

Competition with Forward Contracts: A Laboratory Analysis Motivated by Electricity Market Design*

By

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Abstract

We use experiments to study the efficiency effects for a market as a whole of adding the possibility of forward contracting to a spot market. We focus on the strategic implications of a forward market. We deal separately with the cases where spot market competition is in quantities and where it is in supply functions. In both cases we compare the effect of adding a contract market to the introduction of an additional competitor, changing the market structure from a triopoly to a quadropoly. We find that, as theory suggests, for both types of competition the introduction of a forward market significantly lowers prices. The combination of supply function competition with a forward market leads to high efficiency levels.

Keywords: Electricity Markets, Forward Markets, Experiments, Competition

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1. Introduction

In the worldwide process of regulatory reform in the electricity industry, the mitigation of market power is one of the basic problems regulators have to deal with. One way that can potentially be used to address this problem is to allow for forward contracts between producers and traders. In this paper we use experiments to study the effects of forward contracting in an imperfectly competitive market.

The original rationale for forward markets is related to the hedging of risk (for a recent study, see Hortacsu and Puller, 2004). An influential study by Allaz and Vila (1993) added a second rationale. They show that the presence of a forward market changes producers' strategic incentives in a way that, in equilibrium, enhances competition and efficiency. In this paper we leave aside demand uncertainty considerations (thereby removing the need for risk hedging) and focus purely on the implications of forward trading for strategic behavior. The strategic consequence of allowing for the presence of forward contracting consists in committing firms to more aggressive output decisions. Selling decisions on the forward market involve a kind of dilemma game. If just one firm sells forward it obtains a Stackelberg-type advantage, but if all firms pre-commit then they are all worse off in terms of their economic profits. The focus of our study will, hence, be on the comparison of efficiency and output levels and on the analysis of behavior in this dilemma-type situation.

Our work can be seen in conjuncture with recent empirical investigations into the effects of forward markets to be discussed below. Our approach is complementary and exploits the fact that in the laboratory one can implement the desired variations with a high degree of control. Laboratory control has several virtues that prove particularly useful when studying electric power markets (Rassenti *et al.*, 2002).¹ Most importantly for us, it enables a comparison of allocations with and without forward markets under truly *ceteris paribus* conditions. In an empirical comparison of field data collected before and after the introduction of a forward market (or across countries with and without forward markets) there are typically many things that changed simultaneously with its introduction. Econometric analysis provides some means to correct for other factors, but it often remains difficult to pinpoint the effect of the forward market *per se*. Laboratory control allows one to isolate this effect. In doing this we are able to focus exclusively on the strategic effect of forward markets. Whereas other experimental studies (Forsythe *et al.*, 1982, 1984; Friedman *et al.*, 1983) have shown that market performance is enhanced by the possibility of hedging risks, laboratory control allows us to isolate the strategic effect first described by Allaz and Vila (1993).² In addition, it allows us to compare the impact of a forward market under distinct institutional arrangements.

¹ Recently, experiments have been used to study how market power in the electricity industry can be limited by other means than forward markets (Staropoli *et al.*, 2000; Rassenti *et al.*, 2003; Weiss (2002). Abbink *et al.* (2003) and Rassenti *et al.* (2001) compare prices and efficiency levels under the uniform and the discriminatory price call auctions and find that the first auction format has more desirable properties.

² These studies on risk hedging refer to markets in general. As far as we know, there are no studies that investigate the effect of risk hedging in the specific context of electricity markets. Such studies could provide an interesting complement to our investigation of the strategic effect of forward markets. Le Coq and Ortzen (2002) present experimental results on the strategic effect of forward markets. However, their design is not related to electricity markets. They simulate the contract

We will focus on two institutional arrangements in particular: the case where spot market competition is in quantities and the case where it is in supply functions. Spot market competition in the electric power industry is often analyzed by quantity competition (see Bushnell *et al.*, 2005, for a recent example). However, market rules often correspond more closely to supply function competition as introduced by Klemperer and Meyer (1989). Examples are the spot markets for electricity in Australia, Chile, England and Wales, New Zealand, Scandinavia and Spain. In those markets firms typically submit multiple bid-quantity combinations. The quantity competition model has the advantage that it typically yields distinct theoretical predictions. Allaz and Vila (1993) and Bolle (1993) study the effects of forward contracting for this setting and provide unique predictions. In contrast, supply function competition generally implies multiple equilibria. For the case without forward markets, Klemperer and Meyer show that there is a continuum of equilibria; it is possible to obtain a unique equilibrium once a specific type of demand uncertainty is introduced, however (*e.g.*, Baldrick *et al.*, 2000; Bolle, 2001; Rudkevich, 1998). Newbery (1998) and Green (1999) present models combining forward markets with supply function competition in the spot market. They base their analysis on restrictions on functional forms and also need demand uncertainty to obtain a unique prediction. Because our setup does not involve demand uncertainty our supply function competition yields a continuum of equilibria similar to the Klemperer and Meyer case.

Our results show that in both cases the introduction of forward markets increases the quantity supplied. As a consequence, efficiency increases from 94.2% to 96.7% with quantity competition and from 96.8% to 98.5% in case supply functions are used. We observe even higher production (but not efficiency) levels if competition is increased by adding one producer to the market instead of introducing a forward market. Our results on forward markets are in line with those of a number of empirical studies based on field data. Green (1999) documents changes in the forward contract holdings of suppliers in the UK market since the start of the market. He argues that a major factor in explaining both the lower price and reduced volatility of prices during the first two years of the market is the high level of vesting contracts held by National Power and PowerGen, the two largest suppliers in the UK market. Wolak (2000) uses data on the actual forward contracting of a large supplier in the Australian electricity market and documents a continuous decline in prices that followed forward contracting. Wolak (2003) identifies the lack of forward contracting in the California electricity market as the primary cause of extremely high spot prices for the period June 2000 to June 2001. Bushnell (2004) also concludes that in the poor performance of the California market in 2000 the very limited amount of forward contracting was a significant factor.³

market and deal exclusively with quantity competition with marginal costs equal to zero. Miller *et al.* (1977), Hoffman and Plott (1981) and Williams and Smith (1984) report on other experiments in which some participants act as traders arbitraging between different time periods.

³ In these empirical studies, Bushnell does not specifically address the risk hedging versus strategic effects of forward markets, Green refers to both and Wolak stressed the strategic impact we focus on.

The remainder of this paper is organized as follows. Section 2 gives the experimental design and procedures. In section 3 we derive predictions and hypotheses and in section 4 we present our results. In the presentation of the results we will start by looking at average total production for the different treatments comparing them to one-shot game equilibrium predictions and the Walrasian production level. We then study the composition of observed inefficiency into the different components related to consumer and producer surplus and behavior on the forward market focusing on traders' winning bids and profits. Section 5 concludes the paper.

2. Experimental Design and Procedures

2.1. Parallelism

Our aim is to test appropriate theoretical models in a framework that maintains a large degree of parallelism to the markets that motivate us. However, this study should not be seen as an attempt to create a mirror image of an electricity market in the laboratory.⁴ We will need to exclude some potentially important elements from our consideration. The analysis we present here is based on stylized representations of the actual workings of the relevant markets. Here, we discuss the most important design decisions we made to enhance parallelism.

A first basic decision we need to make in the step from electricity markets to an experimental framework concerns the numbers of producers and (in case of forward markets) of traders. Various experimental studies have dealt with quantity competition without forward markets (Binger *et al.*, 1992; Huck *et al.*, 1999; Offerman *et al.*, 2002; and Rassenti *et al.*, 2000b). Huck *et al.* (2001) survey previous results on experimental quantity competition with special attention to the relation between the number of firms and market outcomes. They report that with two firms there is some collusion and that with three firms market outcomes tend to be close to the one-shot Cournot equilibrium prediction. To isolate the effect of forward markets on competition, we therefore start from a situation in which we expect little baseline collusion, *i.e.*, we take three firms as our starting point. With respect to the number of agents in the forward market, we follow the suggestion of Allaz and Vila (1993) and introduce two traders who first compete in prices for quantities posted by producers and then compete with the producers in the spot market. Under this Bertrand-type competition, the forward market is expected to be sufficiently competitive.

