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STRATEGIC BIDDING IN MULTI-UNIT AUCTIONS WITH CAPACITY CONSTRAINED BIDDERS: THE NEW YORK CAPACITY MARKET

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Strategic Bidding in Multi-unit Auctions with Capacity Constrained Bidders: The New York Capacity Market

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October 2012

Abstract

This paper employs a simple model to describe bidding behavior in multi-unit uniform price procurement auctions when firms are capacity constrained. Using data from the New York City capacity auctions, I find that capacity constrained firms use simple bidding strategies to co-ordinate on an equilibrium that extracts high rents for all bidders. I show theoretically and empirically that the largest bidder submits the auction clearing bid. All other bidders submit infra-marginal bids that are low enough to not be profitably undercut. Infra-marginal bidders react to capacity endowments and decrease their bids as the largest firm's capacities and its profits of undercutting increase. Capacity markets, when designed as studied here, are a costly tool to increase security of supply in electricity markets, as capacity prices do not reflect actual capacity scarcity.

Keywords: Auctions, Electricity, Market Design.
JEL-Classification: D43, D44, L11, L13.

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1 Introduction

The volume of goods traded through auctions in the economy has been drastically increasing over the last decades. This increased use of auctions raises the need to better understand and predict economic behavior in bid based selling mechanisms. To address this challenge, an increasing strand of literature tests and expands existing auction models. Because electricity is a completely homogeneous good and produced by a small number of firms, restructured power markets have become a major field of applied auction analysis. Multi-unit auctions are the main auction format used in electricity markets. This paper contributes to the literature by demonstrating that a simple model of multi-unit uniform price auctions is consistent with observed bidding data from capacity auctions in electricity markets. Harbord and Von der Fehr (1993), Le Coq (2002), Crampes and Creti (2005), Fabra and Von der Fehr (2006) and more recently Fabra et al. (2011) developed a multi-unit auction framework in which capacity constrained bidders with constant marginal costs compete in electricity auctions. I focus on a modified version of Fabra and Von der Fehr (2006) and, using data from the New York Independent System Operator (NYISO) capacity auctions, find that these models are sufficient to predict economic bidding behavior in multi-unit auctions when bidders are capacity constrained.

By tailoring a multi-unit auction model to the NYISO capacity market this paper also reveals design flaws in this market and contributes to the discussion on supply security and electricity market design. Generating firms in the NYISO capacity market co-ordinated on an equilibrium play that was extracting the highest possible rents for the supply side between 2003 and 2008. The capacity market was always clearing at the price cap and thus set incorrect price signals for entry and profitability of new peaking units.

The economic theory of multi-unit auctions dates back to the share auction framework by Wilson (1979). Klemperer and Meyer (1989) increased the predictive power of Wilson's model by introducing demand uncertainty and thereby reducing the multiplicity of equilibria substantially. Green and Newbery (1992) were the first to tailor a multi-unit auction model to electricity markets and designed the model to describe the UK spot market for electricity. Early tests of these models by Wolfram (1998) and Green and Newbery (1992) confirmed the models' predictions. More recent structural empirical work by Hortaçsu and Puller (2008) and Oren and Sioshansi (2007) and also earlier by Wolak (2000) provided additional support for the main models, extended them by including forward markets, and introduced non-parametric tests. So far, empirical findings for simple multi-unit auction models in the style of Fabra and Von der Fehr (2006) are not documented, which is partly due to the stylized nature of these models. Capacity auctions take place in an environment very close to the one assumed in Fabra and Von der Fehr (2006) and are ideal to deliver empirical insights on the predictions of such models.

The remainder is organized as follows. Section 2 briefly describes the market structure in the New York electricity market and illustrates the workings of capacity markets. Section 3 introduces a model for multi-unit uniform price procurement auctions with capacity constrained firms that reflects the market design discussed in section 2. Section 4 presents the data. Section 5 discusses the empirical findings. I compare the optimal bids generated by the model to observed bids in the auction, assess deviations from the model, and present estimates of the best response functions. Section 6 concludes on the empirical findings and draws policy recommendations for future market designs of capacity markets.

2 The New York capacity market

This section sketches the market design of the New York ISO energy market and illustrates the workings of the New York capacity market. The New

York power market consists of an energy market and a capacity market. In virtually all other markets, pricing the commodity only is sufficient to promote long run investment. Hence most markets do not need to price capacity. In electricity markets, the existence of dominant firms and the absence of a robust demand response requires that in times of shortage the market price is set administratively. When this price cap is set just above marginal costs (for mostly political reasons this is the case in most major US electricity markets), electricity prices are a weak signal for promoting efficient long run investment.[1] Capacity markets, as they are installed in most markets along the US east coast, supplement the lost revenues, termed 'missing money', that result from the price cap in the energy market. By allowing firms to obtain revenue from holding capacity, regulators get to keep electricity shortage prices at a politically acceptable level and to secure long run investment in electricity generation at the same time.[2]

Capacity markets are artificially created markets that signal the scarcity of aggregate generation capacities relative to future projected power demand. Projected demand for generating capacity is estimated, announced and procured by the system operator, who finances the costs of procurement by passing them on to retailers. When generation capacities are scarce, capacity market rents are high. When there is relatively large market capacity, the capacity market price is low and does not promote further investment. Firms who earn capacity payments must offer to produce power, that is, they must supply a bid below the energy market price cap in the electricity wholesale auction. In the purest form the energy price cap is set at the marginal cost of peaking units, so all rents for peaking units are made in the capacity market. Off-peak units with lower marginal costs earn revenues in

[1]In addition, market imperfections as described by Joskow (2008), such as low real-time demand response or out of market purchases by system operators to balance the network, bias the signaling effect of electricity prices.

[2]This market design is highly debated. For an analysis of energy-only markets see Hogan (2005).

the energy and the capacity market. The capacity market thus imitates the revenues for peaking units that would be earned in an energy-only market in times when the market price would be above the price cap. The overarching policy goal of capacity markets is to protect consumers from market power, while maintaining sufficient peak production and investment incentives in new peak capacity despite the price cap.

The New York state electricity market serves about 20 million final customers and had a peak demand of about 33 GW in 2010, whereas total generating capacity was at about 41 GW.[3] The New York state wide wholesale electricity exchange is organized by the NYISO, who in addition administers a monthly capacity market. Each month firms bid their available capacity into the capacity market and thereby, if they are procured, oblige themselves to offer energy in the energy market during the following month. If generation capacity is scarce relative to the NYISO's demand for generating (and reserve) capacity, capacity prices then generate rents for firms to cover fixed costs of currently running peakers and signal the profitability of new entry.

