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Pricing and Capacity Provision in Electricity Markets: An Experimental Study*

Chloé Le Coq† Henrik Orzen‡ Sebastian Schwenen§

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Abstract

The creation of adequate investment incentives has been of great concern in the restructuring of the electricity sector. However, to achieve this regulators have applied different market designs across countries and regions. In this paper we employ laboratory methods to explore the relationship between market design, capacity provision and pricing in electricity markets. Subjects act as firms, choosing their generation capacity and competing in uniform price auction markets. We compare three regulatory designs: (i) a baseline price cap system that restricts scarcity rents, (ii) a price spike regime that effectively lifts these restrictions, and (iii) a capacity market that directly rewards the provision of capacity. Restricting price spikes leads to underinvestment. In line with the regulatory intention both alternative designs lead to sufficient investment albeit at the cost of higher energy prices during peak periods and substantial capacity payments in the capacity market regime. To some extent these results confirm theoretical expectations. However, we also find lower than predicted spot market prices as sellers compete relatively intensely in capacities and prices. On the other hand, the capacity markets are less competitive than predicted.

Keywords: Price Caps, Electricity, Supply Function Competition, Auctions. JEL Codes: C91, L13, L94

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1 Introduction

Many of today's power markets feature different mechanisms to govern payments to generators and thus to guide investment and reserve margins. In a laissez-faire environment, the level and duration of price spikes determines the incentives to invest in peak generation. In the Australian market, for instance, a price cap of 13.800 A$/MWh allows for high price spikes and thus market signals to guide investment decisions. In contrast, in the UK and most organized US power markets, with the exception of the ERCOT market in Texas, price caps are relatively low, oftentimes binding, and restrict revenues during times of peak demand. Investment instead is guided by capacity markets, where producers receive explicit payments for providing capacity to the market.

The purpose of this article is to compare these different mechanisms in terms of their efficiency properties—that is, their ability to efficiently provide capacity. We consider three energy market designs that vary in their price cap and in capacity payments. Empirical strategies to address such a research agenda are challenging as counterfactual market outcomes do not exist. Therefore, we pursue an experimental approach that allows us to compare different regulatory regimes within a well-defined environment.

As a benchmark case we study an energy-only market with a low price cap that limits extreme abuse of market power during periods of peak demand but leads to underinvestment in generation capacity. We then treat the market by doubling the price cap, which should cause higher price spikes. This change is costly for consumers but may provide signals of inadequate supply and greater incentives to increase investments in capacity. In essence, our data confirms this intuition. More precisely, we find a very pronounced price surge relative to the baseline treatment during peak demand, but the increase of actual prices is less than proportional to the increase of the price cap. The reason is that the improved incentives to build capacity largely work as intended, which in turn makes the market somewhat more competitive at peak times. In this way competition self-regulates prices as well as capacity provision in a new, behavioral, equilibrium.

In a third treatment we introduce a capacity market stage prior to energy market competition. In this scenario the energy price cap is set low and binding as in the benchmark case but capacity payments incentivize investments. The capacity market regime prevents shortages and attenuates price spikes. Yet, at peak times firms still enjoy some degree of market power. Thus, capacity levels that are adequate to put a stop to blackouts are not sufficient to guarantee a fully competitive energy market. Furthermore, the required extra payments to suppliers increase the overall cost to the consumer.

The experimental design applied for the analysis is inspired by several real world features of electricity markets, such as limited numbers of suppliers and stochastic demand. In our setup, four identical generating "firms" (experimental subjects) interact in repeated multi-unit auctions competing to supply electricity. Demand is perfectly inelastic and volatile, both with a deterministic element (known periods of peak and off-peak demand) and a stochastic element (demand varies within peak and off-peak periods). Subjects have to make two types of decisions. First, they decide how much capacity to make available to the market. Then, they repeatedly submit multi-step supply functions, i.e. schedules of quantities and prices specifying how much they are willing to supply at or above a given price.

So far few theoretical articles have explicitly focused on the effect of capacity markets and price caps on electricity spot market competition. Zöttl (2011) derives optimal limits to price spikes in imperfect electricity markets. Joskow and Tirole (2007) show how binding price caps together with capacity obligations can restore investment incentives. Creti and Fabra (2007) show that the competitive effect of capacity markets depends on the opportunity costs of committing to capacity resources when producers have the option to export their electricity. Cramton et al. (2013) provide an overview on the workings of capacity markets and argue why capacity markets are needed when demand is inelastic.

Empirical work has been done on the exercise of market power in deregulated electricity markets (e.g. Borenstein et al., 2002; or Hortacsu and Puller, 2008), but very few have focused on the competitive effect of price caps or capacity markets. Wolfram (1999) analyzes the introduction of a price cap in the UK market and shows the distorting effect on bidding behavior. Schwenen (2015) analyzes strategic bidding in capacity markets in the New York ISO capacity market and finds how simple bidding strategies suffice to abuse dominant positions.

The relevant experimental literature on multi-unit auctions is relatively small (see Engelmann and Grimm, 2009, for an overview). While few experimental papers focus on electricity markets (e.g. Abbink et al., 2003, von Koten and Ortmann, 2013, or Brandts et al., 2014), to the best of our knowledge, there are only two experimental studies on the impact of price caps in a multi-unit uniform price auction and none on the effect of capacity markets. The focus of these studies is on price caps that differ across firms (Kiesling and Wilson, 2007) and on non-binding price caps (Vossler et al., 2009).[5] In contrast, our experimental design specifically addresses the debate on capacity markets and to this end tests the effects of increasing market-wide price caps and of introducing a capacity market on investment and pricing performance.

[5] Henze et al. (2012) examine the network infrastructure investment under three regulatory schemes (a regulatory holiday, forward contracting scheme, and standard price cap regulation). In this setup, the authors focus on the strategic interactions between network operator and users.

Because we are interested in the treatment effect of a market-wide price cap that stimulates investment across all firms, our analysis considers different price cap levels which are equally applicable to all sellers.[6] Moreover, our experimental design tests the effect of increasing price caps and adding a capacity market on the investment and pricing performance.

With regard to the experimental literature, this article is most closely related to the study by Brandts et al. (2014) who apply a similar multi-unit auction environment and find that pivotal suppliers (i.e. suppliers whose capacity is needed to cover all demand) exercise market power as predicted by theory, as for instance in Fabra et al. (2006). While we also find that market prices are causally linked to the presence of pivotal suppliers, we contribute by changing the price cap and showing that higher price caps attract larger investment—leading to fewer market situations with pivotal supplier power.

The remainder of the paper is organized as follows. In the next section we describe the experimental design and the three treatments considered. Section 3 derives our hypotheses, relying on the existing literature on multi-unit auctions. In section 4 we present the results of the experiment. Finally, section 5 concludes and discusses policy implications.

2 Experimental design

Our experiment examines the effects of three regulatory designs on price competition and capacity provision in electricity markets. In each case, subjects compete repeatedly to sell on the electricity spot market. In the following we will refer to a sequence of six periods of spot market competition as a "round." Subjects were paid according to their profit as a firm. We used an artificial laboratory currency, e$, where 100 eCents = e$1.

Supply. The supply side of a market consists of four firms who begin each round by choosing their generation capacity, simultaneously and independently. Each unit of capacity comes at a cost of e$7 and a firm can acquire up to nine such units. Firm *i*'s chosen capacity, $\bar{q}_i$, determines the maximum firm *i* can supply on the market during the round, i.e. in each of the six spot market periods. Total market capacity is $Q = \sum \bar{q}_i$. Firms cannot change the capacity level during the round and their initial expenditures on capacity are non-refundable. In the spot market stage there is a simple marginal cost scheme: The first unit supplied costs e$1, the second unit costs e$2, and so forth until, if chosen, the ninth unit. Thus, firm *i*'s marginal cost function is $c^i = \left(c_1^i, c_2^i, \dots, c_{\bar{q}_i}^i\right)$ where $c_k^i = k$ is the marginal cost of firm *i*'s k^{th} unit.[7] This generation cost arises only if the respective unit is sold.

Demand. Demand for energy, *D*, is completely inelastic and stochastic. The probability distribution of demand is known to firms and is not symmetric: In the first four periods of

[6] In many power markets, especially those without capacity markets, price caps are indeed market-wide. However caps are sometimes also imposed as firm-specific or even unit-specific bid caps.
[7] See Borenstein et al. (2002) for empirical evidence about convex cost functions in electricity markets.

each round the demand is low (7, 8 or 9 units with equal probability), and in the last two periods the demand is high (23, 24 or 25 units with equal probability). Firms are informed of the exact demand realization at the beginning of each period (but not before).

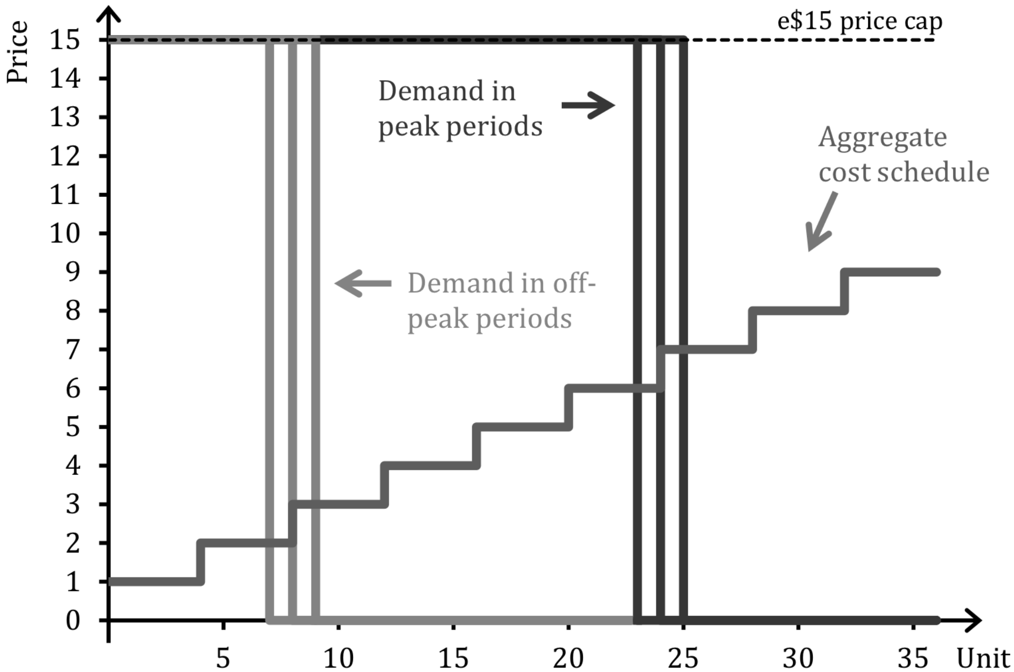

Figure 1: Marginal costs and possible demand realizations in peak and off-peak periods.[8]

Bidding. In each period firms simultaneously submit supply functions. A supply function specifies, for each of a firm's available units, the price at or above which the unit is offered to the market. Thus, each firm *i* submits a price vector $p^i = \left(p_1^i, p_2^i, \dots, p_{\bar{q}_i}^i\right)$ where p_k^i indicates the minimum price that *i* demands in exchange for supplying its k^{th} unit. Firms have to offer bids in non-decreasing order, i.e. $p_1^i \le p_2^i \le \cdots \le p_{\bar{q}_i}^i$, and they cannot specify unit prices below the marginal production costs, i.e. $p_k^i \ge c_k^i$ for all *k*. The price cap is denoted as $\bar{p}$ and so $p_k^i \le \bar{p}$ for all *k*. Depending on the treatment the price cap is either 15 or 30. Note that during the spot market stage firms know their rivals' capacity choices that were made at the beginning of the round. Thus, each firm can identify if its capacity is needed to meet the entire demand.

