram (1998, 1999), or Borenstein and Bushnell (1999)). Moreover, there is evidence that major generators use their available capacity strategically in order to enhance their market power. For the period 1991 to 1995, Patrick and Wolak (2001) find empirical evidence of such strategic behavior in the British market. During the first quarter of 1999, the Spanish competition authority accused the two major firms on the national market of reducing their available capacity in areas with high demand. In January 2000, the Nordic electricity spot market experienced unexpectedly high prices, due to a reduction in available nuclear production (Nord Pool, 2000). During the summer of 2000 in California, the monthly electricity bills were three times higher than usual, while several units were declared unavailable and simultaneously taken out of service (Sioshansi, 2000).

This paper is motivated by the above empirical observations. Available capacities (unlike installed capacity) are choice variables in the short run, since plants can be rendered "unavailable" for maintenance and other reliability considerations.[1] In an electricity spot market, producers make a price bid to supply a given amount of electricity (their available capacity) and the market clearing price is determined by a uniform price auction. Hence, the potential for market power depends heavily on this available capacity.

This paper proposes a two-stage model with asymmetric cost firms, an

[1] Installed capacity determines the firms' overall production capacity. In contrast, available capacity is the capacity used at short notice, which takes into account breakdowns or other unforseeable events.

efficient and an inefficient firm, respectively. In the first period, firms simultaneously choose their available capacity. After observing the capacity levels, the firms set the minimum price for this available capacity. The analysis shows that two subgame perfect equilibria exist where at least one firm withholds its available capacity to induce the maximum price.

Due to the uniform price auction in the price subgame, the market price equals the highest price bid, if demand is higher than the the available capacity of the lowest price bidder. Otherwise, the market price equals the lowest price bid. The lowest price bidder then has an incentive to withhold its capacity, that is, offer an available capacity below demand. In this case, the market price equals the highest bid, the lowest price bidder sells its entire capacity and the other sells the residual demand. Interestingly, the inefficient firm is the lowest price bidder and obtains a relatively large market share in one of the two equilibria.

Withholding capacity has two negative welfare implications. First, when firms are free to choose their capacities, they obtain a market price above the competitive outcome. This is costly for consumers. Second, the efficient firm does not supply the entire demand, since the inefficient firm has a positive market share. This implies that production costs are not minimized.

The literature on the restructured electricity market mainly focuses on the producers' pricing decision.[2] Von der Fehr and Harbord (1993) construct a well-known model where generators compete by submitting bids specifying the prices at which they are willing to make their production available. This setup allows them to identify the price bidding strategies.[3] In particular,

[2] For a recent survey of the theoretical and empirical literature, see von der Fehr and Harbord (1998).

[3] An alternative way of modelling price competition in the electricity spot market has been proposed by Green and Newbery (1992). They assume that firms compete by submitting continuous supply functions, rather than discrete step functions. In the electricity

they show that the level of demand (relative to given available capacities) is important for explaining high market prices on the electricity spot market. This paper extends the von der Fehr and Harbord (1993) model by endogenizing the firms' capacity choices. It complements their analysis by showing more precisely how, in line with the empirical evidence, firms may manipulate their available capacities in order to obtain substantial markups.

Like Kreps and Scheinkman (1983), I consider a two-stage game where firms choose capacities and then compete through prices. However, I obtain different results despite the similarity in the timing of the game. In particular, the reduced-form profit function has the Monopoly form (instead of the Cournot form in the Kreps and Scheinkman model). The most important reason is that the second stage is modeled as a uniform-price auction (instead of Bertrand competition), to follow the actual design of many electricity spot markets (see section 2 for details).

Section 2 introduces the model. Then, the pure strategy Nash equilibria in price bids for given capacity combinations are given in section 3. This yields reaction functions in the capacity space (section 4), which I use to find subgame perfect equilibria for the two-stage game (section 5). The final remarks are given in section 6.

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sector, one unit of capacity is a power plant. Therefore I consider capacity as a discrete variable and I adopt the von der Fehr and Harbord's setup.

2 The Model

Five features are important for capturing the strategic behavior of producers on an electricity spot market. First, a day is divided into periods[4] and, for each period, a uniform-price auction takes place to determine the electricity spot price. Second, the responsible for the market (namely the dispatcher) forecasts a fixed level of demand for each period. Third, producers are responsible for the supply by declaring how much they can produce (available capacity) and at what price (price bid). Since the production of electricity must be planned, the available capacity is determined the day before the transaction and differs from the installed capacity. If a plant is declared unavailable, it is usually announced and published on the home page of the dispatcher. When producers set their prices, they thus play a capacity-constrained game. Fourth, the electricity market has an oligopolistic structure, usually with two dominant actors.[5] Fifth, different production technologies characterized by different costs are used.[6] All these five features are taken into account in the formalization below.

Consider a market for a homogeneous good supplied by two firms. The demand for this good is fixed and given by d. Firms interact in two periods. In the first period, firms 1 and 2 simultaneously and independently choose their available capacities denoted k_1 and k_2, respectively, where capacity k_i means that firm i subsequently produces up to k_i units of electricity at a specific marginal cost.[7] At the end of the first period, each firm learns

[4] On the electricity spot market, the period is usually one hour or half an hour and it is called the load.

[5] This is the case with high demand levels where many producers reach their full output capacities and therefore have no impact on market outcome.

[6] Most electricity is generated by burning fossil fuel (coal, oil, or natural gas) or by nuclear fuel, or by water power (hydroelectricity). Clearly, the costs associated with these production technologies differ.

[7] Note that each firm has an installed capacity exceeding the level of demand. However,

about the capacity of its opponent, and in the second period, firms 1 and 2 simultaneously and independently name price bids p_1 and p_2, respectively. Each firm has its own marginal cost, namely c_1 and c_2, with $c_1 < c_2$.[8] Firm 1 is the efficient firm and firm 2 is the inefficient firm.