To set locationally different signals, the ISO runs three separate capacity markets with different demand curves for New York City, Long Island, and the remaining area of New York state. The data used to empirically assess the auction model comes from the capacity market in New York City. To account for different summer and winter peak demand, the ISO fixes the demand for capacity every six month, while the procurement takes place each month. Each month the New York City capacity spot market clears around 8.5 GW at a capacity price of 7 \$/kw-month during winter months and at around 12 \$/kw-month during the summer period. Retailers are the final consumers of capacity, respectively capacity rights, which enable them to buy electricity from all procured generation capacity. The ISO obliges retailers

[3]See www.nyiso.com. After several years of high capacity prices and resulting new investment in capacities before 2010, this reserve margin is projected to be sufficient until 2018 according to the 2009 Reliable Need Assessment of NYISO.

to hold capacity rights according to the projected electricity demand of their retail customers. Retailers can also buy capacity rights on bilateral and institutional forward markets. Retailers buy capacity on forward markets, notify their position to the ISO, who then procures the missing capacity as a single buyer in the final spot auction and resells the capacity rights to the retailers at the auction clearing price.

Winning firms in the capacity market have to bid their procured capacity into the New York State energy market and deliver at the prevailing energy market price. The NYISO's energy market software employs an automated market power mitigation procedure for energy market bids that are significantly higher than previously submitted bids from the same generation unit during, for example, competitive low demand periods. Hence it is not possible for firms to earn capacity payments and withhold rewarded capacity in the energy market by bidding above the clearing price of the electricity wholesale auction.

The model introduced in the next section is built upon a full information framework to describe the spot market capacity auction run by the NYISO. The model assumes that firms know their rival's forward position resulting from bilateral or institutional forward trading of capacity rights. Hence what we observe in the spot market are best response functions to what firms already sold forward. Given the repeated nature of the auction, this assumption seems realistic.[4] In 2009, the NYISO estimated that approximately 45% of the capacity requirements are transacted through the NYISO administered capacity auctions, at an annual volume of over $850 million. The remaining requirements were met through forward contracts that hedge around the spot market capacity price. Forward and spot prices for capacity reveal that the

[4]Between 2006 and 2008 a financial hedge between two participants in the auction existed. This agreement changed their forward market behavior and was judged to violate the Sherman Act by the Department of Justice. However, the agreement was common information and is in line with the assumption that each firm knows its rivals forward position.

law of one price holds with respect to all forward market transactions.[5]

3 The model

To analyze the data I use a simple model of bidding behavior in multi-unit uniform price procurement auctions. The model builds on the auction framework in Fabra and Von der Fehr (2006), who derive equilibrium outcomes in a variety of multi-unit auction settings. The NYISO market clears as a multi-unit uniform price procurement auction, where the ISO announces the demand schedule and generating firms submit supply bids. The auctioneer, the ISO, announces a linear downward sloping demand function, $D(p)$, that is known to all bidders prior to the auction.[6] I assume that all bidders $i = 1, ..., N$ are capacity constrained so that no bidder has enough available capacity, $\bar{k}_i$, to serve entire demand at a price of zero. Firms can bid a discrete, possibly stepwise, supply function $s_i(b)$, that specifies how much capacity a firm is willing to sell at a price of b. Hence, if firms submit just one bid step, their supply function $s_i(b)$ would be $(b, \bar{k}_i)$. If a firm submits two or more steps, the supply function would split up $\bar{k}_i$ and submit this capacity at two or more different price bids. I assume that firms submit all their available constrained capacities, $\bar{k}_i$, and provide the condition for which it is indeed optimal to offer all capacity up to the constraint in Appendix A.1. The auctioneer orders all bids, independent of who submitted them, in increasing order and finds the market clearing price, p^c, which satisfies the condition

[5] See the ICAP summary section at www.nyiso.com.

[6] In practice, this spot demand function is the total demand for capacity minus all quantities that retailers contracted bilaterally or on forward markets. Also note that the NYISO in fact announces a stepwise demand function, ceiling procurement costs with a maximum price, as depicted in figure 1.

$$\sum_{j=1}^{M} S_j(p^c) = D(p^c), \tag{1}$$

where the index j denotes on bid step $j = 1, ..., M$ in the aggregate bid function $S_j(b)$. The auctioneer sums up all capacity submitted at each price bid and finds the market clearing price. All bids that are lower than the market clearing price will be procured and paid the market clearing price. I drop time indices for each auction. For each auction, firm i's profits are

$$\pi_i = s_i(p^c)p^c. \tag{2}$$

Marginal costs are assumed to be constant and zero. Firms do not face notable costs of offering their capacity on the capacity market. Cramton and Stoft (2005) show that for all firms that plan to sell electricity in the energy market, it is not costly to commit to that in the capacity market. Furthermore, Stoft (2002) shows that capacity markets clear at market prices close to zero in times of overcapacity, which indicates that marginal costs are insignificant. These two features, capacity constraints and constant marginal costs, have significant impact on the firms' strategy choice. When firms are unconstrained or face increasing marginal costs, firms maximize profits by bidding upward sloping supply functions against all residual demand situations. However, when firms are capacity constrained and do not face increasing marginal costs (that force them to bid upward sloping bid functions), simpler strategies suffice. Infra-marginal firms cannot serve their residual demand and only one pivotal firm clears the auction on the margin against its residual demand. Then, profits of the infra-marginal bidders do not change whether they submit upward sloping supply functions or simply submit all their available capacity at some price below the market clearing price, and are rewarded at the clearing price. Only one high and pivotal bidder clears the market in each auction.

Firm's strategies can be described as follows. For the auction to clear, the auctioneer sorts all price bids b_j, where $j = 1, ..., M$, in increasing order. Accordingly, denote the bid ranking such that $b_1 < b_2 < ... < b_M$. At each b_j a cumulated capacity of $K_j = \sum_{s=1}^{j} k_j$ is offered, where k_j is the capacity offered at each b_j. There is one pivotal, marginal bidder, $i = m$, who offers the marginal bid, $b_j = b_m$, that clears the auction and $K_{m-1} < D(b_{m-1}) \ \wedge \ K_m \geq D(b_m)$ holds. The pivotal bidder m maximizes over the residual demand that all other inframarginal and low bidding capacity constrained firms leave unsatisfied. In the NYISO capacity market a bid cap is imposed and therefore the pivotal bidder maximizes profits by finding

$$b_m^* = \min\{\arg\max_b b\left(D(b) - K_{m-1}\right), b^{cap}\}. \tag{3}$$

The pivotal bidder submits the optimal residual monopoly bid, if not bound by the bid cap, and will earn profits of π_m.[7] These profits are considered by the low bidding firms when choosing their strategy. They choose, $s_i(b)$, their inframarginal bids, such that they are low enough to not be undercut by the pivotal bidder. We can derive upper bounds for all bids of the low bidding firms, $b_j < b_m$. Each bid j faces an upper bound, $\bar{b}_j$, that solves

$$\bar{b}_j := \begin{cases} b_j\left(D(b_j) - K_{j-1}\right) = \pi_m & \text{if } \bar{k}_m > D(b_j) - K_{j-1} \\ b_j \bar{k}_m = \pi_m & \text{if } D(b_j) - K_{j-1} > \bar{k}_m. \end{cases} \tag{4}$$