Dispatch and pricing. The spot market clears as a uniform price auction. That is, in each period the computer finds the market supply by aggregating all four firms' individual supply functions, putting all bids in increasing order. To find the market clearing price, the

[8] The figure illustrates the situation in the LowCap and CapMarket treatments. The HighCap treatment setting differs only in that the price cap is raised to e$30.

computer then dispatches the cheapest units first until the demand is met. The last unit dispatched sets the clearing price, p^*, for all dispatched units. Figure 1 illustrates market clearing and depicts the competitive supply curve and market prices for all demand realizations.

Treatments. Subjects are partitioned into three treatments. In our baseline treatment, LOWCAP, the price cap is e\$15. To put this in perspective, if an individual firm was able to sell 9 units (the maximum capacity) at e\$15 in both of the two peak-demand periods it would bear capacity costs of $9\times$e\$7 = e\$63 and variable production costs of $2\times$(e\$1 + e\$2 + $\cdots$ + e\$9) = e\$110, while generating revenues of $2\times9\times$e\$15 = e\$270. This would leave a profit of e\$97 from the two high-demand periods alone, out of which e\$5 would be attributable to the ninth unit. However, as we will show in Section 3, with four competitive suppliers in the market the theoretical prediction is that firms will not find it economically viable to invest sufficiently in peaking units.

The HIGHCAP treatment addresses this problem by raising the price cap to e\$30, which makes capacity investments more profitable. In all other respects LOWCAP and HIGHCAP are identical. The CAPMARKET treatment, finally, introduces a capacity market where firms can commit (in exchange for a monetary compensation) to building and offering capacity. The payments for generating capacity are determined via a procurement auction (for details see below) before energy spot-market market competition takes place. This design is similar to the New York State or New England capacity markets where capacity payments oblige the recipient to offer capacity for many periods (either for an entire month or several years). The spot-market price cap in this treatment is again e\$15. Hence, the only difference between CAPMARKET and LOWCAP is that CAPMARKET firms receive compensation payments for committed units.

Timing. Each session consists of 10 rounds of 6 periods each. Figure 2 summarizes the timing of a round for LOWCAP and HIGHCAP and Figure 3 does the same for CAPMARKET where the capacity choice stage requires an additional step, a multi-unit uniform-price procurement auction to determine the capacity compensation payments.

The timing of a round in LOWCAP and HIGHCAP is as follows. In stage 1, firms acquire the capacity they wish to hold for the six periods of stage 2 (any integer between 0 and 9). During stage 2 the exact level of demand is revealed at the beginning of each period and firms submit their supply functions. Firms are not able to withhold capacity units at this stage (or, for that matter, acquire additional capacity units) but they can of course demand the maximum price for any of their units.

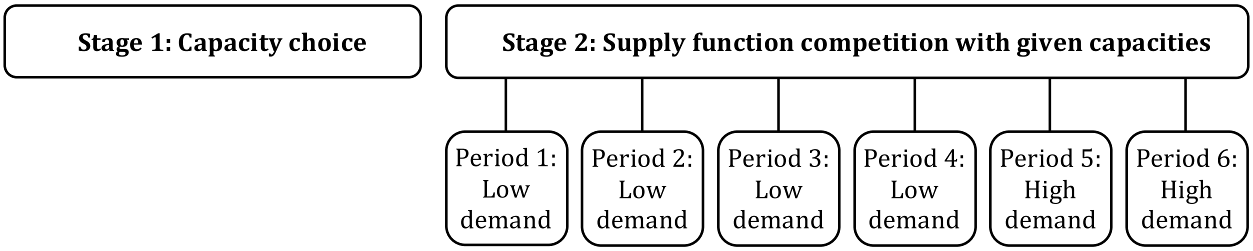

Figure 2: Timing of a round in LowCap and HighCap.

The timing of a round in CapMarket is identical except that the first stage is divided into two steps. In stage 1A firms decide on their bids for the capacity commitment. The bidding process follows essentially the same rules as those described above for the spot markets. Each firm submits a price vector that specifies, for each of the technically feasible nine units, an amount that the firm demands as compensation for creating this capacity unit. For any unit the maximum amount a firm can ask for is e$30. The capacity demand is always 25.[9] The per-unit compensation payment is equal to the 25th lowest bid. Stage 1A is binding in the sense that firms cannot renege on committed units (and they bear the cost of providing these units) but there is no commitment regarding energy prices—as before firms are free to demand the maximum price for any of their units on the spot markets.[10] In stage 1B firms can, simultaneously and independently, decide to "top up" their capacities if they so wish, again at a fixed cost of e$7 per unit.

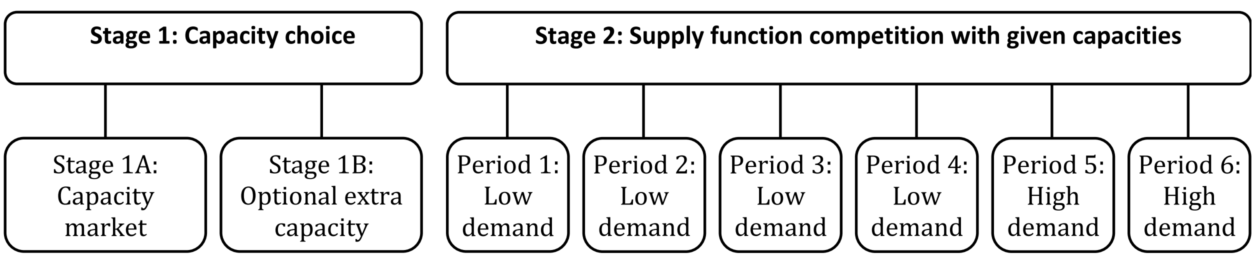

Figure 3: Timing of a round in CapMarket.

In all treatments we skipped stage 1 for the first two rounds. Instead, firms were automatically endowed, at no cost, with the maximum of nine capacity units. We did this, first, to simplify the setting so that participants had a better chance to familiarize themselves with the computer interface and the market environment and, second, to examine, as a benchmark scenario, market outcomes under the presence of excess capacity.

[9] Recall that 25 is the maximum demand realization in the energy market. Thus, this regime prevents blackouts or demand rationing even during the most extreme peak demand periods.
[10] Thus, stage 2 in LowCap and stage 2 in CapMarket are completely identical.

Procedure. A total of 92 students (46 male and 46 female) participated in the experiment, which was conducted at the University of Nottingham, UK. No subject participated in more than one session. We ran two sessions per treatment with 3-4 independent markets per session.[11] The experiment was programmed and run in Visual Basic. At the beginning subjects were seated at computer terminals and given a set of instructions, which were read aloud by the experimenter.[12] Subjects were designated as firms, and randomly and anonymously assigned to groups of four. Each group then formed a quadropoly market. The composition of groups was not altered during a session. Because predicted earnings differed substantially across the three treatments, we adjusted the exchange rates such that expected cash earnings reflected the time subjects spent in the laboratory. On average, participants earned £13.33 (ca. $24 at the time of the experiment) for sessions lasting between 1 and 2 hours, including instructions and payment.

3 Theoretical predictions and hypotheses

In this section we consider the theoretical implications of our game and formulate hypotheses. We solve the game by backward induction; thus, we will discuss the pricing game first and the decision on capacity provision subsequently.

3.1 Price choice and pivotal bidders

Our price subgame shares the basic features of uniform price auction models with capacity constrained firms analyzed, amongst others, by Fabra et al. (2006). A central finding of this literature is that the equilibrium price depends on the number of pivotal bidders in the market, where a firm is pivotal if the market does not clear without its capacity. Hence, the market clearing price depends not only on the demand realization and on aggregate market capacity but also on whether one or several capacity constrained firms are needed to serve the market demand.

Given inelastic demand, the market price predictions are straightforward. If there is no pivotal bidder (i.e. demand can be served without having to rely on one critical firm's capacity), the equilibrium market price is the competitive one. In this case the market price equals the marginal cost of the last dispatched unit. When there is at least one pivotal bidder (i.e. all the demand can only be served if all firms produce), the price cap is the only equilibrium market price. The intuition behind this result is that once one or several firms know that the market does not clear without their capacity, it is profitable to bid above marginal costs and

[11] We had only seven markets in the HighCap treatment as compared to eight in the other treatments. Furthermore, we had to dismiss data from the two last rounds in one market as one subject had to leave the experiment unexpectedly.
[12] Instructions and screenshots are provided in the appendix.

to increase the market price. With perfectly inelastic demand, the optimal bidding strategy is to bid the price cap. These well-established results can be summarized by the following lemma.

Lemma 1: Define a pivotal firm j such that $D - Q_{-j} > 0$, where $Q_{-j} \equiv \sum_i \bar{q}_{i \neq j}$ and $\bar{q}_j > 0$. With at least one pivotal firm, the equilibrium price is the price cap.

With Lemma 1 at hand, we are able to specify our main hypothesis on the price competition stage.

Hypothesis 1 (Market price and pivotal bidder): With at least one pivotal bidder, the equilibrium market price equals the price cap, irrespective of the treatment. When no pivotal bidder exists, the market price equals the marginal cost of the last dispatched unit.