Let $s = (s_1, s_2)$ be the bids submitted by firms 1 and 2, where $s_i = (p_i, k_i)$ $(i \in \{1, 2\})$ and let $P(s)$ and $x_i(s)$ for $i = \{1, 2\}$ denote the market price and the firms' production sold when bids are s.

Without loss of generality, I assume that $c_1 = 0$, $c_2 \leq p_i$ for $(i \in \{1, 2\})$ and efficient rationing is applied when $p_1 = p_2$ (the dispatcher buys first from the lowest price firm). Furthermore, let p^m denote the maximum price so that $p_i \leq p^m$ for $(i \in \{1, 2\})$.[9]

In a uniform-price auction, firms sell their production at the *same* market price, which equals the lowest price bid only if the lowest price bidder can meet the entire demand. Otherwise, the market price equals the highest price bid. Hence,

$$P(s) = \begin{cases} p_i = \min\{p_1, p_2\} & \text{if } \ k_i \geq d; \\ \max\{p_1, p_2\} & \text{otherwise.} \end{cases} \tag{1}$$

Note that the efficient firm (firm 1) supplies $\min\{k_1, d\}$, whenever $p_1 \leq p_2$, and the residual demand $\max\{0, d - k_2\}$, whenever it submits a strictly higher price bid. Hence:

$$x_1(s) = \begin{cases} \min\{k_1, d\} & \text{if } p_1 \leq p_2; \\ \max\{0, d - k_2\} & \text{if } p_1 > p_2. \end{cases} \tag{2}$$

Firm 2 (with the highest cost) sells the residual demand $\max\{0, d - k_1\}$, whenever $p_1 \leq p_2$, and $\min\{k_2, d\}$, whenever it submits a strictly lower price

their available capacity might be lower than the demand level.

[8]It is commonly assumed that there are no start-up costs and constant marginal costs for available capacity (as opposed to installed capacity).

[9]Note that without a maximum price, profits can be infinite, since demand is perfectly inelastic. The maximum price can be interpreted as a price cap corresponding to the highest production cost of power plants.

bid:

$$x_2(s) = \begin{cases} \min\{k_2, d\} & \text{if } p_2 < p_1; \\ \min\{k_2, \max\{0, d - k_1\}\} & \text{if } p_1 \leq p_2. \end{cases} . \tag{3}$$

Note that in a uniform price auction, the lowest price bidder can sell its entire capacity at the highest price bid. This is the case when this firm cannot meet the entire demand. Firm i's profit, as a function of the bids submitted by firms i and j, is given by

$$\pi_i\left(s_i, s_j\right) = \left[P\left(s\right) - c_i\right] x_i\left(s\right), \ for \ \left(i, j \in \{1, 2\} \text{ and } i \neq j\right). \tag{4}$$

Each firm seeks to maximize its profits, and the above structure is common knowledge between firms.

Now, I derive the subgame-perfect equilibria of the two-stage game by backward induction.

3 The capacity-constrained subgame

A pair (p_1^*, p_2^*) is a Nash equilibrium of the price subgame, given $(k_1, k_2) \in R_+^2$ if

$$\begin{aligned} p_1^* &= \arg\max_{p_1} P\left[\left(p_1, k_1\right), \left(p_2^*, k_2\right)\right] x_1\left[\left(p_1, k_1\right), \left(p_2^*, k_2\right)\right] \text{ and} \\ p_2^* &= \arg\max_{p_2} \left(P\left[\left(p_1^*, k_1\right), \left(p_2, k_2\right)\right] - c_2\right) x_2\left[\left(p_1^*, k_1\right), \left(p_2, k_2\right)\right]. \end{aligned}$$

where functions P and x_i are defined in equations (1)-(3) respectively.

Proposition 1 *(Refer to Figure 1) In terms of the subgame equilibria, it is convenient to partition the configurations of capacities into the four categories of supply.*

1.*(Strong supply). If* $\min\{k_1, k_2\} \geq d$*, then*

$$p_i^*(k_1, k_2) = c_2, \text{ for } i \in \{1, 2\}.$$

2. *(Weak supply). If* $k_1 + k_2 \leq d$*, then*

$$p_i^*(k_1, k_2) = p^m, \text{ for } i \in \{1, 2\}.$$

3. *(Asymmetric supply). If* $\min\{k_1, k_2\} < d \leq \max\{k_1, k_2\}$*, then*

$$p_1^*(k_1, k_2) = \begin{cases} p^m & \text{if } k_2 \leq (1 - c_2/p^m)\, d < d \leq k_1; \\ c_2 & \text{otherwise.} \end{cases}$$

$$p_2^*(k_1, k_2) = \begin{cases} p^m & \text{if } k_1 < d \leq k_2; \\ c_2 & \text{otherwise.} \end{cases}$$

4. *(Intermediate supply). If* $\max\{k_1, k_2\} < d$ *and* $k_1 + k_2 > d$*, then*

$$(p_1^*(k_1, k_2), p_2^*(k_1, k_2)) \in \begin{cases} \{(c_2, p^m)\} & \text{if } k_2 > d - (c_2/p^m)\, k_1; \\ \{(c_2, p^m), (p^m, c_2)\} & \text{otherwise.} \end{cases}$$

Proof: : See Appendix A.

The subgame price equilibria found in Proposition 1 are given by the vectors in brackets in Figure 1. Note that the equilibria are unique except for intermediate supply when $k_2 \leq d - (c_2/p^m)\, k_1$. In this later case, let IS^L denote the equilibrium where firm 1 submits the lowest price bid c_2 (in which case, firm 2 submits p^m). Similarly, let IS^H denote the equilibrium where firm 1 submits the highest price bid p^m (in which case, firm 2 submits c_2).