Aside from competition with (only) three producers and competition with three producers and two traders in a forward market, we also consider the case with four producers (and no forward market). We do so for two reasons. First, these treatments provide a policy-motivated standard of comparison for the impact of a forward market, since the possibility of increasing competition through new entry or divestiture is one of the main options often mentioned in the public debate on regulatory reforms in the electricity industry (*e.g.*, Newbery, 2002). Specifically, governments may consider removing

barriers to entry or even subsidizing entry. To compare the effects of forward markets to this kind of entry stimulating policies, we consider the best possible outcome of such policies: the situation where the policy was successful and entry has taken place. Second, it provides a control for the presence of a ‘pure numbers effect’. Given the way in which we represent the forward market, the number of active participants in the subsequent spot market will be equal to the number of producing firms plus, possibly, a trader who is active in the spot market. If behavior were driven purely by the number of active agents then adding a forward market would lead, in principle, to the same outcome as adding one more competitor. By obtaining information on the case with four producers we will be able to control for this ‘pure numbers effect’.⁵

Next, we need to make some choices on the cost and demand conditions. Our main point of interest is in the behavior of producers in distinct environments. As in most experiments in this field (*cf.* Huck *et al.*, 2001), we therefore simulate the demand side of the market and simplify the situation considerably by assuming linearity. As mentioned in the introduction, given that we want to focus on the strategic aspects related to the introduction of forward markets, we chose not to impose demand uncertainty in our experiments.

On the producers' side, we assume a technology with decreasing returns to scale, which characterizes well the technological constraint under which the electricity industry operates (Wolfram, 1998). Such a constraint implies convex marginal costs so that in the experiments we use a quadratic marginal costs schedule.⁶ Increasing marginal costs may be particularly important when studying the effect of forward markets. Given the asymmetry that they cause in losses due to over versus under producing, they may mitigate the willingness to sell substantial amounts on the forward market and, thus, reduce the effects. Therefore, it is important for our purposes to incorporate cubic cost functions into the experiment.

Throughout we choose to implement a complete information environment where all participants know the demand and cost functions and the latter is common to all producers. The theoretical models we will relate our experiments to also assume complete information.

Summarizing, our experiments use a stylized representation of electricity markets with quadratic marginal cost functions and (simulated) linear demand. The treatments called C(ournot)3.0 and S(upply)F(unction)3.0 are our benchmark spot market treatments with 3 producing firms and, due to the absence of a contract market, 0 traders. C3.2 and SF3.2 are treatments with a spot and a forward contract market, where the number 2 now stands for the presence of two traders. C4.0 and SF4.0 both involve only spot markets with 4 producing firms.

⁴ For a discussion of the use of laboratory experiments to study ‘real world’ problems, see Schram (2005).

⁵ The notion of a pure numbers effect is an intuitive one and not based on game-theoretic analysis. For a reference to pure numbers effect in the context of other Cournot competition experiments, see Holt (1995).

⁶ Similarly, Green and Newbery (1992) model high end marginal cost as quadratic. Borenstein, Bushnell and Wolak (2002) present data-based marginal cost schedules that exhibit a ‘hockey-stick’ shape at high quantity levels similar to ours.

2.2 Procedures

The experiments were conducted at the CREED laboratory for experimental economics of the University of Amsterdam. Subjects were recruited by public advertisement on campus and were mostly undergraduate students in economics, business and law. They were allowed to participate in only one experimental session. At the outset of each session, subjects were randomly allocated to the laboratory terminals and were asked to read the instructions displayed on their screens.⁷ Then they were introduced to the computer software and given five trial rounds to practice with the software's features. Subjects were told that during these trial rounds, other subjects' decisions were simulated by the computer, that is programmed to make random decisions and that gains or losses made during those rounds would not count. Once the five trial rounds were over, the pool of subjects was divided into independent groups (markets). For the triopoly (quadropoly) treatments, each of these groups was composed of 3 (4) subjects and for the triopolies-with-contracts, each group consisted of 5 subjects (3 producers and 2 traders). Three or four markets ran simultaneously in a session. Subjects stayed in the same market and same role for the whole session and did not know who of the other subjects were in the same market as themselves. Each session consisted of 25 repetitions (rounds) and lasted for about 2 to 4 hours. One round took approximately 3-5 minutes to be completed.

Earnings in the experiment were denoted in experimental francs. We used an exchange rate of 5000 francs to 1 Dutch guilder (\approx € 0.45). The average earning from participating in these experiments was € 24,60. There was no show-up fee. As will become clear below, it was possible to have negative earnings in our experiments (especially for traders, for whom expected equilibrium earnings are zero, as will be discussed, below). For this reason we gave each trader a capital balance of 45000 francs plus an additional 2000 francs per round and each producer one of 5000 francs. Nevertheless, the possibility of bankruptcy remained. In the instructions, subjects were informed that if they exhausted their capital balance, they would be asked to leave the experiment without earnings. In total, we ran 12 sessions with 45 groups and bankruptcy occurred for 5 individuals. As will be explained in section 5, we will disregard from our data analysis the groups in which a bankruptcy occurred.

Subjects remain in fixed groups throughout a session. This procedure approximates best actual circumstances in most oligopolistic markets and, in particular, in the kind of electricity markets that we are interested in. It is followed in all previously cited experiments on quantity competition, as well as in many other oligopoly experiments (Holt, 1995). The procedure has also the advantage that the observations from the different groups are completely independent from each other.

2.3 Demand and Supply

The demand function used is the linear function

⁷ A transcript of the instructions is included in Appendix 1. Appendices are available from the authors upon request and are downloadable from the CREED web site <http://fee.uva.nl/creed/pdffiles/EJAppendix2006>.

$$p(q) = \max\{0, 2000 - 27q\}, \quad q \geq 0, \quad (1)$$

where p denotes price and q quantity. Subjects are not given this equation but can see a table on their screen (through which they can scroll) and also receive a printed version of the table on a handout. In the sessions with quantity competition, this table has two columns, giving aggregate quantities and the corresponding market price. In the supply function sessions, the table has the same two columns containing the demand information, as well as an additional column giving the aggregate supply function submitted by the producers.

The marginal cost function used (*cf.* section 2.2) is:

$$\text{mc}(q) = 2q^2, \quad q \geq 0, \quad (2)$$

Production takes place in discrete units. Cumulative costs are given by:⁸

$$c(q) = 2 \sum_{l=1}^q l^2, \quad (3)$$

These functions are also given in tabular form – both on the screen and as a handout - with columns representing the number of the unit, the marginal cost of that unit and the cumulative costs. The screen in the Cournot sessions has a fourth column, where the subject can indicate the quantity she wants to offer. In the supply function sessions the extra column is used by subjects to indicate the minimum price they require in order to produce that unit.

2.4 Cournot treatments

We now turn to a description of the actual decision sequences in the various treatments. In any given round t of C3.0 and C4.0 each of the participants i has to independently decide how many units, $q_{it} \in N$, to produce and supply to the market. Each producer has a capacity limit of 30 units, i.e., $0 \leq q_{it} \leq 30$; note that the demand at a price of zero is less than the sum of the capacities of the three producers. After producers have made their decisions the computer aggregates the units produced by the different producers in a group ($q_t = \sum_i q_{it}$), determines the market price, p_t , using eq. (1), and each producer's profits in round t , π_{it} , as:

$$\pi_{it} = p(q_t)q_{it} - c(q_{it}), \quad t = 1, \dots, 25 \quad (4)$$

where $p(\cdot)$ is given in eq. (1) and $c(\cdot)$ is determined using eq. (3). The aggregate supply (and production), q_t , and corresponding market price, p_t , are highlighted on the screen in the table

⁸ Note that the total cost function in (3) is not a simple integration of (2) because only discrete levels of production are possible in the experiment. In fact, in the experiment (1) and (2) are only evaluated at integer values of q .

corresponding to the demand function. Then the next round starts. Rounds are independent of each other in the sense that supply can not be transferred across rounds.

In C3.2 each round is composed of three phases. In phase 1 the 3 producers independently post quantities $q_{ii}^f \in N, i=1,2,3$, for sale on the forward market. These are aggregated, $(q_t^f \equiv \sum_i q_{ii}^f)$, and offered for purchase to two traders. Then the round enters phase 2 in which each trader j can independently bid unit prices, b_{ij} , for the purchase of the total quantity offered by the producers.⁹ The bidder with the highest of the two bids ($b_t \equiv \max_j \{b_{ij}\}$) obtains the total quantity offered, with a random assignment in case of a tie and no sale if both bids are 0. Producers are then informed about total forward production (q_t^f), the winning bid (b_t), and their profits from sales on the forward market¹⁰:

$$\pi_{ii}^f = b_t q_{ii}^f - c(q_{ii}^f), \quad t = 1, \dots, 25 \quad (5)$$

where $c(q_{ii}^f)$ is determined by the cost function (3).