3.2 Capacity choice under different price caps

We now examine stage 1 and turn to the equilibria in capacities for the LowCap and HighCap treatments. We focus on the (quasi-)symmetric equilibrium in pure strategies. This does not preclude the existence of other equilibria as in Fabra et al. (2006) but suffices for stating Hypothesis 2. We first formulate these pure strategy equilibria in Lemma 2.

Lemma 2: The pure strategy equilibria in capacities are for any $i \in \{1,2,3,4\}$:

1. $\bar{q}_i = 6$ in the LowCap treatment and
2. $\bar{q}_i = 7$ and $\bar{q}_{-i} = 6$ in the HighCap treatment.

The intuition behind Lemma 2 relates to the expected cost of running the seventh unit for a firm, given that all the other firms are providing 6 units. Note first that in equilibrium the seventh unit is only dispatched when demand is equal to 25 units. Hence for any firm i the total expected cost of installing and running the seventh unit include the initial investment, e\$7, plus the marginal cost conditional on the seventh unit being dispatched, e\$7×(2/3), totaling to expected costs of e\$11.67.[13] In contrast, the expected revenue of running a 25th unit is $\bar{p}\times(2/3)$ because the seventh unit is pivotal whenever demand is 25 and can be submitted at a market clearing bid of $\bar{p}$. Note that for any $\bar{p} <$ e\$17.5 the expected costs exceed the expected revenue and it is not beneficial to invest in the seventh unit. Lemma 2 can be reformulated to state the following hypothesis on the capacity provision.

[13] The marginal cost of e\$7 occurs when the seventh unit is dispatched at a demand realization of 25, which can arise only during two of the six periods, each time with a probability of 1/3.

Hypothesis 2 (Capacity choice and price cap): There is underinvestment in LowCap and sufficient investment in HighCap.

Hypothesis 2 states that none of the firms should invest in a seventh unit in LowCap. Therefore, demand rationing is predicted for this treatment whenever the demand realization is 25 units. In contrast, the price cap in the HighCap treatment yields sufficient revenue to warrant the provision of a seventh unit. However, there is a coordination problem as only *one* of the firms should hold such a seventh unit.

3.3 Capacity choice with a capacity market

How does the capacity market affect firms' capacity choices? The CapMarket and LowCap treatments impose the same spot market price cap of e$15. As stated in Lemma 2, given our probability distribution of peak demand realizations this price cap suffices to incentivize the provision of 24 units of market capacity but is too low to render investing in a 25$^{\text{th}}$ unit worthwhile. Under the capacity market regime, however, a 25$^{\text{th}}$ committed unit earns additional revenues in stage 1A independently of the peak demand realizations. Following the same reasoning as above, the expected cost of the 25$^{\text{th}}$ unit (the seventh unit for an individual firm) is e$11.67 whereas the expected revenue is now $(2/3)\bar{p} + f$, where f is the compensation fee for each committed unit on the capacity market. Hence, given $\bar{p} =$ e$15, the expected revenue exceeds the expected cost for $f \geq 5/3$ and it becomes profitable to invest in the additional unit. We summarize this condition in the following lemma on the capacity choice with a capacity market.

Lemma 3: In the CapMarket treatment, the pure strategy equilibria in capacities are defined as in the HighCap treatment, $\forall i \in \{1,2,3,4\}$: $\bar{q}_i = 7$ and $\bar{q}_{-i} = 6$, for any capacity payment $f \geq$ e$1.67.

In the symmetric pricing equilibrium of stage 1A bidding strategies produce a capacity payment of exactly $f =$ e$1.67: If a firm's rivals demanded higher prices for their individual seventh units, that firm would have a strict incentive to marginally undercut these offers; but undercutting a price of e$1.67 for the seventh unit would yield an expected loss. Hence, the symmetric equilibrium in stage 1A consist of each firm i submitting a bid $\tilde{p}_{ij} \leq$ e$1.67 for all units $j \in \{1, \dots, 6\}$, $\tilde{p}_{i7} =$ e$1.67 for the seventh unit and $\tilde{p}_{ij} >$ e$1.67 for all remaining, technically feasible, units $j \in \{8,9\}$. The tie for the firms' seventh units will be resolved randomly and so three of the four competitors will be compensated for six units with a total payment of 6×e$1.67 = e$10, and one firm will be compensated for seven units with a total payment of 7×e$1.67 = e$11.67. To summarize this result we reformulate Lemma 3 as follows.

Hypothesis 3 (Capacity choice and capacity market): There is sufficient investment in the CapMarket treatment ($\bar{q}_i = 7$ for one firm i and $\bar{q}_j = 6$ for all remaining firms $j \neq i$). The capacity payment is $f = \text{e\$}1.67$.

Note that this stimulus to investment in CapMarket differs in its mechanism from the traditional argument of competition-enhancing forward market commitments (e.g. Allaz and Vila, 1993; Le Coq and Orzen, 2006). Both, traditional forward contracting and capacity markets, induce quantity commitments prior to the pricing stage. However, with forward markets a prisoner's dilemma among producing firms leads to aggressive forward commitments, which reduce the spot market demand. With capacity markets, commitments are instead incentivized via regulatory payments and have no impact on the spot market demand.

4 Results

We begin by comparing aggregate capacity provision across treatments. Second, we examine pricing behavior. Finally, we discuss the efficiency of capacity provision across treatments and the roles of the price cap and the capacity market.

4.1 Capacity choices

According to our theoretical predictions underinvestment should occur only in the LowCap regime. Indeed, we do find, as shown in Table 1, that capacity choices differ across treatments and are lowest in the LowCap treatment. While there is always—in all treatments and periods—enough capacity when demand is low, the 21.8 units of average aggregate market capacity in LowCap are not even sufficient to meet the *lowest* of our three possible high-demand levels (23, 24 or 25 units). As a result, rationing occurs regularly when demand is high: Demand exceeds supply in 71 out of 128 peak periods (55%).[14]

This means that at least a subset of players miss out on some profitable investment opportunities. One might hypothesize that this could be due to subjects' uncertainty about their rivals' investment choices, paired with some degree of risk aversion. As apparent in Figure 4, there is a pronounced upward time trend in capacity levels up to round 7. Focusing on rounds 8 to 10 when subjects have gained more experience with the market and other players' choices, the average LowCap capacity increases to 23.1, closer to the theoretical prediction of 24 units. It seems that subjects learn to invest more profitably. However, supply falls short of demand in 52% of peak periods even in these late rounds.[15] This is partly due

[14] There were 2 peak periods per round, and subjects were able to choose their capacity in 8 rounds (rounds 3-10). With data from eight independent markets we get $2\times8\times8 = 128$ relevant peak periods.
[15] There is substantial heterogeneity across markets. In some there are no shortfalls at all, while in others rationing occurs practically all the time.

to the (theoretically predicted) missing 25th unit: When demand is 25 units the rationing rate increases to 87%. In contrast, when demand is 23 or 24 units the rationing rate falls to 36%.

	Treatment	Mean	SD	Min	Median	Max	Rationing†
Rounds 3-10	LowCap	21.8	4.2	11	23	29	55.5%
	HighCap	26.2	3.9	15	27	33	26.0%
	CapMarket	27.9	2.3	25	27.5	34	0.0%
Rounds 8-10	LowCap	23.1	2.7	17	23.5	27	52.1%
	HighCap	28.4	1.6	25	29	32	0.0%
	CapMarket	27.9	2.3	25	27.5	32	0.0%

†Rationing = Number of peak periods where demand > supply, divided by total number of peak periods.

Table 1: Market capacities by treatment.

The HighCap regime is much more successful in securing sufficient capacity. Although investments are again low during the early rounds there is a strong upward trend and in all rounds after round 4 the average aggregate capacity level surpasses the maximum demand of 25 units. Overall, demand exceeds supply in only 26% of peak periods (and *never* in rounds 8-10). To compare treatments statistically we use a non-parametric two-sided Fisher-Pitman permutation test for independent samples at the level of statistically independent markets. The null hypothesis that HighCap and LowCap produce the same market capacity level is rejected at a p-value <0.001, whether we consider all rounds (i.e. rounds 3-10) or only rounds 8-10.

The CapMarket regime rules out any worries about rationing by design since it guarantees a total capacity of at least 25 units. As it is evident from Table 1 and Figure 4, the average is even higher. This additional capacity is mostly provided by firms with low market shares in the capacity market, i.e. by those who were compensated for fewer units than their competitors in stage 1A. The comparison with LowCap is again highly statistically significant (p-value <0.001 for rounds 3-10 and for rounds 8-10).

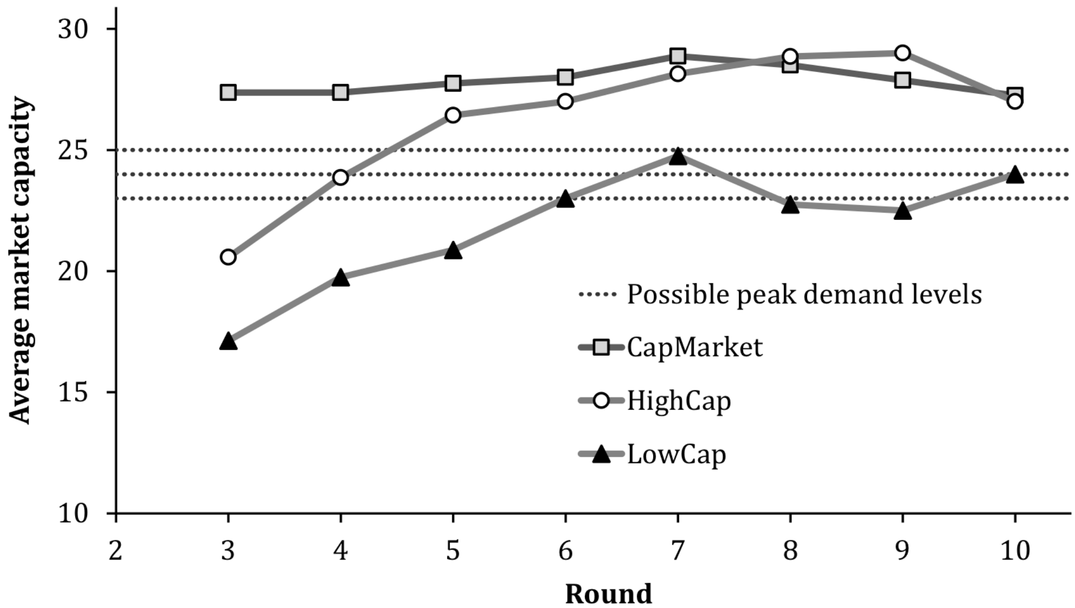

Figure 4: Average market capacity in the three treatments.