Von der Fehr and Harbord find most of the results of Proposition 1, even though the setup is not exactly the same. I only consider pure strategy

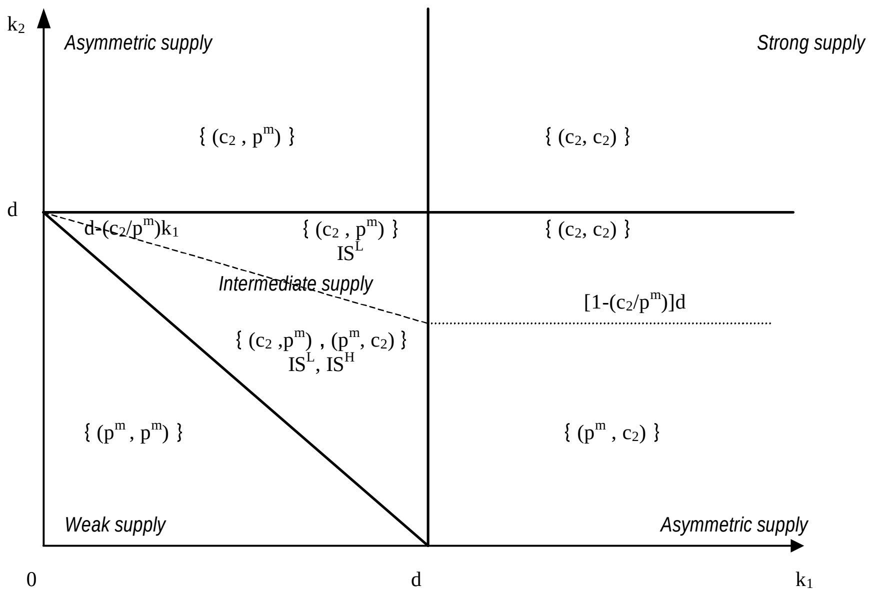

Figure 1: Pure Strategy Nash equilibria in price bids, (p_1^*, p_2^*).

equilibria, but for all possible capacity configurations.[10] Below, I present an intuitive summary of these results.

Like in other markets, the price bid strategy (and therefore the market clearing price) depends on the number of firms being able to supply the entire demand on their own and the cost difference between firms. Due to the uniform-price auction, firms sell their production at the highest bid price, if the firm bidding the lowest price cannot supply the whole market. Hence, the market price is high if both firms' capacities are needed to meet the entire demand. Figure 2 displays the equilibrium market price for each configuration of capacity (note that the market price equals p^m in the case of intermediate supply, irrespective of whether the firms play equilibrium IS^L

[10]Von der Fehr and Harbord show that pure-strategy equilibria do not exist if the uncertainty of demand is large. However, in many cases, the uncertainty about the level of demand is small since producers bid the day before the transaction takes place. Moreover, they do not consider the case of assymetric supply, which turns out to be crucial for the game.

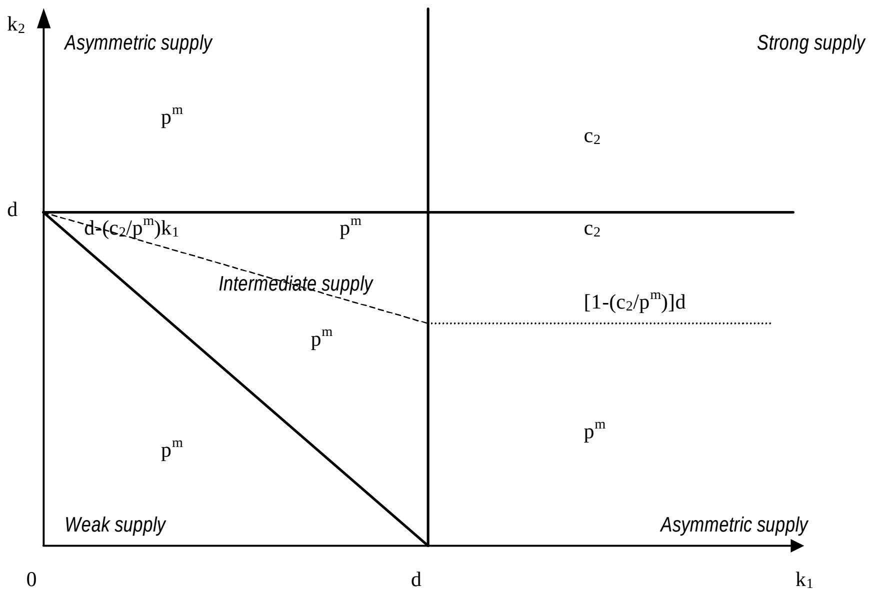

Figure 2: Equilibrium market price

or equilibrium IS^H).

However, this first result holds if the firm which can supply the whole market, bids the highest price. This remark implies that the efficient firm may submit the highest price bid, even though it can satisfy the entire demand. Wolfram (1998) and Garcia-Diaz and Marin (2000) find evidence for this behavior, namely that the largest participants in the electricity market in England and Spain respectively bid more for units than their smaller competitors.

Assume now that firms simultaneously choose their available capacity, which takes place prior to the price game.

4 Capacity best response functions

So far, available capacity has been described as a continuous variable. In reality, the total available capacity for supplying electricity is the sum of the capacity levels of generating units.[11] Hence, available capacity should be considered as a discrete rather than a continuous variable. To this end, let the size of one generating unit be denoted $\kappa \equiv d/n$, where $n \geq 2$ is a natural number.[12]

Assumption 1 *Firm i's total available capacity k_i, $i \in \{1, 2\}$, is a discrete variable such that $k_i \in \{\kappa, 2\kappa, 3\kappa, ...\}$.*

To calculate the best reply correspondence, making the following assumption turns out to be convenient:

Assumption 2 $k_1 \in [0, d - \kappa] \cup [d, +\infty)$ *and* $k_2 \in [0, +\infty)$.