The first case in equation (4) describes all bids that, when slightly underbid by the pivotal firm, are pushed out of the market. In this case the pivotal firm stays pivotal when undercutting those bids. The second case defines upper bounds for bids that, when slightly underbid by the pivotal firm, stay in the market. It is possible that auctions clear and bids only face

[7]Bid caps are firm specific and different from the maximum price in the demand function, as referred to in footnote 3 and shown in figure 1. The bid caps are lower than this maximum price and constrain firms to play on the linear part of demand. They change from winter to summer, as mentioned in section 2.

upper bounds according to the first case. This happens when the pivotal bidder's capacity, $\bar{k}_m$, is large enough to push all bids out of the market. If the pivotal bidder cannot push all bids out of the market, all bids that fulfill $D(b_j) - K_{j-1} > \bar{k}_m$ then face the same upper bound: if the pivotal firm does not want to underbid the highest bid that fulfills $D(b_j) - K_{j-1} > \bar{k}_m$ (and sell all its capacity $\bar{k}_m$), then the pivotal firm also does not want to underbid lower bids that fulfill $D(b_j) - K_{j-1} > \bar{k}_m$, still sell $\bar{k}_m$, and potentially decrease the auction price. In this vein, there only exists, if at all, one strategically important bid for which $D(b_j) - K_{j-1} > \bar{k}_m$ holds, namely the highest of these.

Not defined in equation (4) are cases in which the auction does not clear, $K_m < D(b_m)$, because capacity constraints are too tight. The auctioneer then would find the auction price that ensures $K_m = D(p)$. In this case there is no strategic relation in the firms' bids. As described, there is, if at all, only one bid (the highest for which $D(b_j) - K_{j-1} > \bar{k}_m$ holds) that determines the bound for all bids that cannot be pushed out of the market by the pivotal firm. In the remainder, such bids are denoted b_j^I. In each auction there are, if at all, one or more bids for which $\bar{k}_m > D(b_j) - K_{j-1}$ holds. Bids that fall into this category will be denoted by b_j^{II}. If they exist, lower bids for which $D(b_j) - K_{j-1} > \bar{k}_m$ holds are optimal by definition if the bid b_j^I is below its bound.[8]

Figure 1 describes an example of the equilibrium play described above. This example has four bids, meaning maximum four firms but potentially less if one or more firms submitted a stepwise function. The pivotal firm, $i = m$, submits the highest bid and sets the auction clearing price. The pivotal firm simply clears the market by optimizing as a monopolist over its residual

[8] Note that with inelastic demand in some case when a bid b_j^I is undercut, the market does not clear at this bid b_j^I, because the pivotal capacity is too small. Then the next highest bid b_{j+1} will clear the auction, and, given that b_{j+1} is below its bound, bid b_j^I becomes optimal by definition in the same sense of all bids below b_j^I.

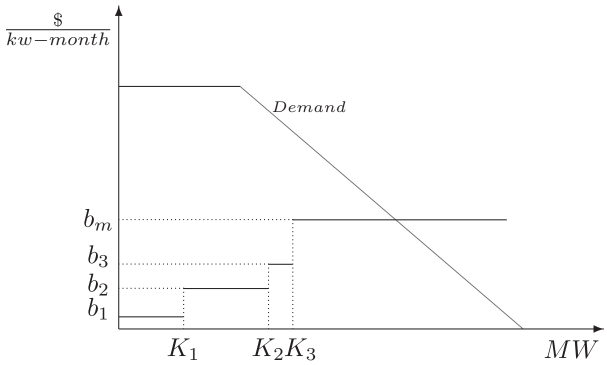

Figure 1: *Example of the auction clearing.*

demand, see equation (3). The high bidding firm is bound however by the price cap and chooses the minimum out of the optimal residual monopoly price and the price cap. All low bidding firms submit bids, $b_j \in [0, \bar{b}_j]$, such that they will not be undercut according to equation (4). The second highest bid, b_3, has an upper bound that solves $b_j\,(D(b_j) - K_{j-1}) = \pi_m$. In this case the capacity of the pivotal bidder is large enough to completely push bid b_3 out of the market. However, already the second lowest bid, b_2, given its position in the merit order in this example, will still be among the winning bids when undercut by the pivotal firm. When the pivotal firm underbids and submits $b_2 - \epsilon$ it cannot cover the whole residual demand and bid b_2 will set the auction clearing price. Firm m then would sell all its capacity, hence for b_2 the upper bound is $\bar{b} = \frac{\pi_m}{k_m}$. For, b_1, the bound is the same bound as for b_2. All bids below b_2 will never be underbid, because if they are, the underbidding pivotal firm will potentially decrease the market price and still sell all its capacity, compared to the price it obtains when only underbidding b_2.

Last, what is not graphed above is the case when the auction does not clear. This happens in the data, because the capacity constraints are very tight in some auctions. Since the system operator would set the price such that $D(p) = K_M$, firms then just have to bid below that price, otherwise they would not be procured at all. The equilibria described above are summarized by the first proposition.

Proposition 1 *In the multi-unit uniform price procurement auction with capacity constrained firms, the equilibrium in pure strategies is characterized by one pivotal firm who submits the auction clearing bid, while all other bidders submit low infra-marginal bids* $b_j \in [0, \bar{b}_j]$, *if* $D(b_M^*) \leq K_M$.

Proof. See equations (3) and (4) and note that the pivotal bidder does not want to deviate by construction. If low bidders want to deviate and overbid, these particular equilibria do not exist. □

There exist multiple equilibria, in which different firms can be the pivotal bidder. The multiplicity of equilibria is common to the general supply function framework and also to Fabra and Von der Fehr (2006). In Appendix A.2, I show that equilibria in which the largest firm is the pivotal bidder always exist and smaller bidders never want to overbid. Furthermore, in Appendix A.3 I prove that for very asymmetric firm capacities the largest firm never wants to be among the low bidding firms and becomes the pivotal bidder, as stated in the following proposition.

Proposition 2 *When capacity endowments are sufficiently asymmetric, only equilibria exist, in which the largest firm is the pivotal bidder and submits* b_m^*, *while all smaller firms submit low bids* $b_j \in [0, \bar{b}_j]$ *and do not find it profitable to overbid* b_m^*.