Towards the end of the experiment the capacity levels in CAPMARKET and HIGHCAP are very similar (the p-value for rounds 8-10 is 0.446). Thus, overall, doubling the price cap or adding a capacity market has similar positive effects on investments and on the security of supply. These improvements do not come for free, of course. In the CAPMARKET treatment there are direct capacity payments and in the HIGHCAP treatment we expect price peaks. We discuss these issues in the following sections 4.2 and 4.3.

4.2 Spot market prices

4.2.1 Pivotal bidders, demand levels and competition

As discussed in Section 3, the spot market equilibrium depends on whether there are pivotal bidders. In theory there are just two possibilities: Either the price is a competitive marginal cost price or it is equal to the price cap—e$15 or e$30 depending on the treatment. Table 2 shows the average market clearing price (avg. price) during periods of peak demand with and without at least one pivotal player in the market. The 'MC price' is the marginal cost price prediction conditional on the actual capacities in the relevant markets.[16]

Table 2 largely confirms Hypothesis 1. When a marginal cost price is predicted (i.e. no pivotal bidder) average prices are low, and when the price cap is predicted (i.e. at least one

[16] The precise level of the marginal cost price depends on the distribution of the firms' production capacities in the relevant market. For a given level of demand the marginal cost price is lowest when all four firms contribute evenly to meeting that demand; it is highest when capacities are extremely uneven such that the largest firm's most costly production units need to be dispatched.

pivotal bidder) average prices are high. Although the data does not precisely match the relevant point predictions, the price differences between peak periods with and those without pivotal players are very substantial and statistically significant (p-value for LowCap and CapMarket: 0.008; p-value for HighCap: 0.016).[17]

Pivotal player(s)	Treatment	MC price	Avg. price	Price cap
None	LowCap	6.25	7.20	15.00
	HighCap	6.32	7.75	30.00
	CapMarket	6.33	8.46	15.00
At least one	LowCap	6.50	13.23	15.00
	HighCap	6.69	25.14	30.00
	CapMarket	7.05	10.78	15.00

Table 2: Market prices in peak periods.

During off-peak periods players are virtually never pivotal and prices are very competitive, as shown in Table 3. Unsurprisingly, prices are systematically lower in off-peak than peak periods (p-value for LowCap and CapMarket: 0.008; p-value for HighCap: 0.016).

Treatment	MC Price	Avg. price	Price cap
LowCap	2.39	2.89	15.00
HighCap	2.36	2.96	30.00
CapMarket	2.36	3.00	15.00

Table 3: Market prices in off-peak periods.

Figure 5 shows a time series graph of energy prices for off-peak and peak periods. The intense competition in off-peak periods (encircled with a dashed line) leaves very little room for variations across time or treatments. In peak periods, however, there are substantial changes. In the first two rounds, where generation capacity is available in abundance, prices are essentially glued to the competitive level in all treatments. From round 3 onwards, when firms choose their capacities endogenously, we observe a steady upward trend in LowCap towards the predicted e$15 price cap. There is a similar development in the CapMarket treatment although the price increase is more moderate.

In the HighCap markets, in contrast, prices increase dramatically at first but then *fall* during the second half of the experiment down to a level substantially below the e$30 price

[17] The reported p-values stem from a two-sided sign-test conducted at the level of statistically independent markets.

cap. It is noteworthy that this decline coincides with the very high capacity levels in the second half of HIGHCAP, as seen in Figure 4 above. Theory, of course, does not predict a continuous relationship between market capacity and prices—as discussed, the equilibrium merely depends on whether or not there are pivotal firms.[18]

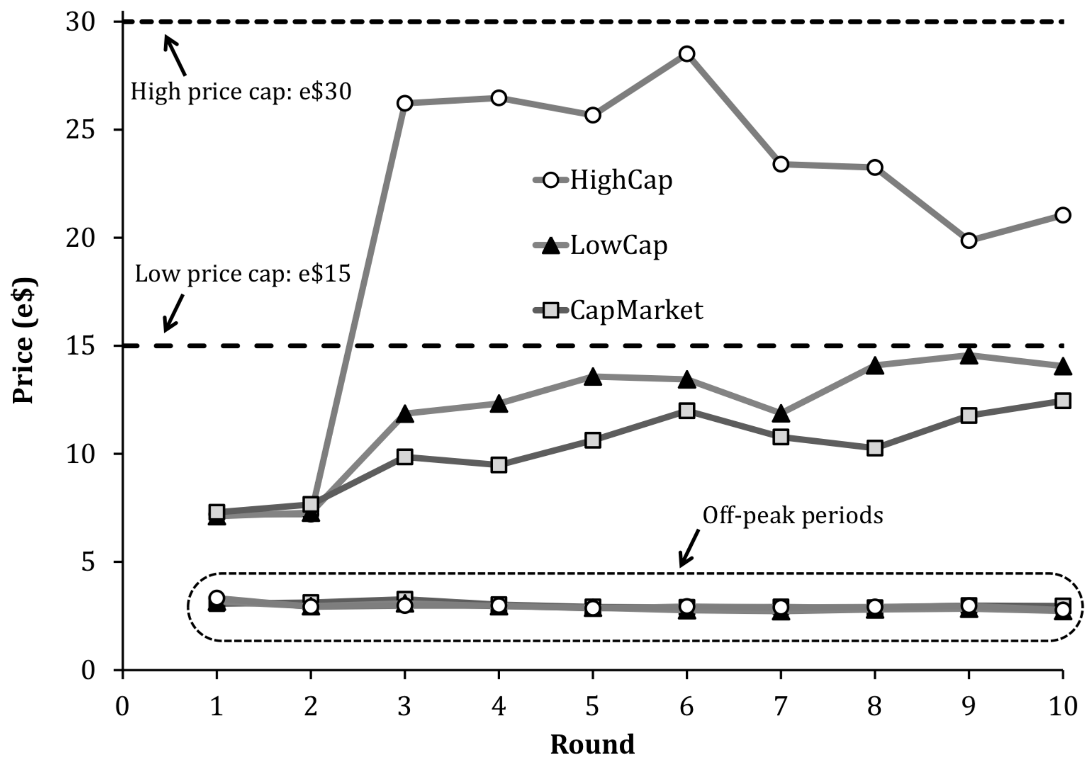

Figure 5: Energy prices in peak- and off-peak periods.

To investigate the role of excess capacity vis-à-vis the pivotality of firms in more detail we run regressions at the level of individual markets that control for both market capacity and for the presence or absence of pivotal players in a market. As in Section 3, a player i is pivotal whenever $Q_{-i} - D < 0$. If at least one seller in the market is pivotal our 'Pivotal' variable is 1; otherwise it is 0. Relative market capacity ('RelCap') is total generation capacity in the market minus demand in the current period: $Q - D$. According to theory relative market capacity should have no effect independently of 'Pivotal'. It does not seem implausible, however, that excess capacity in the market may provoke some competition even when Pivotal = 1.

Our dependent variable is 'Markup'. To calculate the markup in a market period we take as given the actual market capacity and actual demand in that period, determine the marginal

[18] The price drop in HIGHCAP seen in Figure 5 could of course be a manifestation of more frequent instances of markets without pivotal firms. However, the frequency of markets without pivotal firms does in fact not increase.

cost price that would emerge under perfect competition (see footnote 16 above), and then subtract the marginal cost price from the observed market price. To test the robustness of any findings, we also consider model specifications that focus on rounds 8 to 10 when bidders should have advanced in their experience and bidding strategies. Moreover, we control for the round number and for the gender composition in the market.

	Dependent variable: Markup					
	LowCap		HighCap		CapMarket	
	Rounds 1-10	Rounds 8-10	Rounds 1-10	Rounds 8-10	Rounds 1-10	Rounds 8-10
Pivotal	5.800*** (0.000)	7.425*** (0.000)	18.844*** (0.000)	16.417*** (0.009)	2.501*** (0.000)	1.283 (0.277)
RelCap	0.009 (0.496)	0.053 (0.246)	−0.005 (0.881)	−0.145 (0.624)	−0.058*** (0.002)	−0.164*** (0.003)
RelCap × Pivotal	−0.095*** (0.007)	−0.240*** (0.000)	−0.540*** (0.000)	−1.013** (0.033)	−0.156** (0.040)	−0.085 (0.512)
Round	0.040 (0.130)	−0.016 (0.889)	−0.091 (0.170)	−1.146** (0.018)	0.035 (0.205)	0.154 (0.361)
Number of females	−0.272*** (0.000)	−0.033 (0.756)	−0.346 (0.150)	−1.425*** (0.006)	−0.185** (0.025)	−0.040 (0.790)
Constant	0.884** (0.020)	−0.179 (0.833)	2.010** (0.039)	8.591 (0.192)	2.000*** (0.000)	3.700*** (0.003)
N	480	144	384	90	480	144
Adjusted R^2	0.741	0.902	0.847	0.808	0.388	0.535

*,** and *** indicates significance at the 10%, 5% and 1% level, respectively (p-values in parentheses).

Table 4: The relevance of pivotal sellers and market capacity levels.

Table 4 presents the regression results. Even though we control for relative market capacity it usually remains true that whether or not there are pivotal firms has a significant and substantial effect on the markup. This is in line with theory, and in HighCap the effect is more pronounced, as predicted. The only exception occurs in the CapMarket treatment. While there is an overall effect for the entire session (albeit somewhat smaller than in LowCap), the 'Pivotal' coefficient ceases to be statistically significant towards the end of the experiment. Instead, in the late rounds the intensity of competition is more strongly influenced by the level of relative market capacity. The effect of an increase in RelCap appears to be of similar magnitude in both markets with and without pivotal firms. In LowCap and HighCap there is also a competition-enhancing effect from increasing market capacity but only in markets *with* pivotal firms. There is no indication that the data converges to the theoretical prediction in this respect: The importance of relative market capacity appears to become *stronger* over time in all treatments. Furthermore, the regression picks up a gender effect, at least for some treatments and time periods: An increase in the number of female sellers in a market tends to lower the markup somewhat. Finally, there is a small negative time trend in the final rounds of HIGHCAP.