For all (k_1, k_2), such that there are multiple equilibria in price bids when supply is intermediate, let superscripts L and H indicate that the firms select the equilibrium IS^L and IS^H, respectively.[13] Neither of the equilibria Pareto-dominates the other, firm 1 is better off in IS^L and firm 2 in IS^H. Therefore, it is interesting to analyze both equilibria. For $j \in \{L, H\}$, let firm 1's and

[11] A single generator and its directly associated equipment are termed as a generating unit. Although individual units can be and usually are dispatched separately, they often belong to one producer.

[12] Since $n \geq 2$, a firm can choose its available capacity to be less than the entire demand, without reducing it to 0.

[13] Note that Proposition 1 defines firm i's price bid p_i^*, $i \in \{1, 2\}$, as a function of each configuration of capacities (k_1, k_2). Due to the multiplicity of equilibria in the price game, I define two such functions for each firm $i \in \{1, 2\}$, denoted $p_i^L(k_1, k_2)$ and $p_i^H(k_1, k_2)$. It is possible to define other such functions. Indeed, the firms could play equilibrium IS^L for only a subset of capacity configurations, when there are multiple equilibria. In my view, coordinating on such equilibria is more complex and therefore, I rule out such type of behavior.

firm 2's best reply correspondences be

$$\beta_1^j(k_2) = \arg\max_{k_1} P\left(s_1^j, s_2^j\right) x_1\left(s_1^j, s_2^j\right) \tag{5a}$$

$$\beta_2^j(k_1) = \arg\max_{k_2} \left[P\left(s_1^j, s_2^j\right) - c_2\right] x_2\left(s_1^j, s_2^j\right) \tag{5b}$$

respectively, where $\left(s_1^j, s_2^j\right) = \left(\left(p_1^j(k_1, k_2), k_1\right), \left(p_2^j(k_1, k_2), k_2\right)\right)$ and functions P and x_i are defined in equations (1)-(3).

Lemma 1 *(Refer to Figure 3) If firms play equilibrium IS^L when supply is intermediate, and Assumption 2 holds, the best reply correspondences of firms 1 and 2 are*

$$\beta_1^L(k_2) = \begin{cases} [d, +\infty) & \text{if} \quad k_2 \leq \kappa \\ d - \kappa & \text{if} \quad k_2 \geq \kappa. \end{cases} \tag{5f}$$

and

$$\beta_2^L(k_1) = \begin{cases} [d - k_1, +\infty) & \text{if} \quad k_1 \leq d - \kappa \\ (1 - c_2/p^m)\, d & \text{if} \quad k_1 \geq d \end{cases}, \tag{5g}$$

respectively.

Proof: Appendix B.

Lemma 2 *(Refer to Figure 4) If firms play equilibrium IS^H when supply is intermediate, and Assumption 2 holds, the best reply correspondences of firms 1 and 2 are*

$$\beta_1^H(k_2) = \begin{cases} d - \kappa & \text{if} \quad k_2 > d - (c_2/p^m)(d - \kappa) \\ [d, +\infty) & \text{if} \quad (1 - c_2/p^m)\, d < k_2 \leq d - (c_2/p^m)(d - \kappa) \ \text{ or } k_2 \leq \kappa \\ [d - k_2, +\infty) & \text{if} \quad \kappa \leq k_2 \leq (1 - c_2/p^m)\, d \end{cases} \tag{8}$$

and

$$\beta_2^H(k_1) = \begin{cases} (1 - c_2/p^m)\, d & \text{if} \quad k_1 \geq d \\ d - (c_2/p^m)\, k_1 & \text{if} \quad k_1 \leq d - \kappa \end{cases}, \tag{9}$$

respectively.