Proof: See Appendix A.3. □

The intuition behind proposition 2 is straightforward. Suppose the by far largest firm is bidding a low infra-marginal price. Then, the residual demand is relatively low and therefore also the auction clearing residual monopoly price that one of the smaller firms would bid. Hence, the largest firm increases its profits by overbidding and increasing the market price, even if it then might not sell all its capacity. In the case of two firms, a firm that owns enough capacities to act as a monopolist would not mind an infinitesimal small firm entering the auction, and would still bid close to its monopoly price. In turn, the small firm would never overbid the large firms monopoly price.[9]

To empirically analyze how the best response functions are describing the low bids, $b_i < b_m$, I employ equation (4). Changing the inequality of the bound to an equality and taking the log yields:

$$ln(b_j) = ln(\pi_m) - ln(\bar{k}_m) \tag{5}$$

for all bids for which $D(b_j) - K_{j-1} > \bar{k}_m$ holds and

$$ln(b_j) = ln(\pi_m) - ln\left(D(b_j) - K_{j-1}\right) \tag{6}$$

if $\bar{k}_m > D(b_j) - K_{j-1}$ holds. Versions of these equations will be estimated to see how low bids react to changing pivotal capacity. The model suggests that infra-marginal bids increase as pivotal profits become larger, while infra-

[9]Note that for this equilibrium structure introducing stochastic quantity offers of the firms and hence stochastic residual demand can only be done for a relatively low support of random capacity offers. When the support of the residual demand becomes too large, low bidding firm's might find themselves setting the market price and in this event like to price high and increase profits. This effect leads to mixed strategies, see Fabra and Von der Fehr (2006). Mixed strategies complicate the analysis significantly. This observation together with the existence of common and zero marginal costs further support the simple full information framework.

marginal bids decrease as the larger firm's profit of undercutting, that is its sold quantity when undercutting, $\bar{k}_m$ or $D(b_j) - K_{j-1}$, increases.

The next section, section 4, presents the data. Section 5 tests the two propositions derived above. Similar to Hortaçsu and Puller (2008), the analysis starts by simply deriving the percentage of cases in which firms behaved as predicted by the model. I first asses the optimality of the pivotal firms profits, and then count how often infra-marginal bidders violated their bounds. Last, I present the results for the estimations of the best response functions in equations (5) and (6).

4 Data and method

This section presents the data and describes the implementation of the model. The data consist of 55 monthly procurement auctions and 1093 bids for installed capacity in the New York City ISO electricity market from June 2003 to March 2008.[10] We do not consider auctions after summer 2008, because in May 2008 the NYISO implemented a new regulatory regime that introduced the possibility for the ISO to buy from the pivotal bidder withheld capacity at a default price. For each capacity auction, the functional form of the demand curve, all bids and a unique bidder ID are available. Table 1 shows selected descriptive auction statistics.

On average 15.3 bidders participated in each auction and submitted around 20 bids (where firm individual stepwise bid functions are decomposed into separate bids at each price). The number of bidders rises over time. In the first auctions, only a few firms, among them the overall larger bidders, participated. The new bidders were small bidders, potentially retailers, who bought too many capacity rights in the forward markets and then sold their

[10]Partly missing and partly imprecise bid data from November 2003 and December 2004 is excluded. Auction 1 is June 2003, auction 55 is the February 2008 capacity auction for making capacity available in March 2008.

	mean	min	max
number of bidders	15.3	3	35
number of bids	19.5	4	63
offer share largest firm	66.6%	30.4%	85.3%
offer share two largest firms	81.8%	51.0%	99.8%
offer share three largest firms	89.0%	65.0%	100%

Table 1: *Auction statistics.*

excess capacity rights. As table 1 illustrates the largest offer submitted by a bidder covered on average 66.6 % of all offered capacity in each auction. Together with the second largest bidder, the offer share of the two largest firms already cover on average 81.8 % of all offers. The three largest firms nearly account for all offered capacity. These numbers indicate that the auction outcome will be determined in the game with two or three bidders.[11] For ten auctions the ISO had to clear the market, because available capacity was not large enough to clear the auction at the highest bid.

The implementation of the model proceeds in several steps.[12] First, I check each auction to see if infra-marginal bidders are indeed capacity constrained, and if it is optimal for them to submit all their capacity, as derived in Appendix A.1. Then, for each auction, I find the pivotal bidder, subtract all capacity offered by lower bids than the pivotal bid from the demand curve, and calculate the optimal residual monopoly price. I compare this theoretically optimal price to the observed market clearing bid. This comparison shows how close the pivotal firm was to its profit maximizing market clearing bid. I use the theoretically optimal auction clearing bid to calculate the high bidders profits in each auction. I use these profits to back out upper bounds

[11]During the period of this study, the major players in the New York electricity market have been Keyspan, NRG, ConEd and Reliant. The largest bidder is with very high probability Keyspan.

[12]I used matlab to program each step and apply it to the data.

for the low bids as characterized in equation (4). Then I discuss how these bounds describe the observed low bidding patterns. Last, I use the generated data on the pivotal firm's profits together with the observed data on the demand curve, the capacity and bid offers to estimate different versions of the best response functions in equations (5) and (6).

5 Results

This section presents the results. I look ex post at the equilibria in each auction, implement the model, and compare the model to the observed bids. In other words, I check if deviation was profitable for some bidders and hence if the firms did not play within the equilibrium as outlined above.

5.1 Capacity constraints

Only the offers and not the endowment of capacity (that remains from their forward capacity market commitments) are observable in the data. Therefore Appendix A.1 derives a theoretical limit on the optimal aggregate capacity that would be bid by all infra-marginal bidders. If all capacity submitted by the infra-marginal bidders is less than this limit, each firm could gain by increasing its capacity offer. In the data, aggregate infra-marginal capacity is below the limit, which shows that each infra-marginal firm could gain by offering more capacity. This fact allows us to focus on the price game as described in the model section without modeling a stage for the decision on how much capacity to submit prior to the price game. The result that all firms submit less than *one* theoretically derived optimal capacity offer, and the resulting conclusion that firms are capacity constrained is hence conditional on the underlying theory. However, this conditional result is strongly supported by the fact that the market was mostly clearing at the price cap. Withdrawing capacity leaves the market price unchanged and hence only lowers profits of infra-marginal firms. This intuition is also confirmed when looking at the optimal pivotal bid discussed below, which is significantly above the price cap. Infra-marginal firms would clearly have gained by submitting additional capacity.