4.2.2 Pricing in LOWCAP versus HIGHCAP

To what extent does a switch from LOWCAP to either HIGHCAP or CAPMARKET affect the ability of firms to charge supra-competitive prices and what are the channels of any differences? We first look at the change in the price cap. Doubling the price cap has no impact on market prices in off-peak periods (across all rounds the p-value for LOWCAP versus HIGHCAP is 0.429), and we obtain a similar result for peak periods when we restrict the analysis to instances where there are no pivotal players (p-value = 0.350). In peak periods with pivotal players, however, the price difference between LOWCAP and HIGHCAP is substantial and statistically significant (p-value < 0.001), in line with Hypothesis 1.

However, as we have seen in Figure 5, HIGHCAP peak-period prices are substantially below the price cap of e$30, particularly towards the end, whereas LOWCAP peak-period prices converge to a level close to the e$15 price cap. Thus, one could say that in relative terms the HIGHCAP markets appear to end up being *more* competitive than the LOWCAP markets: A higher price cap does not translate into proportionally higher market prices. What is the reason for this? One possibility is that market periods without pivotal firms are more common in HIGHCAP than in LOWCAP, but this turns out not to be the case (in fact there is no difference at all). Another possibility is that there is increased competitive pressure in HIGHCAP due to generally higher capacity levels in markets with pivotal firms. To explore this idea we run regressions that examine the relationship between treatments, relative capacity levels and the degree of market competitiveness. In doing so, we focus on "experienced" market participants, i.e. on rounds 8-10. In order to rule out market pivotality as a confound we first consider only markets *with* pivotal firms and then only markets *without* pivotal firms. In each case we examine treatment effects both with and without controls for relative market capacity ('RelCap').

Our dependent variable for this regression is the 'degree of market power abuse' which we define as

$$\mathrm{DMPA} = 100\times\frac{p - p_{MC}}{\bar{p} - p_{MC}}$$

where p is the observed market price, p_{MC} is the marginal cost price contingent on actual capacity levels in a market and $\bar{p}$ is the price cap. If the observed price is equal to the marginal cost price the degree of market power abuse is 0. If the observed price is equal to the price cap (e$15 or e$30) the degree of market power abuse is 100.

	Dependent variable: DMPA in rounds 8-10			
	Markets with at least one pivotal firm		Markets without pivotal firms	
HIGHCAP	−24.023*** (0.001)	−2.941 (0.846)	−2.364** (0.044)	−3.688 (0.726)
CAPMARKET	−28.763*** (0.000)	−9.714 (0.317)	1.171 (0.342)	44.521*** (0.000)
RelCap		−3.196** (0.042)		0.257 (0.266)
HIGHCAP × RelCap		−1.490 (0.680)		−0.012 (0.982)
CAPMARKET × RelCap		−2.651 (0.292)		−2.295*** (0.000)
Round	3.411 (0.286)	1.560 (0.625)	−0.199 (0.708)	−0.596 (0.190)
Number of females	3.064 (0.295)	−0.381 (0.901)	−0.874* (0.067)	−1.164*** (0.007)
Constant	75.927*** (0.000)	85.677*** (0.000)	6.536*** (0.000)	4.209 (0.303)
N	123	123	255	255
Adjusted R^2	0.202	0.271	0.058	0.346

*,** and *** indicates significance at the 10%, 5% and 1% level, respectively (p-values in parentheses).

Table 5: Market power abuse across treatments.

The results are displayed in Table 5. Our first specification confirms the impression that the HIGHCAP markets with pivotal firms are more competitive than the corresponding LOWCAP markets: The degree of market power abuse is about 24 points lower and the difference is highly significant. This is in stark contrast to the theoretical prediction formulated in Lemma 1. Model specification 2 shows that this effect is almost entirely due to the higher market capacity levels in HIGHCAP. In markets without pivotal firms the difference between the two treatments is very small to begin with and it becomes statistically insignificant once the market capacity variables are introduced.

4.2.3 Pricing in LowCap versus CapMarket

Next, we investigate how market prices in CapMarket compare to those in LowCap. Given the identical price cap in these two regimes and according to Hypothesis 1 one would expect similar price choices. Indeed, in off-peak periods there is no statistical difference between the two treatments (p-value = 0.305). During peak periods, however, prices in CapMarket are significantly lower than in LowCap (p-value = 0.015). We obtain similar results when we restrict our attention to the last three rounds (p-value for off-peak periods: 0.218; p-value for peak periods: 0.002).

Specifications 1 and 2 of our regression reported in Table 5 show that the treatment effect is again largely explained by higher capacity levels relative to the baseline treatment: Competition is more intense because the CapMarket guarantees higher investments.

In markets without pivotal firms (specification 3) there is no overall treatment effect. When we control for capacity levels and their specific effects in the different treatments (specification 4) the picture becomes more nuanced: The CapMarket regime appears to produce *greater* levels of market power abuse per se but this is kept in check by the presence of additional capacity as well as the strong pro-competitive effect of this additional capacity in the pricing stage of the CapMarket treatment.

4.3 The capacity market

As we have seen, the additional capacity in the CapMarket treatment has a clear pro-competitive effect on the spot market and, although market power abuse is not fully eradicated, average peak-period prices are the lowest of all treatments. We now consider the flipside of this, the capacity payments made in stage 1A. Figure 6 plots the average capacity market prices over time, together with a 95% confidence interval for the estimated mean price.[19]

As the figure shows, the average capacity market price falls during the session but even towards the very end it still exceeds the predicted e$1.67 by far. This discrepancy is statistically significant (p-value = 0.008; two-tailed sign test). Instead, the mean apparently converges to the marginal cost of providing a unit of capacity: For rounds 8-10 we cannot reject the null hypothesis that the average is e$7 (p-value = 0.656). Thus, it would appear that the capacity market is used for obtaining direct reimbursements for the fixed costs of providing capacity units, not accounting for the profits that firms expect to make from owning generation capacity during the round. On the other hand, a substantial proportion—32% in rounds 8-10—of submitted prices for units that receive capacity payments are less than or equal to e$1.67 and 76% are strictly lower than e$7. Thus, the competition on the capacity market is partially fierce—subjects typically want to make absolutely sure that they secure at least 4

[19] The estimates for the confidence intervals were computed by resampling 10,000 times from the empirical distribution of capacity market prices.

or 5 units—but these low bids are often not the ones that determine the capacity market price.

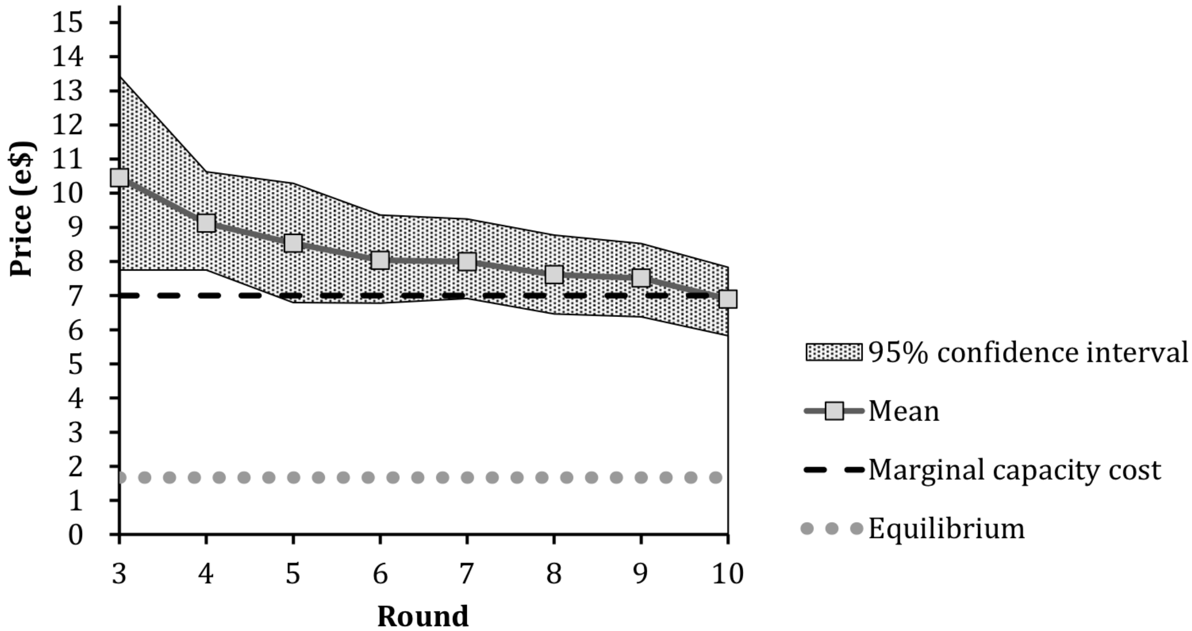

Figure 6: Mean capacity market prices over time.

4.4 The cost of capacity provision

Both the HIGHCAP and the CAPMARKET treatments lead to an increase in capacities as compared to the baseline LOWCAP case and both eliminate rationing. To get a better sense of the relative efficiency of these regimes we now evaluate the cost side of capacity provision. Specifically, we consider consumers' average expenditures on energy, taking into account both spot market prices and explicit capacity payments.[20] Overall, LOWCAP consumers pay e$8.77 per unit of energy served, HIGHCAP consumers pay e$15.46 and CAPMARKET consumers pay e$10.33. The corresponding figures for the last 3 rounds are e$9.46, e$13.90 and e$10.40, respectively. The difference between LOWCAP and HIGHCAP is quite pronounced—the per-unit cost in rounds 8-10 is nearly 50% higher in HIGHCAP—and also statistically significant (p-value = 0.001). The comparison between LOWCAP and CAPMARKET is less stark (cost increase: about 10%; p-value = 0.068). In this sense the capacity market appears to deliver relatively good value for money.

While the HIGHCAP regime turns out to increase capacity in a less efficient way in our experiment, it should be noted that this result might be heavily influenced by our choice of

[20] We refrain from fully addressing welfare since this would require additional assumptions about consumers' preferences, in particular regarding the value of lost load. However, in the absence of rationing, and given inelastic demand, capacity provision at least costs is equivalent to capacity provision at highest consumer surplus.

price caps. Had the HighCap price cap been lower it might still have been sufficient to incentivize investments and might have produced extra capacity at lower cost. Of course, in the CapMarket treatment the price cap could also have been lowered to curb abuse of market power in the energy market, without compromising the security of supply via the capacity market. This stresses how important it is that regulators calibrate price caps correctly.

5 Concluding remarks

In this paper we use experimental methods to investigate the relationship between prices, market power and investment in generation capacity in partially deregulated electricity markets under different regimes. Specifically, we analyze capacity provision under three different regulatory regimes: a price cap regime restricting scarcity rents (LowCap), a price spike regime allowing for scarcity rents (HighCap) and a capacity market regime with explicit compensation payments for capacity investments (CapMarket). Each environment is motivated by market designs that are applied in different power markets across the globe.