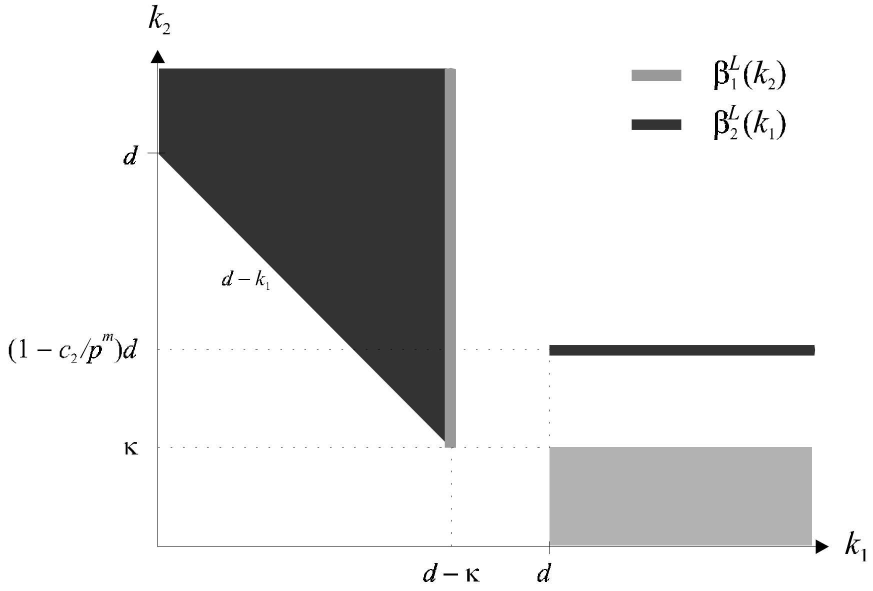

Figure 3: Best Reply Correspondence with IS^L

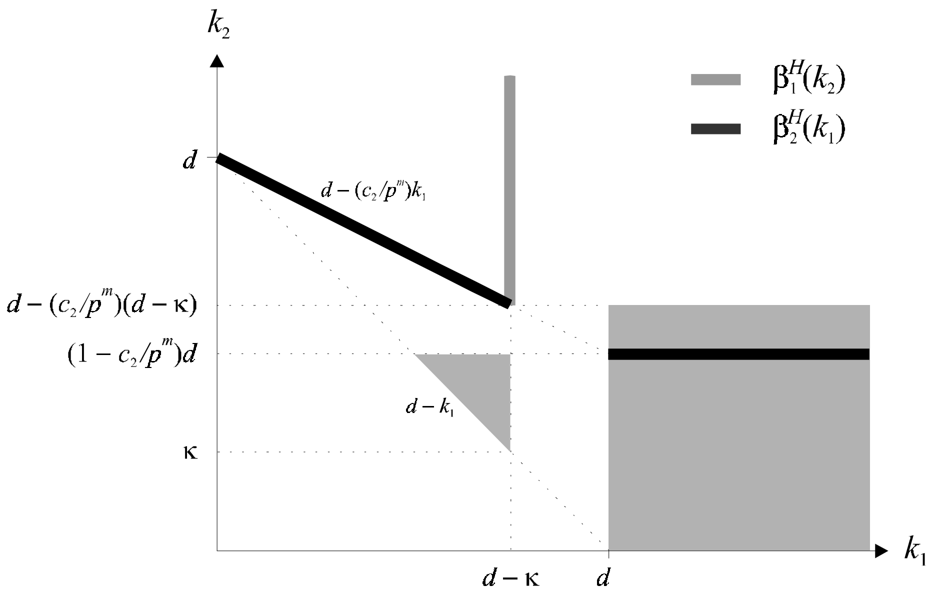

Figure 4: Best Reply Correspondence with IS^H

Proof: Appendix C.

The intuition for a firm's best reply correspondence is given by the comparison of the profits received by the lowest price bidder (lb) and the highest price bidder (hb).

If $p_i < p_j$, firm i, $for\ i, j \in \{1, 2\}$ and $i \neq j$, is the lowest price bidder and receives the following profit:

$$\pi_i^{lb} = \begin{cases} (p_i - c_i)\, d & \text{if} \quad k_i \geq d \quad (\alpha) \\ (p_j - c_i)\, k_i & \text{if} \quad k_i < d \quad (\beta) \end{cases}$$

If $p_i > p_j$, firm i,is the highest price bidder and receives the following profit:

$$\pi_i^{hb} = \begin{cases} 0 & \text{if} \quad k_j \geq d \\ (p_j - c_i) \min\{d - k_j, k_i\} & \text{if} \quad k_j < d \end{cases}$$

While setting its capacity, firm i takes two things into account. First, it chooses between being the lowest vs. the highest price bidder, which depends on $\pi_i^{lb} \gtrless \pi_i^{hb}$. Second, given that it is the lowest price bidder, it chooses between selling the entire demand at the lowest price bid or selling a quantity less than the demand at a high price, which depends on $(\alpha) \gtrless (\beta)$. A change in capacity affects the marginal profit as well as the likelihood of being the lowest price bidder. There is an obvious trade-off between the two elements. Contingent on being the lowest price bidder, the firm would like to sell the entire demand, but to be the lowest price bidder, it needs to propose a low available capacity to undercut the rival.

In the next section, it is shown that firms choose their capacities in such a way that supply is either weak (when firms play IS^L) or asymmetric (when firms play IS^H) and therefore, the market price is the maximum price.

5 Equilibria in the full two-stage game

The analysis of the best response correspondences in section 4 now allows me to examine the optimal choice of capacity by both firms. I show that at least one firm withholds its available capacity, in order to offer an available capacity lower than demand.

In the following, I characterize the subgame perfect equilibria in capacities. Using equations 5a and 5b, a pair $\left(k_1^j, k_2^j\right)$, $j \in \{L, H\}$, is a subgame perfect equilibrium in capacities if and only if

$$\begin{cases} k_1^j \in \beta_1^j\left(k_2^j\right) \\ k_2^j \in \beta_2^j\left(k_1^j\right). \end{cases}$$

5.1 Capacity withholding by the efficient firm

Proposition 2 *If firms play equilibrium IS^L when supply is intermediate, Assumption 1 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the strategy $[(p^m, d-\kappa), (p^m, \kappa)]$ is a subgame perfect equilibrium.*

Proof: From the firms' best reply correspondences given in equations (5f) and (5g), the pairs $\left(k_1^L, k_2^L\right)$, such that $k_1^L = d - \kappa$ and $k_2^L \in [\kappa, +\infty[$, are equilibria in the capacity game. The pair $\left(k_1^L, k_2^L\right) = (d - \kappa, \kappa)$ is an equilibrium under Assumption 2. Since Assumption 2 allows for a larger set of deviations than Assumption 1, it follows that $\left(k_1^L, k_2^L\right) = (d - \kappa, \kappa)$ must be an equilibrium also under Assumption 1.■

The equilibria identified in Proposition 2 are straightforward to identify in Figure 3. They are given by the intersection of the two best reply correspondences, that is, the thick grey line and the black area where $k_1 = d - \kappa$ and $k_2 \geq \kappa$.

According to Proposition 1, with an available capacity below demand, the efficient firm is certain to be the lowest price bidder. Therefore, it faces the following trade-off: selling a quantity smaller than demand at the highest price bid, or selling the entire demand at a lower price. The efficient firm resolves this trade-off by slightly withholding its capacity; it sells a large quantity $(d - \kappa)$ at a high price (p^m), the other firm selling the residual demand at the same price. Finally, note that firm 1 would have little incentive to withhold capacity if κ is very large. Therefore, the condition $\kappa < (1 - c_2/p^m)\, d$ is not surprising, since it provides an upper bound on κ.

5.2 Capacity withholding by the inefficient firm

To clarify the exposition, we introduce the following definition.