The round then proceeds to phase 3, the spot market. Now, producers decide whether and how much to produce for sale on the spot market, in addition to what they have already sold on the contract market. The trader who purchased the quantity offered on the forward market decides how much of it to offer for resale on the spot market. Then the market operates in the standard quantity competition way. The quantities (produced and) offered by the producers in the spot market, $q_{ii}^{s1} \in N (\leq 30 - q_{ii}^f)$ and the quantity offered by the trader, $q_t^{s2} \in N (\leq q_t^f)$, are aggregated to obtain the total quantity supplied on the spot market ($q_t^s \equiv \sum_i q_{ii}^{s1} + q_t^{s2}$). The spot market price is determined by q_t^s and the demand function in eq. (1). The producers are then informed of their profit from spot market sales, π_{ii}^{s1} , and the active trader of his overall profits, π_t^{s2} . These are given by:

$$\pi_{ii}^{s1} = p_t(q_t^s) q_{ii}^{s1} - 2 \sum_{l=q_{ii}^f+1}^{q_{ii}} l^2, \quad t = 1, \dots, 25 \quad (6)$$

$$\pi_t^{s2} = p_t(q_t^s) q_t^{s2} - b_t q_t^f, \quad t = 1, \dots, 25 \quad (7)$$

⁹ In order to simplify their calculation of profitable bids, the bids are made as a per unit offer. The winning bidder must buy all units offered in phase 1, however. Traders could see on their screens what the two bids had been in the previous round.

¹⁰ From a conceptual point of view the fact that producers are informed about aggregate forward positions is an important procedural detail. In their theoretical analysis, Hughes and Kao (1997) show that if the hedging motive is not present (as in our experiments) then the unobservability of forward positions makes the strategic effect of forward markets disappear. In natural markets individual forward positions may not be easy to observe. In fact, as noted by a reviewer for this journal, suppliers may have an incentive to obscure their forward positions. However, *aggregate* forward positions are typically known in European countries. Most empirical studies actually consider that the aggregate positions are known. In Spain there is also information about individual forward sales.

where q_{ii} now denotes the total quantity *produced* by producer i ($= q_{ii}^f + q_{ii}^{s1}$). Contrary to the case without traders (eq. 4), the quantity produced need not be equal to the quantity sold to consumers on the spot market. Technically, the winning trader may choose to withhold units bought in the forward market from the spot market, so that $\sum_i q_{ii} \equiv q_t = q_t^f + \sum_i q_{ii}^{s1} \geq q_t^{s2} + \sum_i q_{ii}^{s1} \equiv q_t^s$.¹¹

Eq. (6) shows that the costs of producing units for the spot market depend on the quantity produced for the forward market. This is important because of the quadratic form of the marginal cost function (2). Furthermore, eq. (7) shows that traders must pay for all units bought in the forward market, even if they do not sell them all (*i.e.*, even if $q_t^{s2} < q_t^f$).

As in the case without forward markets, the aggregate supply in the spot market, q_t^s , and the corresponding market price, p_t , are highlighted on the screen in the table corresponding to the demand function. Then the next (independent) round starts. The round profit for a producer is simply then sum of profits from the forward and the spot market. The round profit of the trader that won in phase 2 is simply his spot market profit, while the other trader's profit is zero in the round.

2.5 Supply function treatments

We now move to the supply function treatments. In each round of the SF3.0 and SF4.0 treatments each producer has the opportunity of offering up to 30 units of production at possibly distinct prices. Denote the vector of submitted minimum prices (*i.e.*, the individual supply function) by $S_{ii} \equiv (s_{ii1}, \dots, s_{ii30})$, using the convention that $s_{ii1} \equiv \infty$, if unit 1 is not offered at any price in round t . Individual supply functions are subject to the restriction $l > k \Rightarrow s_{iil} \geq s_{iik}$, *i.e.* higher cost units may not be offered at lower prices than lower cost units.

After each of the producers has submitted S_{ii} , the computer aggregates these individual supply functions to a market supply function, denoted by $S_t^m \equiv (s_{t1}^m, \dots, s_{t(30n)}^m)$, by ordering all offers s_{iil} , $i = 1, \dots, n$, $l = 1, \dots, 30$, in period t from smaller to larger; n denotes the number of producers in the market.¹² Then, the computer determines the quantity produced (and sold) as the highest quantity for which the price consumers are willing to pay (eq. 1) exceeds the price that the producers wish to receive. Formally, the (integer) quantity q_t sold and produced in period t is found by solving:

$$q_t = \left\{ \max q \in N \mid \max \{2000 - 27q, 0\} \geq s_{1q_t}^m \right\}, q = 1, \dots, 30n \quad (8)$$

¹¹ As will be shown below, the fact that traders could choose not to resell units has no practical importance in our experiments, since typically traders resold all units.

¹² In case of a tie the order is determined randomly.

This implies that $q_t > 75$, only if $s_{tq_t}^m = 0$, $q < q_t$, *i.e.*, such large quantities will only be produced (and sold) if a large number of zeros are included in the supply functions.

Next the transaction price is determined. It is the same for all units sold.¹³ In principle, any price $p_t \in [s_{tq_t}^m, s_{t(q_t+1)}^m)$ will yield quantity supplied q_t . The division of surplus between consumers and producers varies in this interval. We chose to have prices determined by the demand side, so that $p_t = p(q_t)$, where q_t is determined by eq. (8) and $p(\cdot)$ by eq. (1). By eq. (8), producers are willing to sell the q_t^{th} unit. They might also be willing to sell the q_{t+1} -st unit, but that would decrease the price on the demand side. This is carefully explained to the subjects in the instructions. In case all bids are accepted the price is set equal to the maximum amount the demand was willing to pay at the total quantity supplied. After q_t has been determined, the individual quantities produced (and sold), q_{ti} , are derived from S_t^m and producers' profits are determined in the same way as in the Cournot case (eq. 4).

SF3.2 is the most complex treatment. Each round involves three phases, the first two being identical to those in the C3.2 treatment: producers post quantities on the contract market with the total quantity offered being purchased by the highest-bidding trader. Producers' profits in the forward market are given in eq. (5). In phase 3 producers can offer additional units for sale on the spot market using a supply function as described above for the treatments without forward market (SF 3.0 and SF 4.0). The winning trader has the opportunity of offering the purchased quantity for sale on the spot market, also using a supply function. The aggregate market supply function is now represented by $S_t^m \equiv (s_{t1}^m, \dots, s_{t90}^m)$, which is the composition of the individual supply functions submitted by the three producers and the winning trader. The total transaction quantity and the price are then determined in the same way as for SF3.0 and SF4.0 (eq. 8 and the price-setting rule $p_t = p(q_t)$), with q_t^s replacing q_t to denote that we are dealing with the spot market. Subjects' earnings (profits) are then calculated as before.

After each round subjects are informed about the total quantities produced by each of the producers. To hold the information feedback constant across treatments subjects in supply function sessions are not informed about others' bid functions but only about the total quantities traded.

¹³ In many ways, our SF setup resembles that studied in the efficient auction literature (e.g., Dasgupta and Maskin, 2000). This literature discusses efficient auction design for fixed supply, when bidders' values are interdependent. It shows that efficient auctions may exist if the bidders' private signals satisfy certain technical conditions or if an alternative definition of efficiency is used. In our SF markets, producers may be seen as bidders. The value of a producer's supply depends on the 'price-quantity' bids of all other suppliers and, hence, bidders' values are interdependent. The efficient auction results do not apply, however, because (1) the aggregate quantity that suppliers are bidding for (in our case this is demand) is not fixed and (2) suppliers' bids are not based on 'private signals' drawn from some probability distribution but on players' endogenous decisions.

3. Theoretical predictions and hypotheses

Table 1 reports three possible predictions for key variables that will be used as benchmarks in our analysis. These are the production levels that give the producers' joint profit maximization (JPM), the Nash equilibria (NE) for the one-shot Cournot games and the Walras market equilibrium (W). The JPM and W predictions in table 1 are derived straightforwardly from the demand and supply functions in eq. (1) and (2), adjusting for the fact that only discrete production levels are possible. The derivation of the Cournot equilibria is standard, the Nash equilibrium with forward trading is based on Allaz and Vila (1993). Throughout the paper we only consider symmetric behavior and equilibria. Our results indeed show little evidence of asymmetries in producers' production levels. Details are given in Appendix 2.