The LowCap baseline environment is chosen so that underinvestment prevails in equilibrium. The experimental data confirms that underinvestment indeed occurs in this setting. In line with underinvestment, subjects also exploit their market power in times of high demand, typically to the largest extent possible. Both of the alternative regimes effectively cure underinvestment in the sense that they avert rationing. In the HighCap treatment this is achieved by permitting suppliers to charge even higher prices. This has no effect on prices in off-peak periods as competition keeps spot market prices in check. During peak periods prices increase relative to the baseline treatment but sellers are unable to sustain prices close to the new price cap. Thus, price spikes both incentivize investments into generation capacity and are at the same time kept in check, at least to some extent, by such investments. However, electricity does nonetheless become more expensive.

The CapMarket treatment introduces a capacity market in which sufficient capacity is contracted in advance and paid for via capacity prices determined through an auction. For off-peak periods this again makes no difference. When demand is high average spot market prices come down relative to the baseline treatment although this is more than outweighed by the additional expenses arising from the explicit capacity payments, which are substantially higher than theoretically predicted. Overall, however, the CapMarket provides additional capacity at a lower cost than the HighCap regime with an e$30 price cap.

More broadly, our findings stress the relevance of the price cap in any of the kinds of regimes we consider. For HighCap our results suggest the existence of an optimal price cap that is just sufficient to let price spikes be regulated by competitive investment without allowing for undesirably high producer rents. In the CapMarket regime, market power still prevails in some high-demand periods even though there is adequate investment to prevent blackouts. Thus, also for this treatment a lower price cap could produce a preferable outcome. Our results suggest that such policies should be carefully tested empirically or experimentally because actual bidding behavior in this type of strategic setting with both long-term investments and short-term spot market competition appears to be more intricate than standard equilibrium theory predicts. For example, our markets respond in rather subtle ways to excess capacity or capacity shortages.

For our analysis and experiment we have employed a perfectly inelastic demand function. Many argue that a flexible demand side will ensure efficient capacity provision.[21] Currently, because of a lack of real-time metering and billing, efficient market clearing is not possible at all times. As these flaws are being removed with the advent of smart metering, one extension for future research is to compare the different market design treatments and their effect on capacity provision and pricing with an elastic demand side.

[21] Crampes and Leautier (2015), however, show that an active demand side may lead to a welfare decrease because of the strong asymmetry between consumers (who have private information on their value for electricity) and firms.

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Appendix A: Instructions for the CAPMARKET treatment*

Welcome! This is an experiment in the economics of decision making. You will be paid in private and in cash at the end of the experiment. The amount you earn will depend on your decisions, so please follow the instructions carefully.

General Rules

During the experiment you will have the chance to earn "experimental dollars" (e$), which will be converted into cash at the end of the experiment, using an exchange rate of 60e$ = £1. Thus, the higher your e$ earnings are, the more cash you will receive at the end of the experiment.

There are sixteen people in this room who are participating in this session. It is important that you do not talk to any of the other participants until the session is over.

In this experiment each person in the room represents a firm. During the session four different markets will operate and at the beginning of the session the computer will randomly allocate you to one of these. Similarly, the other firms will be randomly allocated to markets. In your market there will be you and three other firms. Your e$ earnings will depend on your decisions and on the other three firms' decisions. The firms you are matched with will be the same throughout the session but you will not learn the identity of the persons who represent these firms.

Rounds and Periods

The experiment will consist of a number of ROUNDS and PERIODS. There will be 10 Rounds, and each Round will consist of 6 Periods.

Description of a Period

In each Period of a given Round the computer will buy units of a good from you and your three competitors. By selling units to the computer you can earn e$s.

How many units the computer will demand will vary from Period to Period, but in Periods 1, 2, 3 and 4 the demand will always be LOW and in Periods 5 and 6 the demand will always be HIGH.

When the demand is LOW then the computer will buy either 7 or 8 or 9 units (with equal probability). When the demand is HIGH then the computer will buy either 23 or 24 or 25 units (again with equal probability).

You will be informed about the *exact level* of demand at the beginning of each Period.

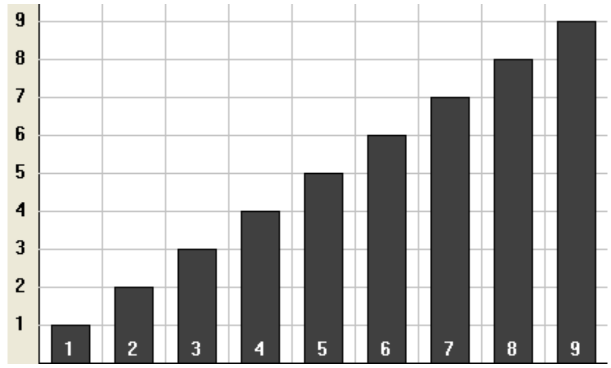
How many of these units the computer will buy from YOU and how many it will buy from the other firms in your market will depend on the prices that you charge and on the prices that your competitors charge. This will be explained in detail below.

Your main task in each Period will be to decide what price you want to charge for each unit you produce. What is important is that you have to pay a production cost for each unit you produce. To be precise, the first unit you produce will cost you 1e$, the second unit you produce will cost you 2e$, the third unit you produce will cost you 3e$, and so on. You can produce up to 9 units.

* Instructions for the other treatments are available from the authors upon request.

The following graph illustrates your production costs.

Note that you will pay production costs only for units you *sell*, not for the other units (for example, if the computer buys 3 units from you, your production costs will be 1e$ + 2e$ + 3e$ = 6 e$).

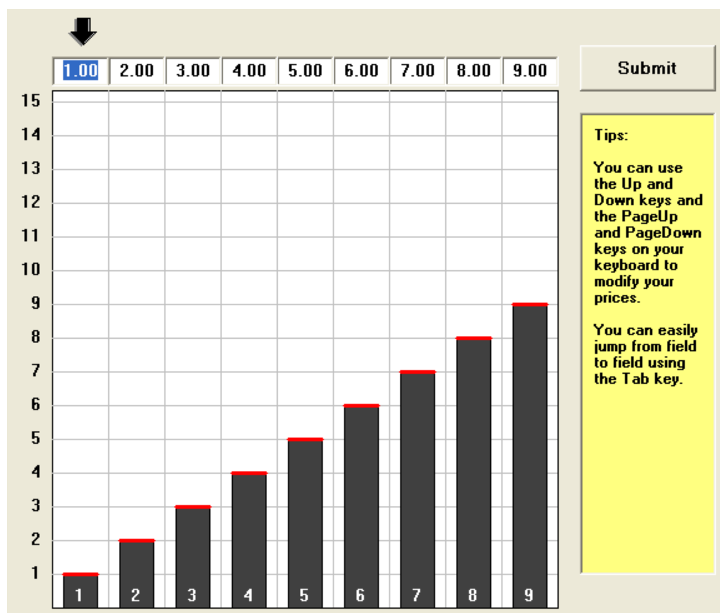


You will decide for each unit separately what price to charge. In principle you can choose your prices freely, but there are a few restrictions:

- You cannot charge a price below the production cost. That is, for Unit 1 you cannot charge a price below 1.00, for Unit 2 you cannot charge a price below 2.00, and so on.
- The maximum price you can charge is 15.00.
- The prices are not allowed to decrease from unit to unit. That is, the price for Unit 2 must not be lower than the price for Unit 1, and the price for Unit 3 must not be lower than the price for Unit 2, and so on. (However, you are allowed to charge the *same* price for different units.)

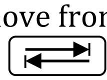
This is how the decision screen for a Period will look like at the beginning of the experiment.

You will be able to enter your prices at the top of the screen. The arrow indicates which price you are currently editing. Initially all prices are set to be equal to the production cost of the relevant unit.



There are different ways to modify your prices. You can simply type in a new price using your keyboard, or you can use the PageUp/PageDown keys on your keyboard to change the current price by an amount of +/–0.20 or the normal Up/Down keys to change the current price by an amount of +/–0.01. Little red markers on the screen will illustrate your current choice of prices.

The computer will automatically make correcting adjustments to your prices if your current choice of prices violates any of the three restrictions mentioned above.

You can move from field to field either by clicking on a field, or by using the Tab key on your keyboard: 

When you are happy with your choice of prices, please click on the "Submit" button. In each Period you will have 60 seconds to decide which prices you want to charge. When the 60 seconds are over the computer will simply take your current selection of prices.

How your payoffs are determined

Once everybody has submitted their prices (or the 60 seconds are over), the computer will determine the Market Price and how many units it buys from each firm.

To do this, the computer will first rank all the 36 submitted prices (36 because each of the 4 firms submits 9 prices), from lowest to highest.

The computer will then buy the number of units that it demands in the current Period (which will be 7, 8 or 9 units in Periods 1, 2, 3 and 4 and 23, 24 or 25 units in Periods 5 and 6, as explained above), starting with the lowest-priced unit and then working its way up to the more expensive units.

What is important to note, is that it will buy all units at the same price, the Market Price. The Market Price is the price of the *last* unit that the computer buys.

An example: Suppose that the demand is 5 units (this will never be the case in the experiment, this is simply an illustration), and the 4 firms have submitted the following prices.

	Firm 1	Firm 2	Firm 3	Firm 4
Price for Unit 1	4.50	3.76	2.31	3.90
Price for Unit 2	11.59	10.77	4.20	5.31
⋮	⋮	⋮	⋮	⋮

The computer then ranks these prices and buys the 5 cheapest units. It buys these units at the Market Price, which is the price of the last (in this case the 5th) unit that the computer buys.

		Price	Offered by…
	Cheapest Unit	2.31	Firm 3
	2nd cheapest Unit	3.76	Firm 2
	3rd cheapest Unit	3.90	Firm 4
	4th cheapest Unit	4.20	Firm 3
Market Price →	5th cheapest Unit	**4.50**	Firm 1
	6th cheapest Unit	5.31	Firm 4
	7th cheapest Unit	10.77	Firm 2
	8th cheapest Unit	11.59	Firm 1

Thus, the Market Price in this example would be 4.50, and the computer would pay 4.50 for each of the 5 units it buys. Firms 1, 2 and 4 would each sell 1 unit and firm 3 would sell 2 units. Firms 1, 2 and 4 would each have production costs of 1 and therefore each make a profit of 3.50. Firm 3 who produces 2 units would also make a profit of 3.50 for its first unit, but would make an additional profit of 2.50 for its second unit (a profit of 6.00 in total).