Definition 1 *When $\kappa < (1 - c_2/p^m)\, d$, let*

$$\bar{k}_2 = \max \{k_2 \in \{\kappa, 2\kappa, ...\} : k_2 \leq (1 - c_2/p^m)\, d\}.$$

Proposition 3 *If firms play equilibrium IS^H when supply is intermediate, Assumption 1 holds, and $\kappa < (1 - c_2/p^m)\, d$, then the strategy $\left[(p^m, d), \left(c_2, \bar{k}_2\right)\right]$ is a subgame perfect equilibrium.*

Proof: From the firms' best reply correspondences given in equations (8) and (9), the pairs $\left(k_1^H, k_2^H\right)$, such that $k_1^H = [d, +\infty)$ and $k_2^H = (1 - c_2/p^m)\, d$, are equilibria in the capacity game. The pair $\left(k_1^H, k_2^H\right) = (d, (1 - c_2/p^m)\, d)$ is an equilibrium under Assumption 2. Under Assumption 1, however, firm 2's equilibrium capacity must be a multiple of κ. As a result, $k_1^H = d$ and $k_2^H = \bar{k}_2$ become an equilibrium. To see this, note that firm 2 reduces its profits to 0 if unilaterally increasing its capacity above $\bar{k}_2$, since the market price then equals firm 2's marginal cost. Moreover, firm 2 reduces its profits if it reduces its capacity below $\bar{k}_2$, since firm 2 then sells a lower quantity without affecting the equilibrium market price. Finally, note in Figure 4 that $k_1^H = d$ constitutes a best reply to $k_2^H = \bar{k}_2$, since Assumption 2 allows for a larger set of deviations than Assumption 1 and since $\bar{k}_2 \in [\kappa, (1 - c_2/p^m)\, d]$.■

The equilibria identified in Proposition 3 are straightforward to identify in Figure 4. They are given by the intersection of the two best reply correspondences, that is, the thick black horizontal line.

Unlike the case when IS^L is selected, the efficient firm is not certain to be the lowest price bidder whenever its available capacity is below demand (see Figure 1). In fact, by sufficiently withholding its available capacity (and leaving a subsequent residual demand), the inefficient firm becomes the lowest price bidder and sells its entire capacity at the highest price bid. In this case, the efficient firm is the highest bidder and sells the residual demand. Moreover, firm 1 satisfies the residual demand only, despite the fact that it is able to undercut firm 2 and meet the entire demand. Hence, firm 2 uses its available capacity strategically, obtaining a market share much larger than in equilibrium IS^L.

The intuition for withholding capacity is that the market price equals the highest bid only if the available capacity of the lowest price bidder is below demand. Otherwise, the market price equals the lowest price bid. Therefore, the lowest price bidder may withhold its capacity to obtain the highest bid as a market price. Note that an alternative strategy is to choose an available capacity above demand and sell the entire demand at the lowest bid. Hence, a firm withholds its capacity under two conditions. First, the firm has to be sure that it is the lowest price bidder, and thus, the capacity must be small enough to make the other firm the highest bidder (and receive the residual demand). Second, selling a quantity (smaller than demand) at a high price must be more profitable than selling full demand at a lower price; therefore available capacity must be large enough. The ability to withhold capacity depends on several factors, however. First, withholding is possible when demand is high, since many producers then reach their full output capacity and have no impact on the market outcome. The remaining producers can then profitably reduce their output, knowing that most of their capacity-constrained competitors will be unable to respond with increased production. Second, a flexible production technology facilitates such behavior. For instance, it is easier to withhold capacity with hydropower, as opposed to nuclear power, since water can be stored and used gradually.[14]

6 Concluding remarks

The two-stage model analyzed in this paper illustrates the strategic use of available capacity in the electricity spot market. More precisely, the analysis shows that withholding capacity can be sufficient to obtain high markups. [15]

The strategy of withholding capacity has two negative welfare implications. First, when firms are free to choose their capacities, they obtain a market price above the competitive outcome, which is costly for consumers. Second, the efficient firm does not supply the entire demand, since the inefficient one has a positive market share. Hence, both Propositions 2 and 3 predict productive inefficiency. Note that in Proposition 2, however, the productive inefficiency may be small, in particular if κ is small. In Proposition 3, the productive inefficiency does not depend on the size of κ but only on

[14]As Bushnell (1998) points out, hydropower, unlike other technologies, allows firms to shift electricity generation between different time periods, thereby making electricity storable. However, in a dynamic game, witholding capacities has a consequance for future possibilities of withholding capacity in the case of hydropower. In particular, storage might oblige the firm to supply even if demand is high.

[15]Note that Ausubel and Cramton (1998) argue that buyers may have withheld their quantity for the auctions of spectrum rights in the United States.

the ratio c_2/p^m. Hence, if the cost of firm 2 is not too large (c_2 is not too close to p^m), the productive inefficiency may be large.

The strategy of withholding capacity is not explicitly taken into account by competition authorities, although some of these have been concerned by the Californian or Nordic examples discussed in the Introduction. Note also that the concentration index often used by competition authorities cannot detect that type of strategy. Indeed, the results in this paper indicate that if a dominant firm chooses to withhold its capacity, the market price remains high even though the market concentration decreases. The ideal thing would be Ideally, one would like to combine a concentration index such as the Hirschmann-Herfindahl Index with a markup ratio such as the Lerner index.[16]

Detecting such a strategy is not suffisant and the market design should be changed so as to avoid such a strategy. Reducing the price cap is one option, although this may have negative effects, in the short as well as in the long run. In the short run, producers may be induced to export their production. This happened in California when the regulator decided to reduce the price cap on the wholesale market, from \$750/MWh to \$250/MWh in the summer of 2000. As a result, the producers stopped supplying the Californian market and instead exported electricity to neighboring states. In the long run, high price caps may induce players to invest in new power production. Changing the auction mechanism might be a better option for avoiding a withholding strategy. The theoretical and empirical literature as it stands today, does not provide clear-cut recommendations, however.

[16]Note that Borenstein et al. (1999) discussed this issue for horizontal market power in the electricity market.

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A Proof of Proposition 1

It is straightforward to show points 1 (weak supply) and 2 (strong supply) in Proposition 1. Therefore, I focus on the two more complicated cases.