5.2 The pivotal bidder

As theoretically derived in proposition 2, the pivotal firm bids the largest amount of capacity. This also holds in the data, in each auction over all years. The largest bidder in table 1 is the pivotal bidder. Hence, firms played an equilibrium as described in proposition 2. When assessing the bidding strategy of the pivotal bidder, the price cap constrains the analysis. When the unconstrained optimal price is above the price cap, we cannot compare the optimal bid to the observed bid, but only state that the firm behaved optimally in submitting the price cap. This lowers the value of the comparison. Since the price cap was indeed binding, the pivotal firm always submitted the price cap in all auctions. This is in line with the model's prediction. Figure 2 shows that the unconstrained optimal price was (with minor exceptions) above the price cap, and hence the pivotal bidder maximized profits by submitting a bid at the price cap. In the early years of the market the optimal residual monopoly price in each auction was significantly above the price cap. As the market capacity increased over time, this optimal high bid declined and during summer months almost equaled the price cap in the later auctions. Figure 2 also reveals the constrained nature of the low bidding firms. Especially in the early auctions bids below the pivotal bid could have offered more capacity without decreasing the auction price.

Figure 2 also shows that the regulatory bid cap, which was around 7 $/kw-month during winter months and at around 12 $/kw-month during the summer period, is significantly constraining the bid in the first auctions, while in the later auctions it did not substantially constrain the high bidder.

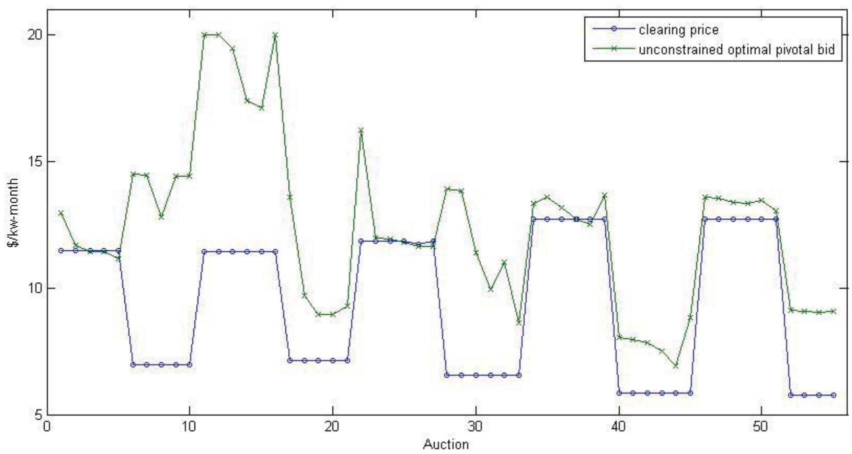

Figure 2: *Modeled and observed high bids for auctions June 2003 to March 2008.*

The strategic importance of the price cap also adds to the debate among policymakers on whether capacity market demand should be linear and price elastic or completely inelastic, see e.g. The Brattle Group (2009). The above results illustrate that clearing prices for capacity do not necessarily change depending on whether demand is elastic or completely inelastic, if the price cap is binding in both cases.

5.3 Infra-marginal bids

This subsection compares to what extent the observed bids fall into the bounds derived in equation (4). Bids for which $D(b_j) - K_{j-1} > \bar{k}_m$ holds are denoted by b_j^I, while the bound for those bids in the following is denoted by $\bar{b}^I$. Bids that can be pushed out of the market when undercut, so for which $D(b_j) - K_{j-1} \leq \bar{k}_m$ holds, are denoted by b_j^{II}, while the bounds for those bids are in the following denoted by $\bar{b}_j^{II}$. The comparison shows that the bounds fit the observed low bids to a high degree. In total, in the 55 auctions 1093 bids were submitted. Not accounting for 239 bids that were submitted when capacities were very scarce and the ISO had to set the price, 854 bids were submitted when the auction was clearing. Of these 854 bids, 97 bids came from the pivotal firm, leaving 757 infra-marginal bids. Eventually, of these 757 infra-marginal bids, 346 are bids that follow bounds $\bar{b}_j^{II}$ and 80, that follow bounds $\bar{b}^I$. 331 bids were bids below b_j^I, that all face the same bound determined by $\bar{b}^I$. As the next table illustrates, the bids b_j^I show the largest number of deviations from the model. In 7.5% of all cases, the firms bid above the bound $\bar{b}^I$. However, more than 5% percentage points of those violations come from the first five auction rounds. It can be conjectured that firms learned over time, and lowered their bid accordingly. Neglecting the first five auction rounds, more than 95% of all strategically important infra-marginal bids can be explained by the model. Table 2 lists the percentage of observed bids that are higher than their modelled bounds.

Bound	Frequency	Violations in %
$\bar{b}^I$	80	7.5 %
$\bar{b}_j^{II}$	346	4.6 %
$\bar{b}^I$ and $\bar{b}_j^{II}$	426	5.2 %

Table 2: *Frequencies and violations of bounds.*

While in some auctions many firms simply bid the lowest possible bid of zero, in other auctions a lot of capacity is offered at higher prices close to the bounds. Figure 3 shows the example of auction number 37, and plots the bounds and the optimal high bid.

In this auction the optimal monopoly price and the observed firm's bid (the dashed line) were the price cap. The gray lines are the low bids. A lot of capacity was submitted at prices close to zero. The thick black lines plot the bounds for infra-marginal capacities. In this particular auction all firms submitted bids below the bounds. The largest infra-marginal bid, in terms of capacity, was submitted at a price of 0$/kw-month, whereas this

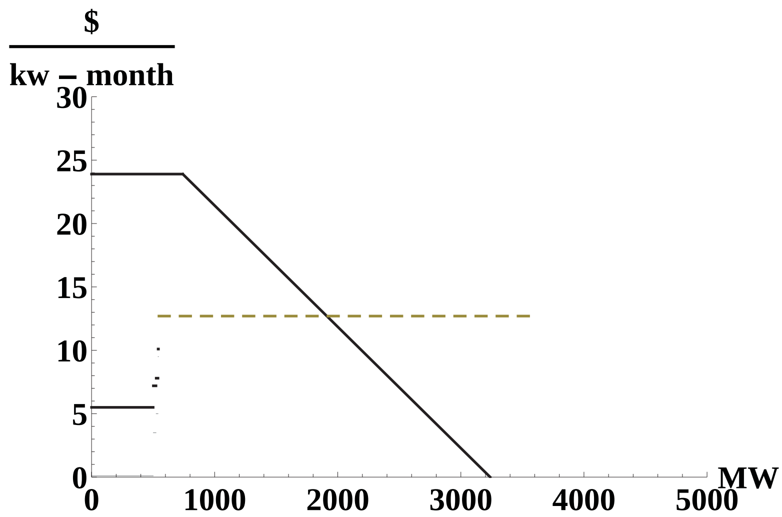

Figure 3: *Auction 37 and calculated bounds for all bids.*

bid could have been submitted up to a bid of around 5.5$/kw-month to not be profitably undercut by the pivotal firm.