Table 1: Benchmarks^a

	JPM (n=3)	JPM (n=4)	NE C3.0	NE C3.2	NE C4.0	Walras (n=3)	Walras (n=4)
q_{ii}^f	---	---	---	6	---	---	---
q_{ii}	11	9	14/15 ^b	15/16 ^c	12/13 ^d	17	14
q_t	33	36	43	45	49	51	56
p_t	1109	1028	866	785	704	623	488
<i>Prod.S.</i>	33561	34728	29537	27885	27638	21063	19208
<i>Cons.S.</i>	14256	17010	24381	26730	31752	34425	41580
<i>Total S.</i>	47817	51738	53918	54615	59390	55488	60788
<i>Eff. (%)</i>	86.2	85.1	97.2	98.4	97.7	100	100

^a q_{ii}^f = forward production by producer i ; q_{ii} = total quantity produced by producer i ; q_t = total quantity produced in the market; p_t = transaction price; *Prod.S.* = total producer surplus (trader surplus is equal to 0); *Cons.S.* = consumer surplus; *Total S.* = total surplus; *Eff.* = efficiency (as % of Walrasian Surplus).

^b Any distribution where one producer produces 15 and two produce 14 units each.

^c Once the spot market is reached, the winning trader sells all 18 units, and each of the three producers produces 9 additional units with probability .944343 and 10 units with probability .055657, so that $q_t = 45.056$. See Appendix 2 for details.

^d Any distribution where one producer produces 13 and three produce 12 units each.

A few things can be noted from table 1. First of all, the Walras equilibrium varies with n due to the increasing marginal cost schedule. Second, a forward market boosts output and surplus less than the entry of an additional producer does, though it does give higher efficiency (due to the lower surplus in the Walras equilibrium). Third, the gain in total surplus when comparing three producers with a forward market to four producers without one, benefits only the consumers, the producer surplus (now shared by four instead of three) is slightly lower in the latter case. Finally, any quantity between the Cournot equilibrium and the corresponding Walras outcome can be part of a supply function equilibrium for the corresponding market structure. Without forward markets, this is a standard result in the absence of demand uncertainty (e.g., Klemperer and Meyer, 1989). Appendix 2 shows that this

holds for all of our supply function treatments, including that with a forward market and also that no quantity outside of this interval can be part of such an equilibrium.¹⁴

Table 2 summarizes the predictions for our treatments.

Treatment	Quantity		Efficiency (%)	
	Cournot	Supply Function	Cournot	Supply Function
3.0	43	[43,51]	97.2	[97.2,100]
3.2	45	[45,51]	98.4	[98.4,100]
4.0	49	[49,56]	97.7	[97.7, 100]

Using these predictions, we have the following hypotheses:¹⁵

HYPOTHESIS q.1. In the Cournot treatments, production is highest in the case with no forward market and 4 producers and lowest with no forward market and 3 producers. Formally:

$$q(C4.0) > q(C3.2) > q(C3.0) .^{16} \tag{Hq.1}$$

HYPOTHESIS q.2. In the supply function treatments the multiplicity of equilibria does not directly yield an ordering of the production levels. We posit that the range of the quantity intervals suggests the following ordering:

$$q(SF4.0) > q(SF3.2) > q(SF3.0) . \tag{Hq.2}$$

HYPOTHESIS q.3. Using a similar reasoning as for hypothesis q.2 we hypothesize that production is higher with supply function competition than with Cournot competition within the same market structure. Formally:

$$q(SF4.0) > q(C4.0); q(SF3.2) > q(C3.2); q(SF3.0) > q(C3.0) . \tag{Hq.3}$$

To investigate the effect of forward markets on efficiency, Appendix 3 provides a detailed analysis of efficiency in our context. There, we conclude that changes in efficiency can come from five possible sources: (i) consumer surplus lost due to an inefficient level of production; (ii) an additional loss in consumer surplus due to units not resold by traders; (iii) a gain in producer surplus due to a lower quantity sold; (iv) production inefficiency because units are produced at higher costs than necessary;

¹⁴ One way for sellers to exert market power here is by submitting appropriate step functions: some units are bid in at a low price to make sure they are sold and some units are bid in at a high price to obtain high profits. In Appendix 2, we show how this can be an equilibrium.

¹⁵ For notational convenience, we drop the subscript t indicating the round.

¹⁶ The corresponding price prediction goes in the opposite direction.

(v) producer surplus lost or gained because not all units produced for the forward market are resold. We will distinguish between these five sources when analyzing the efficiency effects observed in our experiments. Specific hypotheses pertaining to efficiency can be derived from table 2:

HYPOTHESIS $\Omega.1$. In the Cournot treatments, efficiency is highest in the case with forward market and lowest with no forward market and 3 producers. Using $\Omega(x)$ to denote efficiency in market structure x :

$$\Omega (C3.2) > \Omega (C4.0) > \Omega (C3.0) \quad (H\Omega.1)$$

HYPOTHESIS $\Omega.2$. Using a similar intuitive reasoning as above, we order efficiency levels as follows:

$$\Omega (SF3.2) > \Omega (SF4.0) > \Omega (SF3.0) \quad (H\Omega.2)$$

HYPOTHESIS $\Omega.3$. We posit that efficiency is higher with supply function competition than with Cournot competition within the same market structure:

$$\Omega (SF4.0) > \Omega (C4.0); \Omega (SF3.2) > \Omega (C3.2); \Omega (SF3.0) > \Omega (C3.0) \quad (H\Omega.3)$$

Because of the quadratic marginal costs in our experiments, the possibility of inefficient production arises. If production is not spread evenly across producers, shifting a unit from a high quantity producer to a low quantity producer will decrease the costs of production. Intuitively, the likelihood of inefficiencies in production increases with the complexity of the market structure. This yields the following hypothesis.

HYPOTHESIS Φ . An increase in the number of producers or the introduction of a forward market decreases production efficiency. Using $\Phi(x)$ to denote production efficiency in market structure x :

$$\Phi(C3.2) < \Phi(C3.0); \Phi(C4.0) < \Phi(C3.0) ; \Phi(SF3.2) < \Phi(SF3.0); \Phi(SF4.0) < \Phi(SF3.0) \quad (H\Phi)$$

4. Experimental Results

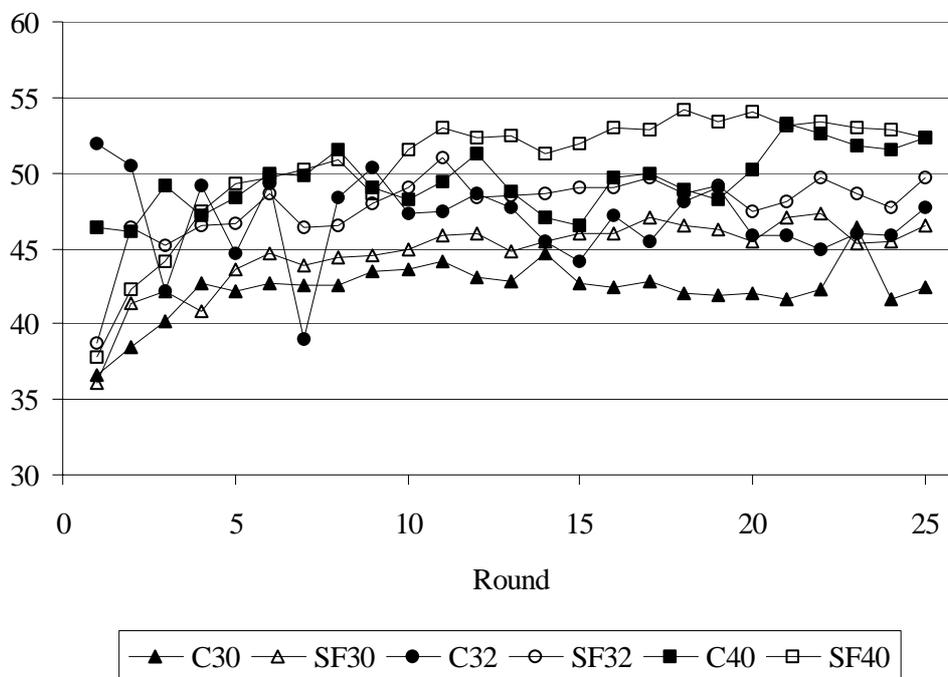
We have complete data from seven groups of C3.0, SF3.0, C4.0 and SF4.0 and six groups of C3.2 and SF3.2; these groups are statistically independent, since each individual participated in only one group. In addition, in one session of each of the C3.2, C4.0, and SF3.0 sessions and in two groups in the SF3.2 treatments a bankruptcy occurred in rounds 2, 2, 15, 1 and 5, respectively. Only in the last case was it a trader that went bankrupt, the other four participants concerned were producers. Because we

have so few data from these groups, our analysis will disregard the data from all groups where a bankruptcy occurred.¹⁷ Moreover, since decision-makers in electricity markets are experienced professionals who interact with each other frequently, we are particularly interested in subjects' behavior towards the end of the experiment. Much of the analysis will therefore be based on the last ten rounds of the experiment. In section 5.1 we first present an overview of behavior across rounds and treatments. In section 5.2 we will test the hypotheses presented above. Section 5.3 considers, for treatments C3.2 and SF3.2, behavior in the forward and the spot markets separately.