Asymmetric supply and price equilibrium: The supply is asymmetric when $k_i < d$ and $k_j \geq d$ where $i, j = \{1, 2\}$ and $i \neq j$. According to equation 1, the market price equals p_j. First, firm i has no incentive to submit the highest price, since it then sells nothing as firm j satisfies the entire demand. If firm i submits the lowest price ($p_i \leq p_j$), it supplies its capacity at price p_j.[17] Therefore, firm i always submits c_2. Second, firm j plays differently whether it is firm 1 or firm 2. If $k_2 \geq d$ (so that $p_1 = c_2$), then firm 2 obtains the same residual demand ($d - k_1$) for any price higher than or equal to c_2, according to equation (3). Therefore, firm 2 chooses p^m. In contrast, if $k_1 \geq d$ (so that $p_2 = c_2$), then firm 1 faces the following trade-off represented in equation (2). On the one hand, by submitting the low price $p_1 = c_2$, the market price equals c_2 and firm 1's profit is $c_2 d$. Firm 1 serves the entire demand at a low price c_2. On the other hand, by submitting a high price $p_1 = p^m$, the market price equals p^m and firm 1's profit is $p^m (d - k_2)$. Firm 1 sells the residual demand $(d - k_2)$ at a high price p^m. Therefore, firm 1 chooses p^m only if $k_2 \leq (1 - c_2/p^m) k_1$.

Intermediate supply and price equilibrium: The supply is intermediate when $\max\{k_1, k_2\} < d$ and $k_1 + k_2 > d$. According to equation (1), the market price in this case is $P(s) = \max\{p_i, p_j\}$, where $i, j = \{1, 2\}$ and $i \neq j$. If firm i submits the lowest price ($p_i = c_2 < p_j$), it supplies its capacity at price p_j. Given firm i's optimal strategy, firm j gets the residual demand. By submitting a price below the maximum price ($p_j < p^m$), firm

[17] Due to the efficient rationing rule, however, firm 2 sells nothing, even though $p_2 = c_2$ if $k_1 > d$ and $p_1 = c_2$. Nevertheless, note that $p_2 = c_2$ is a best reply to $p_1 = c_2$ also in this case.

j makes less profit than by submitting $p_j = p^m$, since $(p_j - c_j)(d - k_i) < (p^m - c_j)(d - k_i)$ according to equation (4). Therefore, firm j submits p^m. Note, however, that $p_1 = p_m$ is the best response to $p_2 = c_2$ if and only if $c_2 k_1 \leq p^m (d - k_2)$, which is equivalent to $k_2 \leq d - (c_2/p^m) k_1$.

B Proof of Lemma 1

The proof proceeds in four steps. First, it defines the firms' equilibrium price bids as a function of (k_1, k_2). Second, it derives the equilibrium market price as a function of (k_1, k_2). The third and fourth step derive firm 1's and firm 2's best reply correspondence, respectively.

Step 1: Since the firms play equilibrium IS^L, Proposition 1 defines firm i's equilibrium price bid, $i \in \{1, 2\}$, as a function of (k_1, k_2). This function, denoted $p_i^L(k_1, k_2)$, is equal to $p_i^*(k_1, k_2)$ in Proposition 1 whenever $p_i^*(k_1, k_2)$ is a singleton. Otherwise, $p_1^L(k_1, k_2) = c_2$ and $p_2^L(k_1, k_2) = p^m$.

Step 2: Note that $\min\{p_1^L, p_2^L\} = p_1^L = c_2$ if $k_1 \geq d$ and $k_2 > (1 - c_2/p^m) d$. Moreover, $\max\{p_1^L, p_2^L\} = p_1^L = p^m$ if $k_1 \geq d$ and $k_2 \leq (1 - c_2/p^m) d$. Also, $\max\{p_1^L, p_2^L\} = p_2^L = p^m$ if $k_1 \leq d - \kappa$. By equation (1), the equilibrium market price is thus given by:

$$P\left(\left(p_1^L, k_1\right), \left(p_2^L, k_2\right)\right) = \begin{cases} c_2 & \text{if } k_1 \geq d \text{ and } k_2 > (1 - c_2/p^m) d \\ p^m & \text{otherwise.} \end{cases} \tag{10}$$

Step 3: Note that the following three (in)equalities are true. First, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$. Second, $p_1^L = c_2 = p^m$ if $k_1 \geq d$ and $k_2 > (1 - c_2/p^m) d$. Third, $p_1^L = c_2 < p_2^L = p^m$ if $k_1 \leq d - \kappa$ or $k_1 \geq d$ and $k_2 \leq (1 - c_2/p^m) d$.

By equation (2), firm 1's final supply is thus given by:

$$x_1\left(\left(p_1^L,k_1\right),\left(p_2^L,k_2\right)\right)=\begin{cases}k_1 & \text{if } k_1\leq d-\kappa\\ d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d\\ d-k_2 & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d.\end{cases}\tag{11}$$

By equation (4), firm 1's profits are given by Px_1, since $c_1=0$. By equations (10) and (11), firm 1's profits are thus given by:

$$\pi_1\left(\left(p_1^L,k_1\right),\left(p_2^L,k_2\right)\right)=\begin{cases}p^m k_1 & \text{if } k_1\leq d-\kappa\\ c_2 d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d\\ p^m\left(d-k_2\right) & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d.\end{cases}\tag{12}$$

Use this expression for π_1 in (5a) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_1^L\left(k_2\right)$ in equation (5f), provided that $\kappa<\left(1-c_2/p^m\right)d$.