The case of ties: If there are ties at the Market Price (for example, imagine that Firm 4 had charged 4.50 for its second unit instead of 5.31), it has to be determined which firm gets to sell the last unit. In this case the computer will select a firm at random for each unit where two or more sellers are tied.

At the end of each period your screen will display the Market Price, how many units you have sold and how much profit you have made. (You will not see the other firms' individual prices.) Also, you will be able to scroll back to the outcomes of previous Rounds and Periods.

Description of a Round

As mentioned earlier, there will be 10 Rounds, and each Round will consist of 6 Periods of the kind described above. However, from Round 3 onwards one aspect of the experiment will change.

In each Period of Rounds 1 and 2 you are able to produce up to 9 units. In other words, your Production Capacity is 9 units. From Round 3 onwards you will be asked to *choose* your Production Capacity at the beginning of a Round. How this is done will be explained below, but note that your choice will affect your ability to produce in all 6 Periods of that Round. For example, if you choose a Production Capacity of 2, you can only produce up to 2 units in each Period of that Round.

From Round 3 onwards your Production Capacity will come at a cost: each unit of Production Capacity will cost you 7.00 e$. You can choose to have up to 9 units of Production Capacity at the beginning of a Round. (The 9 units Production Capacity you will have in Round 1 and Round 2, however, will be free.)

The cost of Production Capacity will be deducted from your e$ earnings. However, there is a chance that you receive a compensation payment for your Production Capacity expenses. This is explained in the following.

How you choose your Production Capacity

The procedure for choosing your Production Capacity will consist of two steps: Step A and Step B.

Step A: Compensation Payments for Production Capacity

In Step A, before you have made any choice about your Production Capacity, you will make a bid to the computer to request compensation payments for Production Capacity. A compensation payment means that the computer will pay you an amount of e$ as a contribution to your expenses associated with the Production Capacity.

As mentioned above, each unit of Production Capacity will cost you 7.00 e$, but in Step A you can request from the computer any amount between 0.00 e$ and 30.00 e$ for each unit of Production Capacity. You will be able to make separate bids for each unit of Production Capacity, just as you can choose separate prices for your units in the Periods (see above). In other words, you can request different amounts of compensation payments for different units.

Likewise, your three competitors can submit requests for compensation payments like this. The computer will collect all 36 request (36 because each of the 4 firms submits one separate request for each of the 9 units of Production Capacity) and will pay a compensation for the ***25 lowest*** requests.

To determine how much to pay, the computer will use the same procedure as when it determines the Market Price in a Period (explained above). That is, it will compensate the 25 lowest requests and for each of these 25 units it will pay an amount equal to the 25th lowest request. The amount of compensation the computer pays for each of these units can be higher or lower than 7 e$, depending on the submitted requests. It will not pay any compensation for the 11 highest requests in your market.

At the end of Step A your screen will display how much compensation the computer pays for each unit, and for how many units *you* receive a compensation payment.

Step B: Choosing Additional Units of Production Capacity

In Step B you will have the opportunity to choose *additional units* of Production Capacity. For example, suppose that in Stage A it has turned out that the computer pays you a compensation for 6 units of Production Capacity – this means that in Stage B you now have the option to increase your Production Capacity to 7 or 8 or 9 units (at a cost of 7e$ per extra unit).

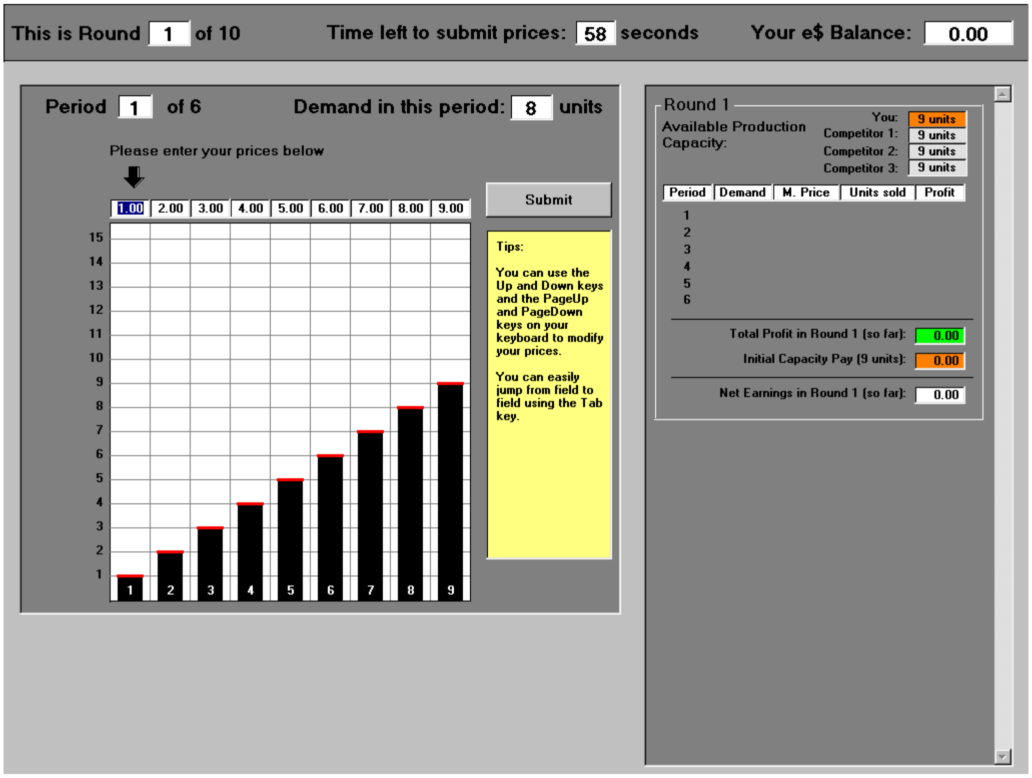
However, you *cannot reduce* your Production Capacity in Step B. That is, you MUST keep all units of Production Capacity for which the computer pays you a compensation! You should also keep this in mind when you submit your requests in Step A.

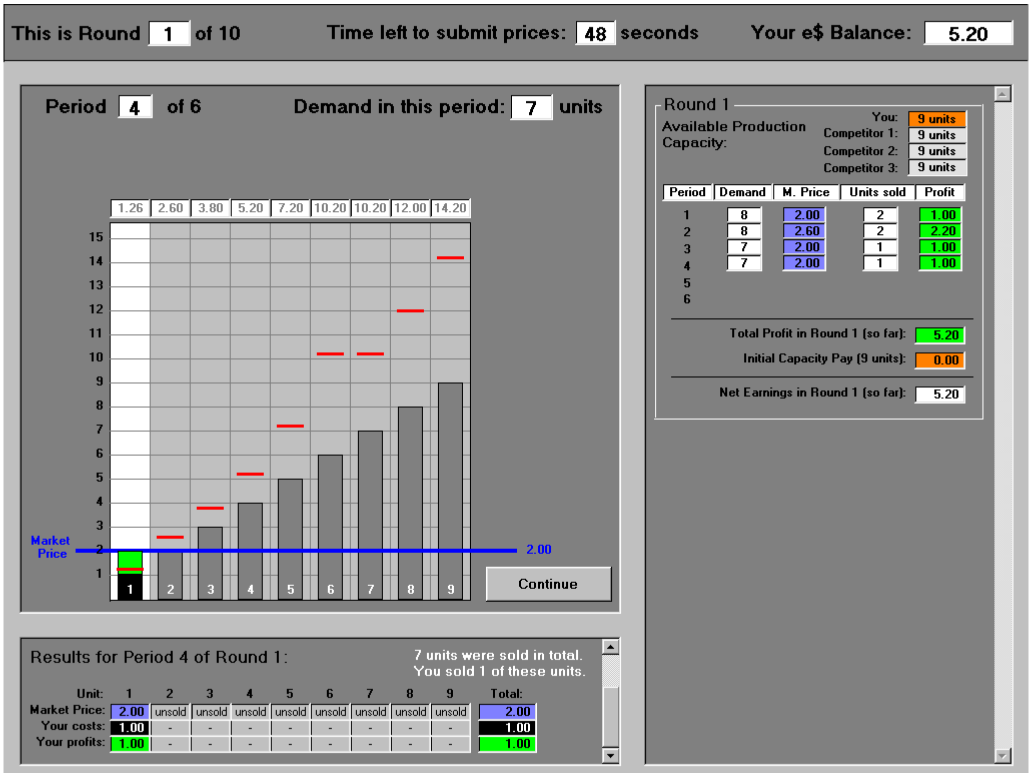
To assist you with your decisions in Step A and Step B, the software provides an "Analysis Tool". When you click on the "Analysis" button the screen will display how much profit you have made with each of your units in previous Rounds. (This excludes any compensation payments.)

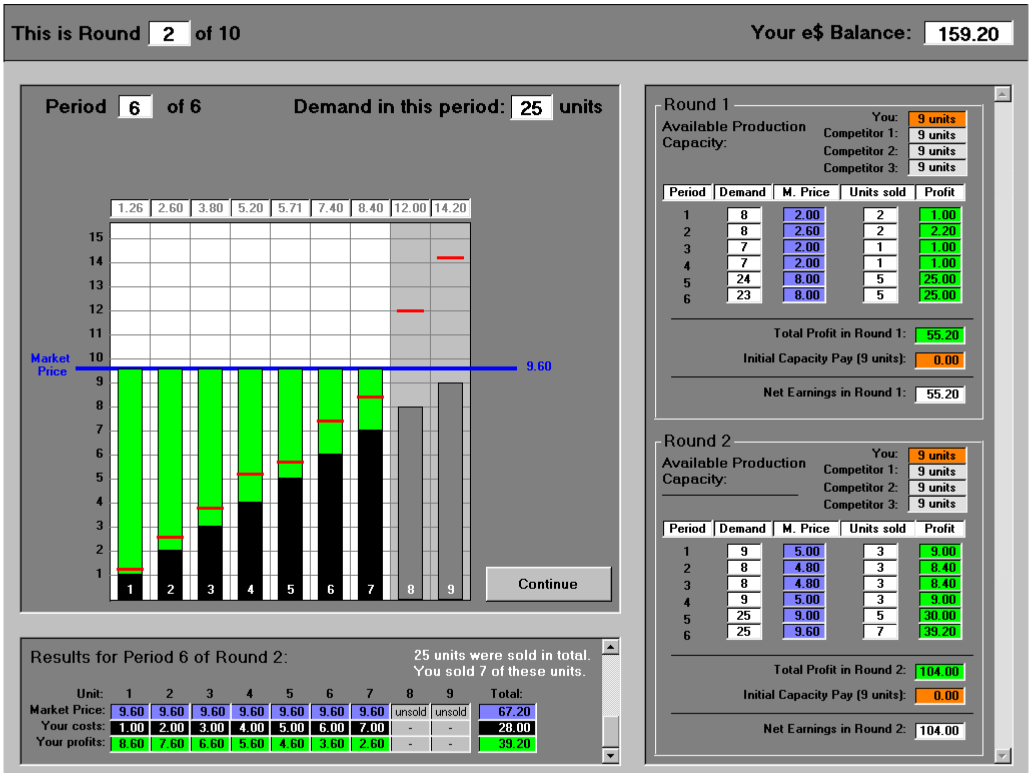
When you have decided how many extra units of Production Capacity you wish to have, please click on the "Submit" button to start the next six Periods. Note that once you have submitted your choice for the Production Capacity you cannot change it for the current Round!