4.1 Aggregate production and efficiency per treatment

Figure 1 shows for each treatment the evolution of total quantities sold, averaged over groups. Market structure is distinguished by the markers on the lines (squares for 4.0, circles for 3.2 and triangles for 3.0). Cournot versus supply function treatments are distinguished by the filling of the markers (Cournot treatments having filled markers). Where applicable, the quantities shown in figure 1 are aggregated over forward and spot markets. Note that behavior has more or less stabilized by round 15. Some learning is apparently needed before choices converge. In this respect, it appears from figure 1 that the last 10 rounds are indeed a suitable period to base our tests on.¹⁸

Figure 1: Average Number of Units produced per round



¹⁷ In the C4.0 case, the bankruptcy transformed the group into a C3.0 case after round 2. None of our conclusions change, if we add this group to the C3.0 data.

¹⁸ In Rassenti *et al.* (2000) behavior under quantity competition appears to be much more volatile, even in the last 25 of their 75 rounds. Their experiments involve differences in firms' (constant) marginal costs and this may explain the volatility.

With respect to changes in means, there appears to be some initial upward adaptation for C3.0, SF3.0, SF3.2 and SF4.0 but not so for the other two treatments (C3.2 and C4.0). In late rounds, the highest mean quantities are observed for the two 4.0 treatments, followed by the two 3.2 treatments, with the two 3.0 treatments having the lowest means. In all cases, the SF treatment shows higher average means in late rounds than the corresponding C treatment. These observations are confirmed by table 3 (second row), which reports the average and standard deviations of the total quantities sold per treatment in the last 10 rounds (averages per group are presented in Appendix 4).

Table 3: Average Total Production in the last 10 rounds

	C3.0	SF3.0	C3.2	SF3.2	C4.0	SF4.0
Average production	42.54 (5.57)	46.29 (3.80)	46.60 (2.91)	48.78 (2.41)	50.87 (5.86)	53.21 (1.74)
Average efficiency	94.2 (6.68)	96.8 (2.57)	96.7 (2.48)	98.5 (1.67)	95.4 (3.67)	97.1 (1.20)

Note: Standard deviations are in parenthesis. The average standard deviation is computed on the basis of the values of the average levels for the different groups.

Comparing the average production levels in the Cournot treatments to the corresponding Nash equilibria in table 1 (43 for C3.0, 45 for C3.2, 49 for C4.0) we find that, in aggregate, our results for the C treatments correspond quite closely to the Nash predictions. We cannot reject at conventional levels the null hypothesis that the difference between *observed* and *predicted* production levels is equally likely to be positive and negative (all p-values > 0.22, binomial tests). Moreover, considering the observed average production level as percentage of the Nash level, we find 99%, 104% and 104% for C3.0, C3.2, C4.0, respectively. This compares nicely to the 103% and 105% that Huck et al. (2001) report for similar settings (with no forward markets involved).

For all three SF treatments observed average production is higher than the corresponding Cournot-Nash equilibrium quantity. For SF3.0 and SF4.0 we reject (at the 10%-level) the null of no difference between results and predictions in favor of the alternative that observed quantities are more likely to be higher ($p = 0.063$ for SF3.0, $p = 0.008$ for SF4.0, $p = 0.109$ for SF3.2, binomial tests). Recall that each Cournot equilibrium quantity constitutes the lower bound of the set of equilibrium quantities for the corresponding SF case.¹⁹ On average, behavior in the SF treatments appears to yield quantities in the interior of this set. We will provide a formal test of the difference between both institutions, below. For SF3.2, the difference with the corresponding Cournot equilibrium is not significant, though once again the quantity observed in C3.2 is closer to the prediction. Given that the focus of our paper is on the effect of introducing a forward market, we will not investigate further this

¹⁹ Here we just report different kinds of aggregated information. Appendix 5 contains a summary of individual supply function bidding.

difference between the Cournot and Supply Function institutions. Note that for both cases the forward market has the effect of increasing quantities and lowering prices.

Figure 2 reports the average efficiency across rounds. Treatments are distinguished in the same way as in Figure 1. Efficiency stays above 90% in all treatments and shows remarkably little volatility in the last 15 rounds. The highest efficiency is observed for the supply function treatment with forward market (SF3.2). Moreover, efficiency in the supply function treatments and in the Cournot treatment with forward market (C3.2) appear to exceed that in the other two Cournot markets.

Figure 2: Average Efficiency per round

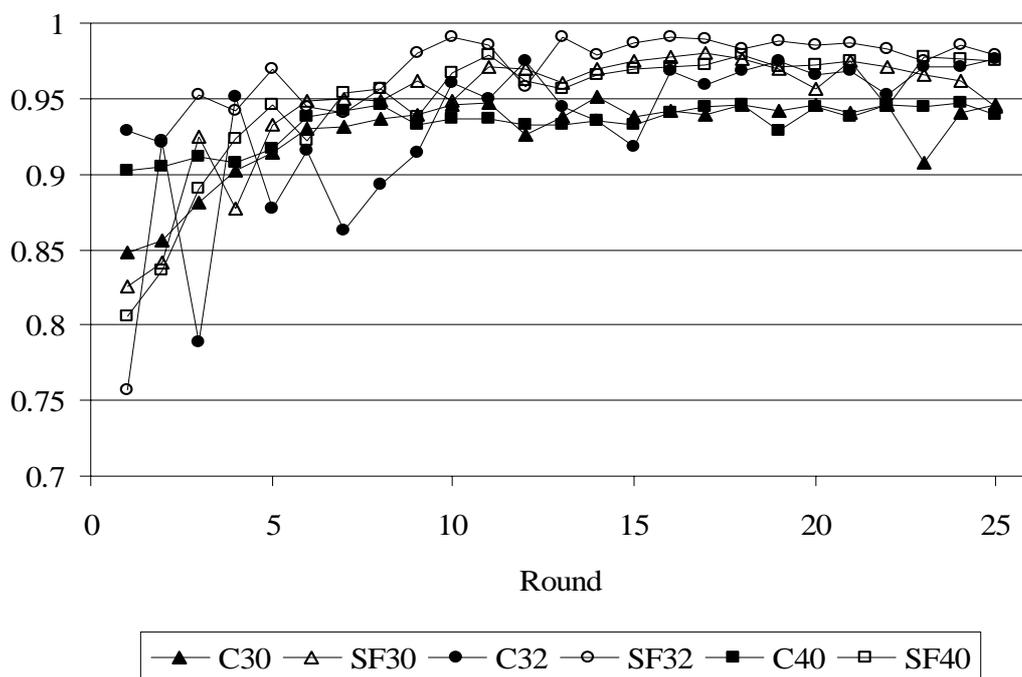
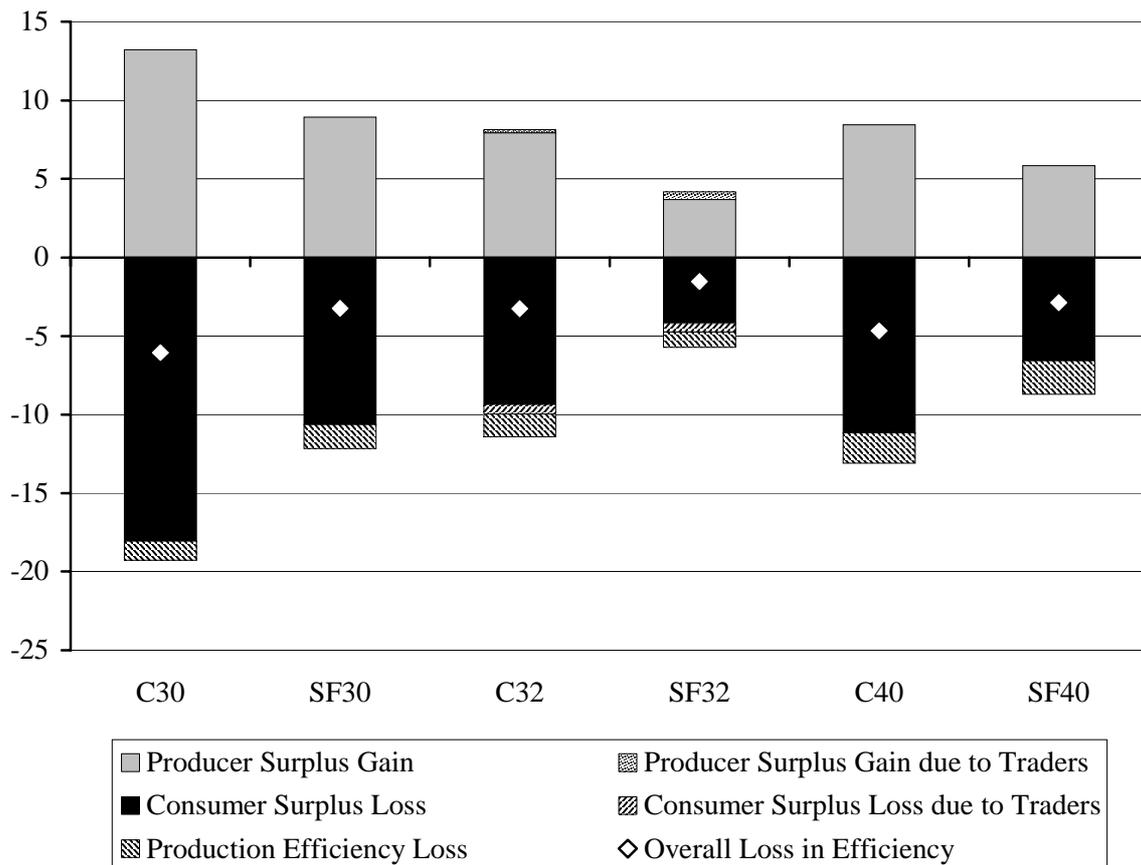