5.3.1 Best response function regressions

While like in auction 37 most of the low bids were submitted at relatively low levels below the bound, over all auctions a lot of bids were submitted just below the bound. Figure 4 shows a histogram of each bids' difference to its bound. At 0, the bid was zero, while at 1, the submitted bid was equal to its bound. Values above 1 signal the percentage of bids that violated their bound, as described in table 2.

The histogram in figure 4 only depicts bids that fall in the categories of $\bar{b}^I$ and $\bar{b}^{II}$, and shows that the distribution of bids is bi-modal. Firms chose to submit bids at the ends of the support of its allowed interval $b_j \in [0, \bar{b}_j]$. In fact, 135 bids equal zero. In the following I use the fact that, however, a number of bids were submitted just below their bound.

I use the best response functions in equations (5) and (6) with the ob-

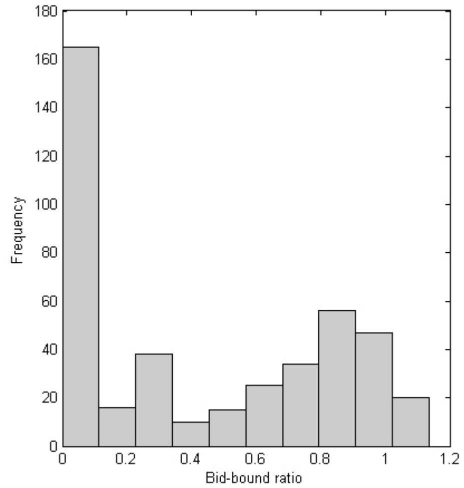

Figure 4: *Histogram bid-bound ratio.*

served bids instead of their modeled bounds. Because in each auction there can only be one bid that satisfies the conditions for b_j^I, there is only a small number of observations to estimate equation (5). However, results for estimating b_j^I are supported by the estimation results for the model in equation (6), which are presented below and are based on a sufficient number of observations. For testing equation (5), I regress the log of the bid b_j^I on the log of pivotal bidders profits and the log of the pivotal bidders capacity in each auction.[13] I add the reservation price, denoted by $p(0)$, of each auction and a dummy for winter months to control for the level of demand, because otherwise a higher demand would simply inflate profits and bids alike. For equation (5) I estimate

$$ln(b_j^I) = \beta_0 + \beta_1 ln(\pi_m) + \beta_2 ln(k_m) + \beta_3 ln(p(0)) + \beta_4 D_W. \qquad (7)$$

Column one in table 3 presents the regression results. The coefficients show a significant and positive relation of low bids, $ln(b_j^I)$, to pivotal profits, $ln(\pi_m)$.

[13]As bids can be exactly zero, I normalize the log of the bids to log(bids+2).

When the pivotal bidder earns more profits, undercutting becomes less attractive, and the low bidding firms can submit higher prices. The regression also shows that the more capacity the high bidder has available, $ln(k_m)$, the lower is the bid by infra-marginal bidders. When the high bidder holds large capacities, undercutting is more profitable and infra-marginal bidders decrease their bids to not be undercut.

	(1)	(2)	(3)	(4)
	$ln(b_j^I)$	$ln(b_j^{II})$	$ln(b_j^{II})$	$ln(b_j^{II})$
$ln(\pi_m)$	2.169***	1.182***	1.024***	1.670***
	(21.33)	(22.60)	(18.76)	(29.91)
$ln(k_m)$	-2.304***			
	(-32.54)			
$ln(D(b_j) - K_{j-1})$		-1.555***	-1.000***	-2.224***
		(-35.40)	(-12.91)	(-34.95)
$ln(p(0))$	0.744***	0.061	0.008	0.132**
	(6.72)	(1.12)	(0.23)	(2.75)
D_W	0.870***	0.300***	0.194***	0.581***
	(12.53)	(5.51)	(5.39)	(11.41)
_cons	-4.337***	2.130***	-0.171	1.966***
	(-6.17)	(3.96)	(-0.66)	(3.93)
R^2	0.93	0.89	0.93	0.89
N	80	346	133	246

t statistics in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: *Regression results for low bidders' best response functions.*

Similar results are shown in the results for bids that belong to the bound $\bar{b}^{II}$. Here, in each auction several bids could have a bound according to $\bar{b}^{II}$. Besides the variables derived from equation (6) I add the reservation price and the dummy for winter months again and estimate

$$ln(b_j^{II}) = \beta_0 + \beta_1 ln(\pi_m) + \beta_2 ln\left(D(b_j) - K_{j-1}\right) + \beta_3 ln(p(0)) + \beta_4 D_W. \quad (8)$$

Results can be found in the second column in table 3. Again, now with a sufficient number of observations, the intuition is confirmed. For increasing $ln\left(D(b_j) - K_{j-1}\right)$, meaning the large bidder has relatively higher residual demand when underbidding, low bids are decreasing to make underbidding less profitable. When comparing results for the models in column one and two, it becomes apparent that the results for bids that follow bounds of $\bar{b}^{II}$ are closer to the theoretical response. On the contrary and not in line with the model, results in column one suggest that inframarginal bids respond to the square of the ratio of pivotal profits to capacity the pivotal firm could sell when undercutting. The reason for this difference in theory and empirical findings might be caused by, first, the small number of observations for $\bar{b}^{I}$ and, second, the fact that these bids often are lower bids, often much lower than their bound and therefore also have more leeway in moving in between a bid of zero and their bound.

To confirm the validity I re-run the second model twice. First, I use only bids that were submitted at above 70% of their bound. The regression results are presented in column three of table 3 and support previous results. Last, I also run a regression for $ln(b^{II})$ where I exclude the 100 bids that were submitted at a bid of zero. I exclude those bids, because firms who might decide to always submit a bid at zero and be a price taker in the auction will be insensitive to the regression's independent variables. Again, the regression results, which are shown in column four of table 3 are in line with previous findings, although the estimates differ in magnitudes. The model predicts only the bound, and hence variation in bids below the bound can change the estimates. In this vein, the estimates for bids close to the bound (in column three) are closest to the model's predictions.