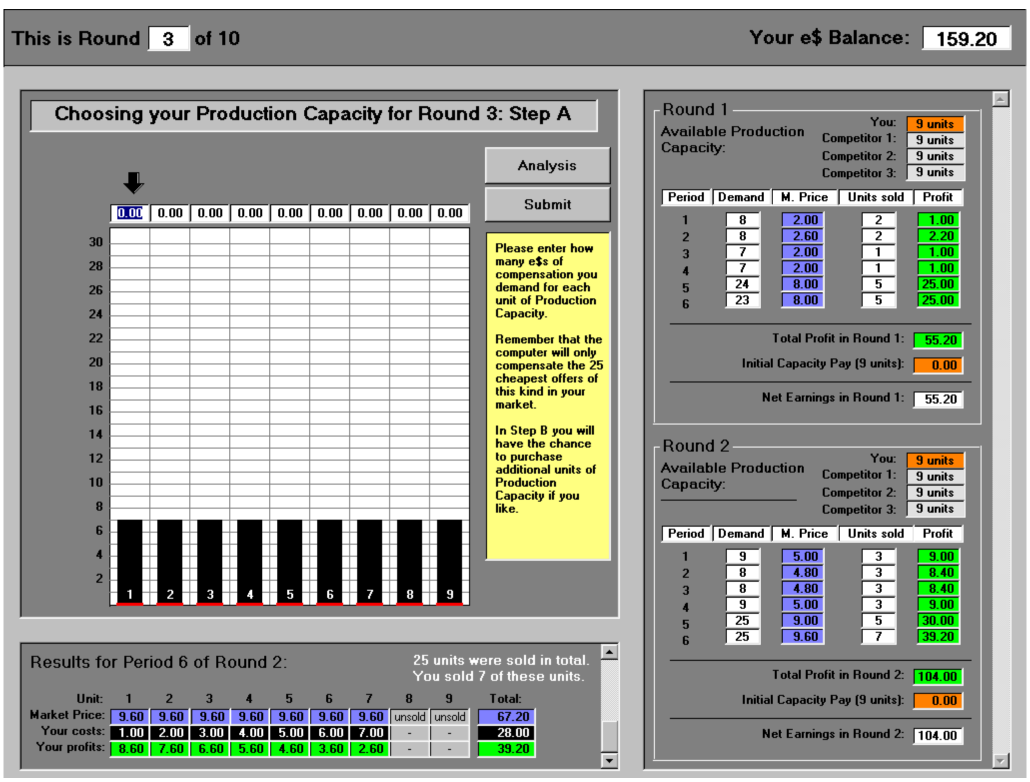
After you have made your choice, the first Period of the current Round will begin. On the right hand side of the screen the Production Capacity Choices of your competitors will be displayed.

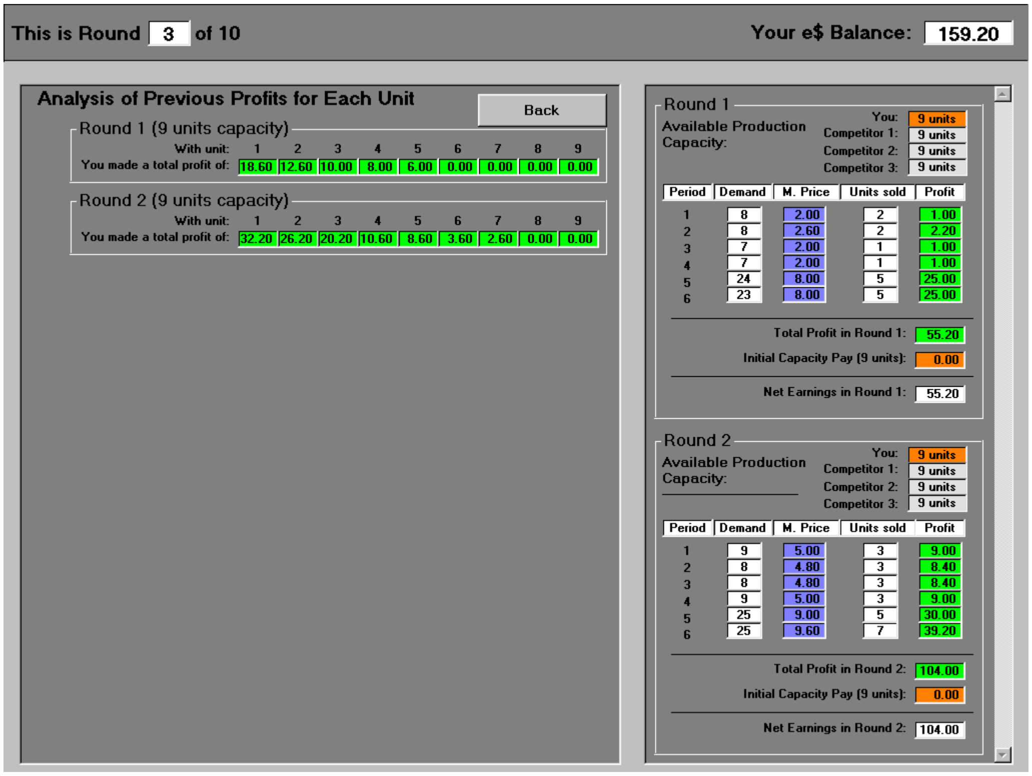
Appendix B: Screenshots (not intended for publication)






This is Round 2 of 10
Your e$ Balance: 159.20
Period 6 of 6
Demand in this period: 25 units
1.26 2.60 3.80 5.20 5.71 7.40 8.40 12.00 14.20
Market Price
9.60
Continue
Results for Period 6 of Round 2:
25 units were sold in total.
You sold 7 of these units.
Unit: 1 2 3 4 5 6 7 8 9 Total:
Market Price: 9.60 9.60 9.60 9.60 9.60 9.60 9.60 unsold unsold 67.20
Your costs: 1.00 2.00 3.00 4.00 5.00 6.00 7.00 - - 28.00
Your profits: 8.60 7.60 6.60 5.60 4.60 3.60 2.60 - - 39.20
Round 1
Available Production Capacity:
You: 9 units
Competitor 1: 9 units
Competitor 2: 9 units
Competitor 3: 9 units
Period Demand M. Price Units sold Profit
1 8 2.00 2 1.00
2 8 2.60 2 2.20
3 7 2.00 1 1.00
4 7 2.00 1 1.00
5 24 8.00 5 25.00
6 23 8.00 5 25.00
Total Profit in Round 1: 55.20
Initial Capacity Pay (9 units): 0.00
Net Earnings in Round 1: 55.20
Round 2
Available Production Capacity:
You: 9 units
Competitor 1: 9 units
Competitor 2: 9 units
Competitor 3: 9 units
Period Demand M. Price Units sold Profit
1 9 5.00 3 9.00
2 8 4.80 3 8.40
3 8 4.80 3 8.40
4 9 5.00 3 9.00
5 25 9.00 5 30.00
6 25 9.60 7 39.20
Total Profit in Round 2: 104.00
Initial Capacity Pay (9 units): 0.00
Net Earnings in Round 2: 104.00


This is Round 3 of 10
Your e$ Balance: 159.20
Choosing your Production Capacity for Round 3: Step A
Analysis
Submit
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Please enter how many e$s of compensation you demand for each unit of Production Capacity.
Remember that the computer will only compensate the 25 cheapest offers of this kind in your market.
In Step B you will have the chance to purchase additional units of Production Capacity if you like.
Results for Period 6 of Round 2:
25 units were sold in total.
You sold 7 of these units.
Unit: 1 2 3 4 5 6 7 8 9 Total:
Market Price: 9.60 9.60 9.60 9.60 9.60 9.60 9.60 unsold unsold 67.20
Your costs: 1.00 2.00 3.00 4.00 5.00 6.00 7.00 - - 28.00
Your profits: 8.60 7.60 6.60 5.60 4.60 3.60 2.60 - - 39.20


This is Round 3 of 10
Your e$ Balance: 159.20
Analysis of Previous Profits for Each Unit
Back
Round 1 (9 units capacity)
With unit: 1 2 3 4 5 6 7 8 9
You made a total profit of: 18.60 12.60 10.00 8.00 6.00 0.00 0.00 0.00 0.00
Round 2 (9 units capacity)
With unit: 1 2 3 4 5 6 7 8 9
You made a total profit of: 32.20 26.20 20.20 10.60 8.60 3.60 2.60 0.00 0.00
Round 1
Available Production Capacity:
You: 9 units
Competitor 1: 9 units
Competitor 2: 9 units
Competitor 3: 9 units
Period Demand M. Price Units sold Profit
1 8 2.00 2 1.00
2 8 2.60 2 2.20
3 7 2.00 1 1.00
4 7 2.00 1 1.00
5 24 8.00 5 25.00
6 23 8.00 5 25.00
Total Profit in Round 1: 55.20
Initial Capacity Pay (9 units): 0.00
Net Earnings in Round 1: 55.20
Round 2
Available Production Capacity:
You: 9 units
Competitor 1: 9 units
Competitor 2: 9 units
Competitor 3: 9 units
Period Demand M. Price Units sold Profit
1 9 5.00 3 9.00
2 8 4.80 3 8.40
3 8 4.80 3 8.40
4 9 5.00 3 9.00
5 25 9.00 5 30.00
6 25 9.60 7 39.20
Total Profit in Round 2: 104.00
Initial Capacity Pay (9 units): 0.00
Net Earnings in Round 2: 104.00