Table 3 (bottom row) presents the average efficiency level per group and treatment in the last 10 rounds. Comparing the average efficiency levels to the Cournot-predictions in table 1, we only find a significant difference (at the 10%-level) for SF4.0 ($p = 0.062$, binomial test). All other differences are insignificant ($p > 0.22$, binomial tests). Observed efficiency is in accordance with the theoretical comparative statics prediction that efficiency is higher in the 3.2 than in the 4.0 treatments. Formal tests of these predictions are presented below. Moreover, all of the SF treatments show a higher average efficiency than all of the C treatments.

Observe the interesting fact that production is higher with more producers than with a forward market, while the reverse holds for efficiency. The increased low cost production capacity that the 4.0 treatments give yields a higher potential surplus than in the 3.0 and 3.2 cases. This leads subjects to higher quantity levels. Relatively speaking, production is not high enough in 4.0, however, as indicated by the lower efficiency than in 3.2.

Finally, figure 3 gives a breakdown of the *inefficiency* in the last 10 rounds of each treatment, for the sessions without and with forward markets, respectively.²⁰ The bars consist of all deviations from efficient surplus. Bars above the horizontal axis denote an increase in surplus (mainly, producer surplus is higher than in the Walras equilibrium because of lower production) and bars below the axis represent surplus lost. The diamonds in the figure give the aggregate effect.

Figure 3: Average Inefficiency Breakdown (in %)



Comparing the realized surplus to the surplus in the Walras equilibrium, there is a loss in consumer surplus as a consequence of reduced production and an additional loss if traders withhold units. Producer surplus is higher than that at the Walras benchmark because of lower production and units withheld by traders but lower as a consequence of production inefficiency.

Note that the production inefficiency is small, compared to the loss in consumer surplus and gain in producer surplus. Apparently, even with the complication of quadratic marginal costs, our producers manage to produce fairly efficiently. Moreover, despite the complexity of the supply function decision problem, production inefficiencies do not appear to be larger in the supply function treatments for the 3.2 markets. In addition, the surplus effect of traders not reselling all units is

²⁰ For a formal discussion of the different sources of inefficiency, see Appendix 3.

negligible. All in all, when focusing on efficiency effects, the main issue seems to be the direct effect on consumer and producer surplus.

An interesting aspect is the extent of redistribution from consumers to producers. This is represented by the size of the bars (from top to bottom) in figure 3. Note that there is always less of this redistribution in the supply function treatments than in the corresponding Cournot case. Moreover, for both C and SF, the lowest spread is observed for the 3.2 treatments. This indicates that both forward markets and supply functions are good ways to mitigate the transfer of surplus to producers.

4.2 Testing the hypotheses

In this subsection, we present and discuss the test results for the hypotheses presented in section 3. Tests are based on the last 10 rounds of each treatment.²¹ A critical issue here is how to control for repeated observations of the same subjects and the same market. We report regression results using the clustering approach to correct for repeated observations due to Liang and Zeger (1986). Unless indicated otherwise, one-tailed F-tests based on an OLS regression for clustered data were used to test the hypotheses. This corrects for possible heteroskedasticity and time correlation within groups (due to multiple observations per group) but assumes independent observations across groups.²² In addition, joint hypotheses of two (in)equalities are tested using the Jonckheere test, which makes no distributional assumptions. Qualitative conclusions about the rejection of hypotheses are drawn based on a 10%-significance level (with p-values given for the reader to draw conclusions for other significance levels).

Hq.1: $q(C4.0) > q(C3.2) > q(C3.0)$ is supported.

- $q(C4.0) = q(C3.2)$ is rejected in favor of $q(C4.0) > q(C3.2)$; p-value = 0.039.
- $q(C3.2) = q(C3.0)$ is rejected in favor of $q(C3.2) > q(C3.0)$; p-value = 0.041.
- $q(C4.0) = q(C3.0)$ is rejected in favor of $q(C4.0) > q(C3.0)$; p-value = 0.003.
- $q(C4.0) = q(C3.2) = q(C3.0)$ is rejected in favor of $q(C4.0) \geq q(C3.2) \geq q(C3.0)$ with at least one of the inequalities being strict; p-value = 0.003. (Jonckheere test)

Together, these results statistically reinforce the conclusion that, on average, behavior conforms closely to the Cournot-Nash predictions. Hence, if the quantity produced is the major variable one is interested in, then the expected effect of increased competition is larger than the effect of a forward market when suppliers bid in quantities. This result is closely related to the convexity of the cost

²¹ The general picture does not change if we include data from all rounds in our tests.

²² In these regressions, the dependent variable is the variable to be tested (produced quantity, efficiency or production efficiency). The independent variables are 6 treatment-dummies and there is no constant term. Clusters are defined by the (40) groups (markets), with 10 observations (rounds) per cluster. Tests are on the equality of coefficients for distinct treatments. For a recent application of this procedure to experimental data see Cooper and Kagel (2005).

function often observed in these markets (e.g. Green, 1999). The increase in the number of producers gives a higher production capacity to the industry at lower average costs.

Hq.2: $q(\text{SF4.0}) > q(\text{SF3.2}) > q(\text{SF3.0})$ is supported.

- $q(\text{SF4.0}) = q(\text{SF3.2})$ is rejected in favor of $q(\text{SF4.0}) > q(\text{SF3.2})$; p-value < 0.001 .
- $q(\text{SF3.2}) = q(\text{SF3.0})$ is rejected in favor of $q(\text{SF3.2}) > q(\text{SF3.0})$; p-value = 0.067.
- $q(\text{SF4.0}) = q(\text{SF3.0})$ is rejected in favor of $q(\text{SF4.0}) > q(\text{SF3.0})$; p-value < 0.001 .
- $q(\text{SF4.0}) = q(\text{SF3.2}) = q(\text{SF3.0})$ is rejected in favor of $q(\text{SF4.0}) \geq q(\text{SF3.2}) \geq q(\text{SF3.0})$ with at least one of the inequalities being strict; p-value < 0.001 . (Jonckheere test)

As with Cournot competition (Hq.1), these results show that the comparative statics observed with supply function bidding correspond to those predicted by the Nash equilibria (which predict any level between the Cournot and Walras quantities). We again observe that increased competition has a larger effect on the quantity produced than a forward market.