5.3.2 Profit equivalence of low bids

As shown in the model section multiple equilibria exist, in which $b_{j<m} \in [0, \bar{b}_j]$ holds and infra-marginal firms can bid any bid in between zero and their bound. Low bidding firms' profits are independent of their own bid as long as they bid low enough to not be undercut. The model disregards other strategic behavior among infra-marginal bidders. To confirm the strategic independence among infra-marginal bidders there should be no difference in the level of the bid depending on other bidder characteristics such as firm size. Figure 5 plots the log of the bid-bound ratio over log of submitted capacity, along with the according regression line.[14] The plot shows that there are considerable differences in the amount of submitted capacity. Firms that submitted relatively small capacity might be retailers reselling capacity rights. Observations to the far out on the x-axis are bids submitted by larger firms. However, it becomes clear that there is no visible pattern in the bid-bound ratio (that is, in the level of the bid) with regard to how much capacity was submitted for that price bid. The simple regression line shown in the plot has an R^2 of 0.004 and there is no significant relationship, what supports the finding that the level of the bid is not determined by firm size.

Figure 5 shows, that there is no relation between the level of the bid and the submitted capacity, supporting the model and the profit equivalence among bids between zero and their bound.

5.4 Counterfactuals

5.4.1 No capacity withholding

Capacity markets in principle are designed to reward the true aggregate market capacity. As shown, gaming in this auction leads to significant with-

[14]As before, I use log(bid-bound ration+2) and log(capacity+2), because of several observations equal to zero.

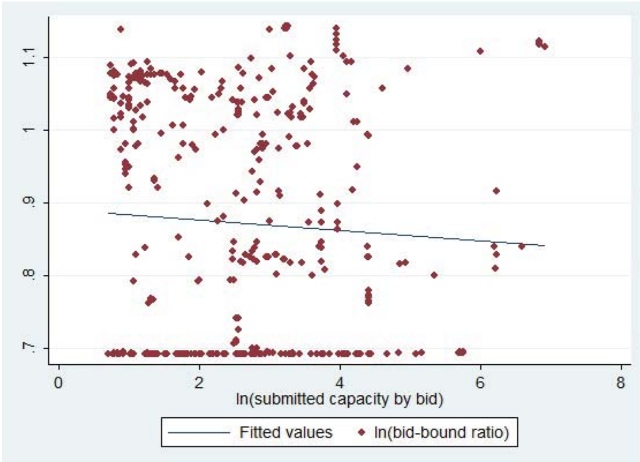

Figure 5: *Bid-bound ratio over submitted capacity.*

holding by the pivotal bidder. The auction price is too high relative to the actual capacity scarcity. As a counterfactual, I calculate the auction price that would occur if all capacity was submitted to the auction, and the pivotal player would not withhold any capacity. I find the hypothetical auction price, p^h, that fulfills $D(p^h) = K_M$. Then I apply this hypothetical price on the full demand curve (spot and forward markets). Subtracting the 'no withholding market volume' from the real and observed market volume yields the potential savings. If the market would have rewarded capacity according to the true capacity scarcity the ISO would then have procured the full market capacity at about 45% less of the costs.[15] A comparison of the realized auction price and the calculated auction price if all capacity was submitted is shown in figure 6.

From figure 6 we can conjecture that high capacity prices in the early years of the market resulted in an increase in capacity over the years and hence the hypothetical market price without withholding falls over time, taking into

[15]This counterfactual is robust to the assumption of zero costs as long as the hypothetical market clearing price is above the marginal costs.

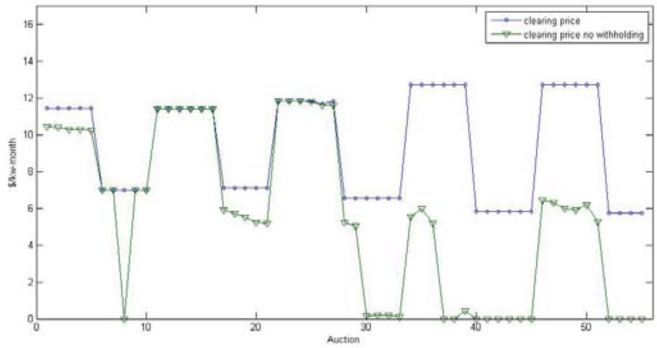

Figure 6: *Real and counterfactual clearing price.*

account different demand in summer and winter periods.[16] Indeed, adding submitted capacities in each auction, I find that the aggregate inframarginal capacities increases considerably after auction 29.

5.4.2 Bid floors

New regulations in April 2008 introduced a bidding floor for newly participating resources and a pivotal supplier test including a must offer of all capacity for pivotal firms. The bid floor was implemented at 0.75 times of the estimated net cost of entry (Net Cone). All new built capacity participating for the first time had to bid above this floor. The bid floor was introduced to prevent uneconomic entry. Opposing to the NYISO regulations, this counterfactual assumes that a bid floor is implemented for *all* participating units. A bid floor for all capacity bids can change the equilibrium price if the bid floor is higher than at least one bound derived in equation (4). Firms are forced to bid higher and it becomes profitable to undercut for the pivotal firm. In turn, in this way a bid floor can lower the equilibrium price. In

[16] I do not have an explanation for auction 8, in which compared to other auctions in that year more capacity entered the auction and could have resulted in a clearing price of zero. One possibility is that the pivotal bidder did not sell enough capacity on the forward market and submitted all remaining capacity to the spot auction.

general, there exist multiple equilibria, whenever the largest firm undercuts, will not be the pivotal bidder, and smaller firms have to clear the auction. Hence this counterfactual indicates whenever equilibria as described in the model section and found in the data will be destroyed by the bid floor. The counterfactual does not derive the new clearing price, which lies in between the old price and the bid floor. For the counterfactual I use two bid floors of 0.3 and 0.2 times Net Cone. For a bid floor of 0.3 the results show that under this bid floor regime the pivotal firm would have profitably undercut and the equilibrium price would have been lower for 16 out of 55 auctions. When the pivotal firm undercuts and also prices at the bid floor, the ISO can effectively use a well adjusted bid floor to lower the market price. Generally the ISO faces a trade-off between the frequency and the amount of price reductions. If the bid floor is too low, the equilibria as described in equations (3) and (4) are still feasible. If the bid floor is too high, the market price potentially becomes higher than without the bid floor. Calculations using a bid floor of only 0.2 times Net Cone show that then the outcome of only 10 auctions would change, but therefore potentially yielding lower auction prices, depending on if the largest bidder leaves residual demand and on how the smaller firms would play against this residual demand.