Step 4: Recall that the following three (in)equalities are true. First, $p_1^L=c_2<p_2^L=p^m$ if $k_1\leq d-\kappa$. Second, $p_1^L=c_2=p^m$ if $k_1\geq d$ and $k_2>\left(1-c_2/p^m\right)d$. Third, $p_1^L=c_2<p_2^L=p^m$ if $k_1\leq d-\kappa$ or $k_1\geq d$ and $k_2\leq\left(1-c_2/p^m\right)d$. By equation (3), firm 2's final supply is thus given by:

$$x_2\left(\left(p_1^L,k_1\right),\left(p_2^L,k_2\right)\right)=\begin{cases}k_2 & \text{if } k_2<d-k_1 \text{ and } k_1\leq d-\kappa\\ d-k_1 & \text{if } k_2\geq d-k_1 \text{ and } k_1\leq d-\kappa\\ 0 & \text{if } k_2>\left(1-c_2/p^m\right)d \text{ and } k_1\geq d\\ k_2 & \text{if } k_2\leq\left(1-c_2/p^m\right)d \text{ and } k_1\geq d.\end{cases}\tag{13}$$

By equation (4), firm 2's profits are given by $\left(P-c_2\right)x_2$. By equations (10) and (13), firm 2's profits are thus given by:

$$\pi_2\left(\left(p_1^L,k_1\right),\left(p_2^L,k_2\right)\right)=\begin{cases}(p^m-c_2)\,k_2 & \text{if } k_2<d-k_1 \text{ and } k_1\leq d-\kappa\\ (p^m-c_2)\,(d-k_1) & \text{if } k_2\geq d-k_1 \text{ and } k_1\leq d-\kappa\\ 0 & \text{if } k_2>(1-c_2/p^m)\,d \text{ and } k_1\geq d\\ (p^m-c_2)\,k_2 & \text{if } k_2\leq(1-c_2/p^m)\,d \text{ and } k_1\geq d.\end{cases} \tag{14}$$

Use this expression for π_2 in (5b) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_2^L(k_2)$ in equation (5g).■

C Proof of lemma 2

The proof follows the same logic as the proof in Appendix C. Therefore, I only report the significant differences between the two proofs.

Step 1: Since the firms play equilibrium IS^H, Proposition 1 defines firm i's equilibrium price bid, $i\in\{1,2\}$, as a function of (k_1,k_2). This function, denoted $p_i^H(k_1,k_2)$, is equal to $p_i^*(k_1,k_2)$ in Proposition 1, whenever $p_i^*(k_1,k_2)$ is a singleton. Otherwise, $p_1^H(k_1,k_2)=p^m$ and $p_2^H(k_1,k_2)=c_2$.

Step 2: Using equation (1) and the functional forms of $p_1^H(k_1,k_2)$ and $p_2^H(k_1,k_2)$, it can be shown that the equilibrium market price is given by:

$$P\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases}c_2 & \text{if } k_1\geq d \text{ and } k_2>(1-c_2/p^m)\,d\\ p^m & \text{otherwise.}\end{cases} \tag{15}$$

Step 3: Using equation (2) and the functional forms of $p_1^H(k_1,k_2)$ and

$p_2^H(k_1,k_2)$, it can be shown that firm 1's final supply is given by:

$$x_1\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2\leq d-k_1 \\ d-k_2 & \text{if } k_1\leq d-\kappa \text{ and } d-k_1<k_2\leq d-\left(c_2/p^m\right)k_1 \\ k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2>d-\left(c_2/p^m\right)k_1 \\ d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d \\ d-k_2 & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d. \end{cases} \tag{16}$$

By equation (4), firm 1's profits are given by Px_1, since $c_1=0$. By equations (15) and (16), firm 1's profits are thus given by:

$$\pi_1\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} p^m k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2\leq d-k_1 \\ p^m\left(d-k_2\right) & \text{if } k_1\leq d-\kappa \text{ and } d-k_1<k_2\leq d-\left(c_2/p^m\right)k_1 \\ p^m k_1 & \text{if } k_1\leq d-\kappa \text{ and } k_2>d-\left(c_2/p^m\right)k_1 \\ c_2 d & \text{if } k_1\geq d \text{ and } k_2>\left(1-c_2/p^m\right)d \\ p^m\left(d-k_2\right) & \text{if } k_1\geq d \text{ and } k_2\leq\left(1-c_2/p^m\right)d. \end{cases} \tag{17}$$

Use this expression for π_1 in (5a) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_1^H(k_2)$ in equation (8), given that $\kappa<\left(1-c_2/p^m\right)d$.

Step 4: Using equation (3), and the functional forms of $p_1^H(k_1,k_2)$ and $p_2^H(k_1,k_2)$, it can be shown that firm 2's final supply is given by:

$$x_2\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases} k_2 & \text{if } k_2\leq d-\left(c_2/p^m\right)k_1 \text{ and } k_1\leq d-\kappa \\ d-k_1 & \text{if } k_2>d-\left(c_2/p^m\right)k_1 \text{ and } k_1\leq d-\kappa \\ 0 & \text{if } k_2>\left(1-c_2/p^m\right)d \text{ and } k_1\geq d \\ k_2 & \text{if } k_2\leq\left(1-c_2/p^m\right)d \text{ and } k_1\geq d. \end{cases} \tag{18}$$

By equation (4), firm 2's profits are given by $\left(P-c_2\right)x_2$. By equations (15) and (18), firm 2's profits are thus given by:

$$\pi_2\left(\left(p_1^H,k_1\right),\left(p_2^H,k_2\right)\right)=\begin{cases}\left(p^m-c_2\right)k_2 & \text{if } k_2\leq d-\left(c_2/p^m\right)k_1 \text{ and } k_1\leq d-\kappa\\ \left(p^m-c_2\right)d-k_1 & \text{if } k_2> d-\left(c_2/p^m\right)k_1 \text{ and } k_1\leq d-\kappa\\ 0 & \text{if } k_2>\left(1-c_2/p^m\right)d \text{ and } k_1\geq d\\ \left(p^m-c_2\right)k_2 & \text{if } k_2\leq\left(1-c_2/p^m\right)d \text{ and } k_1\geq d.\end{cases} \tag{19}$$

Use this expression for π_2 in (5b) and solve the maximization problem. It is easily verified that the solution yields the expression for $\beta_2^H(k_2)$ in equation (9).■