Hq.3: $q(\text{SF4.0}) = q(\text{C4.0})$; $q(\text{SF3.2}) = q(\text{C3.2})$; $q(\text{SF3.0}) = q(\text{C3.0})$ is partially rejected.

- $q(\text{SF4.0}) = q(\text{C4.0})$ is *not* rejected in favor of $q(\text{SF4.0}) > q(\text{C4.0})$; p-value = 0.145.
- $q(\text{SF3.2}) = q(\text{C3.2})$ is rejected in favor of $q(\text{SF3.2}) > q(\text{C3.2})$; p-value = 0.068.
- $q(\text{SF3.0}) = q(\text{C3.0})$ is rejected in favor of $q(\text{SF3.0}) > q(\text{C3.0})$; p-value = 0.064.

Though the equilibrium quantity prediction for Cournot is one of the multiple equilibria for supply function competition, these results show that the observed production levels in SF with three producers (both with and without a forward market) are (statistically significantly) higher than those in Cournot competition. Note that these differences are not significant at the 5% level, however.²³

Next, we turn to our hypothesis about efficiency.

HΩ.1: $\Omega(\text{C3.2}) > \Omega(\text{C4.0}) > \Omega(\text{C3.0})$ is marginally supported.

- $\Omega(\text{C3.2}) = \Omega(\text{C4.0})$ is *not* rejected in favor of $\Omega(\text{C3.2}) > \Omega(\text{C4.0})$; p-value = 0.206.
- $\Omega(\text{C4.0}) = \Omega(\text{C3.0})$ is *not* rejected in favor of $\Omega(\text{C4.0}) > \Omega(\text{C3.0})$; p-value = 0.329.
- $\Omega(\text{C3.2}) = \Omega(\text{C3.0})$ is *not* rejected in favor of $\Omega(\text{C3.2}) > \Omega(\text{C3.0})$; p-value = 0.163.
- $\Omega(\text{C4.0}) = \Omega(\text{C3.2}) = \Omega(\text{C3.0})$ is marginally rejected in favor of $\Omega(\text{C4.0}) \geq \Omega(\text{C3.2}) \geq \Omega(\text{C3.0})$ with at least one of the inequalities being strict; p-value = 0.100 (Jonckheere test).

²³ Though this is an interesting result, it is not the main focus of this paper. Our design aims at studying the effect of forward markets and only distinguishes between quantity and supply function competition to control for the effect of the institutional environment. Hence, we will not elaborate on the observed differences between Cournot and supply function competition.

Note from table 3 (bottom row) that the observed efficiencies go in the right direction: the highest efficiency is found for C3.2 and the lowest for C3.0. The differences are barely statistically significant, however.

H Ω .2: Ω (SF3.2) > Ω (SF4.0) > Ω (SF3.0) is partially supported.

- Ω (SF3.2) = Ω (SF4.0) is rejected in favor of Ω (SF3.2) > Ω (SF4.0); p-value = 0.044
- Ω (SF4.0) = Ω (SF3.0) is *not* rejected in favor of Ω (SF4.0) > Ω (SF3.0); p-value = 0.361
- Ω (SF3.2) = Ω (SF3.0) is rejected in favor of Ω (SF3.2) > Ω (SF3.0); p-value = 0.068.
- Ω (SF3.2) = Ω (SF4.0) = Ω (SF3.0) is rejected in favor of Ω (SF3.2) \geq Ω (SF4.0) \geq Ω (SF3.0) with at least one of the inequalities being strict; p-value = 0.052. (Jonckheere test)

It appears that the comparative statics for efficiency that were predicted for Cournot competition are observed more clearly with supply function competition. Though the efficiency increase in percentage points that is generated by the forward market (1.7 for SF and 2.5 for C, *cf.* Table 3) is larger with Cournot competition, the effect is statistically stronger when bidding is in supply functions.

H Ω .3: Ω (SF3.2) > Ω (C3.2); Ω (SF4.0) > Ω (C4.0); Ω (SF3.0) > Ω (C3.0); is partially supported.

- Ω (SF3.2) = Ω (C3.2) is rejected in favor of Ω (SF3.2) > Ω (C3.2); p-value = 0.069.
- Ω (SF4.0) = Ω (C4.0) is *not* rejected in favor of Ω (SF4.0) > Ω (C4.0); p-value = 0.112.
- Ω (SF3.0) = Ω (C3.0) is *not* rejected in favor of Ω (SF3.0) > Ω (C3.0); p-value = 0.161.

The only support these results offer for the efficiency of supply functions is that supply function bidding is more competitive when there is a forward market. Hence, if the goal is to achieve high efficiency, forward markets with supply function competition offer the best results.

H Φ : Φ (C3.2) < Φ (C3.0); Φ (C4.0) < Φ (C3.0); Φ (SF3.2) < Φ (SF3.0); Φ (SF4.0) < Φ (SF3.0) is partially supported.

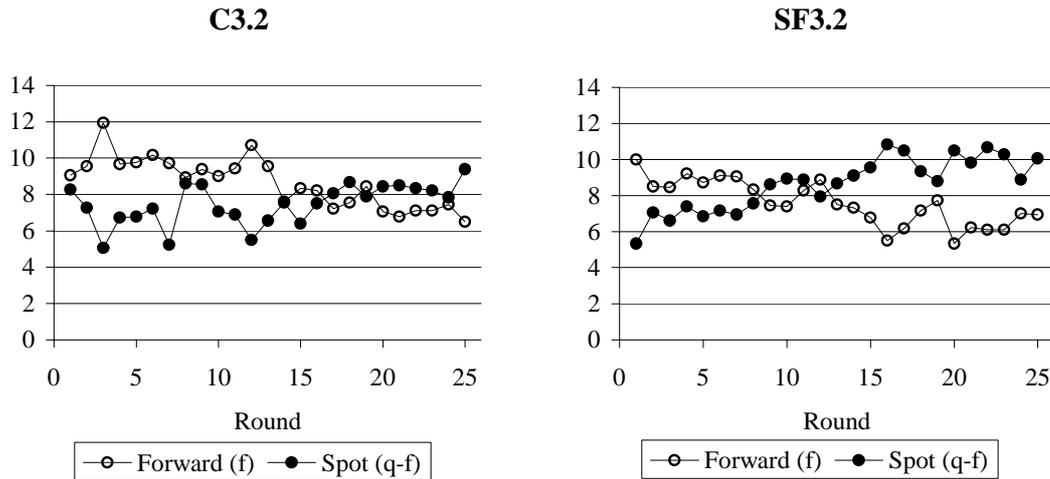
- Φ (C3.2) = Φ (C3.0) is *not* rejected in favor of Φ (C3.2) < Φ (C3.0); p-value = 0.165.
- Φ (C4.0) = Φ (C3.0) is rejected in favor of Φ (C4.0) < Φ (C3.0); p-value = 0.039.
- Φ (SF3.2) = Φ (SF3.0) is rejected in favor of Φ (SF3.2) > Φ (SF3.0); p-value = 0.070.
- Φ (SF4.0) = Φ (SF3.0) is rejected in favor of Φ (SF4.0) < Φ (SF3.0); p-value = 0.054.

Given the high level of productive efficiency (*cf.* figure 3), these results are quite remarkable. Note that the equality between SF3.2 and SF3.0 is rejected in favor of an alternative with the wrong sign, showing higher production efficiency in case of SF3.2 than for SF3.0, 98.6 vs. 96.8, where the opposite was expected. We have no explanation for this outcome. For the other cases, our intuitive conjecture that more complex market organization will lead to higher production inefficiencies finds support.

4.3 Behavior on the forward market

Next, we consider what occurs on the forward markets; recall here that in the supply function case the spot market is a more complex environment than the forward market. We start with a comparison of production for the forward and spot markets.²⁴ Figure 4 shows, for both treatments with contracts, the evolution of average individual production separately for the spot and the forward market.