6 Conclusion

A simple multi-unit uniform price procurement auction model was applied to data from the NYISO capacity auctions in New York City. The results show that the model describes the behavior in the auction to a high degree. The pivotal bidder offers the largest capacity and submits the clearing price in each auction. In this way the firms co-ordinate on an equilibrium that extracts high rents from the auctioneer. Modeled bounds for infra-maginal bids describe around 95% of the observed bid patterns. Where bounds were violated and bids could have profitably been undercut by the pivotal firm, bidders seem to learn over time. A majority of bids that could have been profitably underbid were submitted in the first five auctions, and the magnitude of non-optimal low bids decreases thereafter. Infra-marginal firms reacted to the pivotal firm's profits and its profits of undercutting by adjusting their infra-marginal bids. During the period studied from 2003 to 2008, the capacity market in New York did not clear as intended and was rewarding capacity at too high prices. Capacity markets, if designed in the form studied here, are a costly tool to overcome the problem of supply security and supply adequacy in electricity markets. Counterfactual calculations show that bid floors have the potential to lower auction prices.

A Appendix

A.1 Capacity offers by infra-marginal bidders

I derive a limit on the optimal aggregate capacity submitted by all infra-marginal bidders, K_{m-1}. The residual monopoly price that optimizes equation (3) can be rewritten as $\min\{\frac{a-\sum_{i=1}^{m-1} k_i}{2d}, b^{cap}\}$, where b^{cap} is the bid cap and a and d are demand at a price of zero and the demand slope respectively. Profits of infra-marginal firms become $\pi_{i\neq m} = \min\{\frac{a-\sum_{i=1}^{m-1} k_i}{2d}, b^{cap}\}k_i$. If the bid cap is not binding, $\min\{\frac{a-\sum_{i=1}^{m-1} k_i}{2d}, b^{cap}\} = \frac{a-\sum_{i=1}^{m-1} k_i}{2d}$, taking the F.O.C with respect to k_i, $\frac{\partial \pi_{i\neq m}}{\partial k_i}$, yields $k_i^* = a - \sum_{i=1}^{m-1} k_i$. Summing up all optimal capacity offers of each firm i and assuming ex ante symmetry of low bidding firms we arrive at an aggregate optimal capacity offer of all infra-marginal firms of $\sum_{i=1}^{m-1} k_i = \frac{(m-1)a}{m}$, which is increasing in m. Observing less aggregate capacity by infra-marginal bidders in one auction means that each bidder could have gained by increasing its capacity offer and hence must be constrained. If the pivotal firm is constrained by the bid cap, $\min\{\frac{a-\sum_{i=1}^{m-1} k_i}{2d}, b^{cap}\} = b^{cap}$, the limit on the optimal aggregate infra-marginal capacity can be found by solving $\frac{a-\sum_{i=1}^{m-1} k_i}{2d} = b^{cap}$, which yields $\sum_{i=1}^{m-1} k_i = a - 2db^{cap}$. If the bid cap is binding, the bid cap increases the optimal aggregate infra-marginal capacity until the residual monopoly price equals the price cap.

A.2 Equilibria in which the largest firm is pivotal

All equilibria in which the largest firm is the pivotal bidder and all smaller firms bid in between zero and their bound always exist, because smaller firms never have an incentive to overbid the pivotal firm. If small bidders overbid, the largest bidder will be among the infra-marginal bidders and aggregate infra-marginal capacity increases. This results in a lower residual demand for the overbidding small firm, than the residual demand the largest firm was facing. The auction price decreases, compared to the situation in which the largest firm is pivotal. Hence, all smaller firms always sell all their capacity at the highest possible price, when being among the low bidders. Overbidding the pivotal and largest firm decreases the auction price, and potentially also the sold quantity for the overbidding small firm.

A.3 Conditions for the largest firm to be pivotal

When firm sizes are sufficiently asymmetric, the multiplicity of equilibria in the auction outcome reduces to a smaller set of equilibria, in which the largest firm is the pivotal bidder and all smaller firms submit bids between zero and their upper bounds. Suppose all but the largest firms have an aggregate capacity of K_{m-1}, while the largest pivotal bidder has a capacity of k_m. If k_m is sufficiently larger than the sum of all the small firms' capacities K_{m-1}, the large firm always would like to overbid smaller pivotal bidders and maximize its profits by submitting the market clearing high bid. To see this, note that the residual monopoly price is $\frac{a-K_{m-1}}{2d}$, where a is the demand at a price of zero and d is the demand slope. Residual monopoly profits of the large firm can be derived as $\frac{(a-K_{m-1})^2}{4d}$. When not being the pivotal bidder but among the low bidders, the largest firm can earn the highest profits when being the lowest bidder, and leaving the highest possible residual demand for smaller and auction clearing firms. These highest profits for the large firm, when being infra-marginal, are the profits when the next highest bid by a smaller firm is already the pivotal bid. In this case the large firm earns profits of $\frac{a-k_m}{2d}k_m$. Hence, for $\frac{a-k_m}{2d}k_m < \frac{(a-K_{m-1})^2}{4d}$, the largest firm will always overbid all smaller pivotal bidders. Rearranging yields the sufficient but not necessary (because we only account for the highest possible profits when being infra-marginal) condition of firm sizes for which the largest player would never be among the low bidders. For all k_m and K_{m-1} that satisfy

$$K_{m-1} \leq \sqrt{2(a-k_m)k_m} \tag{9}$$

there is only one set of equilibria in which the largest firm with capacity k_m is the pivotal bidder.

When the bid cap is binding for the pivotal firm, $\min\{\frac{a-\sum_{i=1}^{m-1} k_i}{2d}, b^{cap}\} = b^{cap}$, condition (9) changes. Profits of the pivotal firm m are now $(D(b^{cap}) - K_{m-1})b^{cap}$, while if among the low bidders, with a similar reasoning as above, profits are at most $\min\{\frac{a-k_m}{2d}, b^{cap}\}k_m$. Whenever $\min\{\frac{a-k_m}{2d}, b^{cap}\} = b^{cap}$, and we compare pivotal and low bidding profits, $(D(b^{cap}) - K_{m-1})b^{cap} = b^{cap}k_m$, the largest firm never wants to overbid and become pivotal when being among the low bidders, unless $D(b^{cap}) - K_{m-1} > k_m$ holds and the auction does not clear. When however $\min\{\frac{a-k_m}{2d}, b^{cap}\} = \frac{a-k_m}{2d}$, what happens as long as

$$k_m > a - 2db^{cap}, \tag{10}$$

we compare pivotal and low bidding profits $(D(b^{cap}) - K_{m-1})b^{cap} = \frac{a-k_m}{2d}k_m$ and find that as long as

$$K_{m-1} < D(b^{cap}) - \frac{a-k_m}{2db^{cap}}k_m \tag{11}$$

holds, the largest firm always wants to be the pivotal bidder. Hence, whenever the price cap is not binding and condition (9) holds, or whenever the price cap is binding for the largest firm when being pivotal and conditions (10) and (11) hold, there is only one set of equilibria in which the largest firm with capacity k_m is the pivotal bidder.

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