Figure 4: Average Individual Production per Round on Spot and Forward Markets



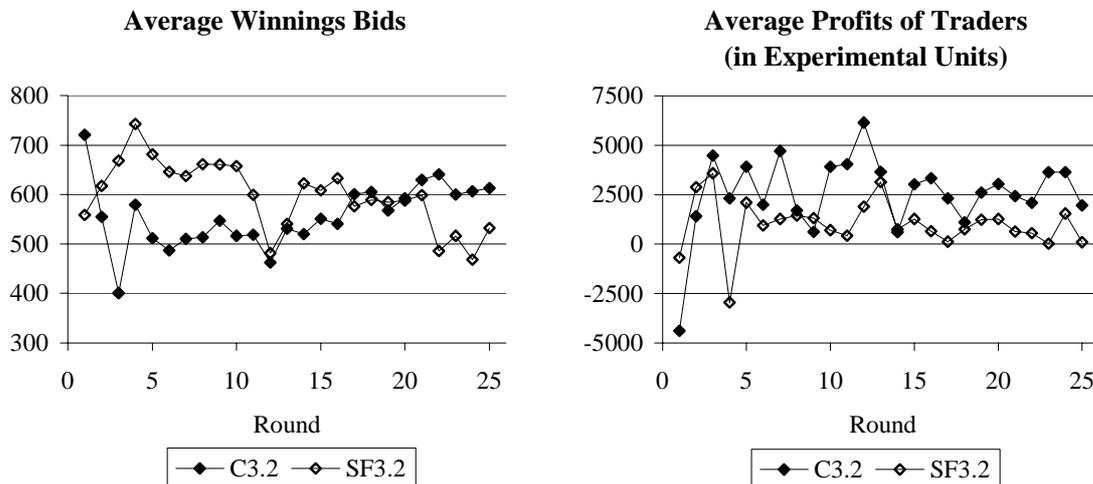
Recall from table 1 that the Cournot-Nash equilibrium prediction (C3.2) is that each firm produces 6 units for the forward market and an additional quantity of either 9 or 10 units for the spot market. First, consider the Cournot case (left panel of figure 4). Here, production comes quite close to equilibrium in the last part of the experiment, with an overproduction of about one unit for the forward market and (except for the final round) an underproduction of one unit for the spot market. Formally the hypotheses that $q^f = 6$ and $q^{s1} = 9-10$ are tested by checking if the differences between *observed* and *predicted* quantity for the forward or spot market are equally likely to be positive or negative. We find that for each market of each treatment, we cannot reject this hypothesis so that we cannot reject the null hypothesis that producers supplied the Nash equilibrium prediction on the forward and the spot markets (p-values > .344, binomial test). The supply function data shown in the right panel of figure 4 exhibit a similar pattern, with spot market output levels overtaking those of the forward market in the last ten rounds.

Notice that for both types of competition, total output remains rather constant over time. However, in both cases producers appear to be increasingly moving away from the contract market

²⁴ The forward market functions as a simple Bertrand-type auction for both the C and SF treatments. Although this introduces an asymmetry in the complexity of the forward and the spot market in the SF treatments, we do think that that our design choice is sensible in this case because adding complexity on the forward market increases symmetry within treatment but decreases symmetry across treatments. This might cause differences in forward market performance across treatments that are unrelated to the performance of forward markets *per se*.

towards the spot market and the question is why. To get further insight we now look at traders' behavior in figure 5. For the average winning bids, shown in the left hand panel, the equilibrium price prediction is 785 (see again table 1) and with respect to the right hand panel data traders are predicted

Figure 5: Winning Bids and Profits of Traders per round



to earn zero in equilibrium. As can be seen, average winning bids are below the prediction for all rounds. At the same time the right hand panel reveals that traders' profits are mostly above the equilibrium prediction of zero, although profits get close to zero in the supply function case. However, traders are typically managing to keep the prices in the forward market low enough to make a profit, and this is causing producers to offer less on these markets over time.

Comparing the Cournot markets to the Supply Function markets, we can see that the higher average production is offered on the spot market and not via the forward market (figure 4). As a consequence of the lower prices on the spot market, traders are decreasing their bids on the forward market for SF3.2. Their profits approach the equilibrium level of zero, as opposed to the profits of traders in the Cournot case. Average trader profits are 689 in the last 10 rounds of SF3.2 (significantly different from zero, binomial test, $p=0.016$). Profits are substantially and significantly higher (average: 2617) in C3.2 ($p\text{-value} = .008$).

Given these test results one can say that the results are closer to the theory in the supply function case with relatively low trader profits. This goes together with relatively low prices on the forward market and high production for the spot market. In spite of the relatively low prices, the strategic incentive of forward markets works: in both treatments, producers are offering quantities on these markets that are close to the C3.2 equilibrium predictions. This boosts total supply to levels higher than in the cases without forward markets.

5. Discussion and Conclusions

We find that, as the relevant theory suggests, the introduction of a forward market does have the effect of increasing total quantity produced and lowering prices paid by consumers. This result emerges from an experimental design that reflects some of the important features of actual electricity markets. Perhaps most importantly we not only study quantity competition, but also the more pertinent supply function competition. Two other central characteristics of our design are that we use increasing marginal costs to better represent production conditions in the electricity industry, and that we have a forward market with actual traders and not a purely simulated one. A final feature that we wish to highlight here is that groups remained constant during the course of our experiment. This is because the field settings that we want to represent involve repeated interactions among the same agents. All these features give the theory based on stage-game analysis a harder shot and yet many of our data are consistent with the theoretical predictions.

In fact, economic theory is consistent with the average quantity data in a number of other respects. For quantity competition we find that average behavior is remarkably close to those predictions. This is in line with evidence from other quantity competition results. However, those other studies did not consider forward markets nor increasing marginal costs, so that our evidence adds to the predictive reliability of the Cournot stage-game equilibrium in environments with repeated interaction.

For the cases with three producers with and without forward markets, prices are lower with supply function than with quantity competition. This supports the intuitive notion that supply functions should lead to prices in between those for price competition and quantity competition. It also supports the equilibrium predictions where the Cournot equilibrium quantity is the lower bound of a set of equilibrium quantities for the supply function case. However, for the cases with four producers and no forward market there is no significant difference between quantity and supply function competition. One may say that when there is a sufficient number of firms in the market the way in which they compete is, from the point of view of consumers, rather secondary.

For the comparison of our two treatments with forward markets we can see that supply function competition leads to less market power than quantity competition. One may ask how this situation arises. Note again that this may be related to the set of possible equilibria. For the case with supply function competition and forward markets (SF3.2), equilibrium may support any price (or quantity) between the Cournot and Walras levels (cf. Appendix 2). This means that even if the trader and the three producers bid in all their units at the Walrasian price in the spot market (*i.e.*, no market power is

exercised) then this is an equilibrium.²⁵ On the other hand, prices above the Walrasian price can also be sustained, so that equilibrium market power is possible. However, as we show in the proof contained in Appendix 2, prices above the Cournot price are not possible in equilibrium. That is the limit to market power under supply functions. Our experimental results show market power in between these two extremes predicted in equilibrium.

Our conclusions are of course conditional on a number of specific design choices. Modifications of the design, like for instance the introduction of different information conditions or of different forward market rules, may modify the results. However, we present the first experimentally controlled study combining supply functions and forward markets and for that we believe our design choices to be an appropriate baseline. Given this baseline, we consider the support our data give to the relevant theory quite remarkable.

At this point, it is important to stress once again that our experiments as well as the theory applied to them abstract from an important aspect of electricity markets: demand uncertainty. The possibility of hedging risks is an additional advantage of forward markets (for experimental evidence, see, e.g., Forsythe et al. 1982,1984; Friedman et al., 1983). By abstracting from this, we are able to isolate ‘strategic effects’ related to forward markets. By and large, our results support the positive strategic effects on efficiency that are predicted by theory. In order to derive policy conclusions about the design of electricity markets, one needs to add information about the effect of risk hedging and take the results of field studies into account. Though we know of no experimental studies that explicitly aim at studying the possibility of hedging risks in an electricity market environment, studies on markets where this possibility exists generally show that it increases market efficiency. Thus, the possibility to hedge risks would add to the strategic advantages of forward markets.

²⁵ To see that the Walras price and quantity may be an equilibrium consider a trader is bidding the Walras price on the forward market and all producers and the trader bidding in all units at the Walras price on the spot market. In this symmetric situation, each producer is selling the individual Walras quantity. Then, a producer will receive the Walras price for any unit sold and any additional unit will be sold at a loss, due to increasing marginal costs. Hence, the best she can do is to sell the Walras quantity, irrespective of whether the units are sold via the forward market or on the spot market. Therefore, she cannot improve upon the situation where she is selling the Walras quantity at the Walras price, given the choices of the others.

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