Evaluating capacity auction design for electricity: An experimental analysis

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Abstract

This paper considers the design of multi-unit procurement auctions relevant for electricity capacity markets drawing on the structure of the market introduced in Great Britain. Simple games are used to generate predictions about the impact of information feedback between auction rounds and the shape of the demand curve. These predictions are used as benchmarks and tested using a series of economic experiments. The results show that participants recognize their own and their opponents' market power opportunities, raising clearing prices and lowering allocative efficiency. No information feedback between rounds reduces average clearing prices and the risk of not achieving the supply target but also typically reduces allocative efficiency. A downward sloping step-demand function leads to competitive prices no matter what the level of feedback is but not necessarily to allocative efficiency. It also significantly increases the risk of not achieving the target level of supply.

Keywords: Capacity auction design, Clock auction, Experimental economics, Market design, Market power

JEL classification: C99, D44, Q40, Q41, Q48

Abbreviations: CRM, Capacity Remuneration Mechanism; EC, Experimental Currency; LAB, Last-Accepted Bid; ORSEE, Online Recruitment System for Economic Experiments; SEEL, Scottish Experimental Economics Laboratory

1 Introduction

During the last decade, many countries stopped relying solely on energy-only markets for maintaining security of electricity supply and have introduced capacity remuneration mechanisms (CRM) alongside existing wholesale markets (Bublitz et al., 2019). The introduction of CRMs addresses the concern that the wholesale energy-only markets do not generate enough revenue for investors to recover all costs and hence, do not provide them with incentives to invest in new capacity (De Vries, 2007; Joskow, 2008, 2007). This "missing money problem" is particularly challenging as renewable energy sources in the electricity market increase (Cramton et al., 2013; Newbery, 2016). In 2014 the UK Government introduced a capacity market for Great Britain (GB) using a descending clock auction, with the aim of ensuring security of electricity supply, but delivering it at minimum cost to consumers (DECC, 2014).

The design of any new market mechanism will affect the market's ability to achieve the capacity levels sufficient to underpin energy security in an economically efficient way. In the design of the new GB capacity market, the potential for participants to exercise market power has been a particular concern (DECC, 2014). In theory, market outcomes can be efficient in the presence of strategic behaviour by firms, although it leads to a transfer of welfare from consumers to firms bidding in the capacity market. This in itself is an important policy issue, as the claim that electricity firms are able to exploit consumers and earn monopoly profits, has been a long-standing political issue within the UK (DECC, 2014).

Market power opportunities for participants in capacity auction markets are also likely to provide incentives for bidding behaviour which undermines market efficiency. Formally the capacity market can be viewed as a multi-unit procurement (clock) auction, where the buyer wishes to secure its target backup capacity via a number of electricity generating units. There are several sellers of generating units and they can potentially offer multiple units in the auction. So in addition to the standard incentives for tacit collusion between participants, sellers may have unilateral market power and incentives to bid much higher prices than the cost of their unit(s). This "supply reduction" behaviour arises as their bid for one unit may set the market price and total payments received for other units (Ausubel et al., 2014; Dormady, 2014; Engelbrecht-Wiggans and Kahn, 1998; Sherstyuk, 2008).

Since 2014 there have been eight main auctions within the GB market focussing on four year ahead capacity. So far the potential market power opportunities have been mitigated due to the large pool of available capacity with extra restrictions imposed on bids from existing plant by the regulator.[1] Within these auctions, there have been payments for 370GW capacity, with an average price of £17.41/kW/year (not adjusted for inflation) against a highest price of £30.59/kW/year, with relatively small amounts of new generating capacity funded (around 4.43% on average) (see Appendix A) (National Grid ESO, 2021). However, as old plants go offline and electricity consumption increases with the electrification of transport and heating, the need for the market to support investment for new capacity will become more important.[2] Then the differences in the costs across new and existing plant covered by the capacity market payments is likely to increase the potential for "supply reduction" behaviour and tacit collusion.

Capacity market design features which seek to limit strategic behaviour by firms may also affect the ability of the market to deliver on its primary mandate, achieving energy security. Designing a capacity market using a clock auction which manages these trade-offs between market power opportunities, economic efficiency while achieving energy security goals, is made more challenging due to the lack

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[1] There is a threshold, called the price-taker threshold, above which price takers (which are mostly existing generators) cannot bid in the capacity auction. For the main four year ahead auctions it was set at £25/kW/year (BEIS, 2014a).

[2] In 2021 the UK government announced the phased-out date for the unabated coal from the UK's energy mix by 2024.

of general theoretical results to help frame choices for market design. Although single-unit ordinary[3] clock auctions have been widely studied theoretically (Cramton and Sujarittanonta, 2010; Krishna, 2009; McAfee and McMillan, 1987) and experimentally (Coppinger et al., 1980; Cramton et al., 2012; Harstad, 2000; Kagel and Levin, 1993), the difficulty in obtaining general results means that the theoretical work in a multi-unit procurement[4] setting is scarce (Krishna, 2009; Trifunović and Ristić, 2013). The difficulties in obtaining general analytical results mean that theory has been developed and tested for specific cases that do not address the specifics of the capacity market, e.g. markets with total supply equal to two, and two bidders with two-unit demand each (Alsemgeest et al., 1998; Burtraw et al., 2009; Engelmann and Grimm, 2009; Kagel and Levin, 2001; Kwasnica and Sherstyuk, 2013; Porter and Vragov, 2006). This lack of specific theory meant that the design of the GB capacity auction drew heavily on experiences from other capacity markets in the United States (US), such as the PJM and ISO-New England (DECC, 2014; Harbord and Pagnozzi, 2014, 2012, 2008; ISO New England, 2021, 2014).

The aim of this paper is to explore key elements of the design of a multi-unit procurement auction relevant for the GB capacity market auction and evaluate whether participants are likely to exploit market power opportunities, the efficiency of the market and its ability to achieve its target supply. Using game theory, the paper generates specific but novel results on the market power opportunities for multi-unit procurement discrete clock auctions relevant to the GB capacity market design, with the information structure in the market allowing these games to be analysed in a complete information setting.

Empirical testing of game theory predictions, such as "agents will use their potential market power", is important as the evidence shows such opportunities may or may not be exploited depending on the context (Aloysius et al., 2016; Cramton et al., 2012; Dugar and Mitra, 2016; Engelmann and Grimm, 2009; Kagel and Levin, 1993; Porter and Vragov, 2006). In this paper, the theoretical predictions are used as a benchmark and are tested using a set of economic experiments as a "policy wind tunnel" to explore how changes in market design and different market power settings might affect market outcomes (Croson and Gächter, 2010; Kagel and Levin, 2016). To our knowledge, this paper provides the first evaluation of key elements of the GB capacity auction design using auction theory derived for the specific market setting. Therefore, it provides a rigorous approach to evaluating elements of the market design which has previously been lacking.

The paper focuses on two design issues which have been a particular focus in capacity markets: the feedback given to participants when the auction is ongoing and the shape of the demand function for capacity. In addition, it also explores whether suppliers with multiple units who have potential unilateral market power exercise this power in experimental situations. To avoid potential biases, the setting is decontextualized, with no reference to the capacity market or to electricity made during the experiment (Dormady, 2014). Hence the results may also have relevance to other real world multi-unit procurement auctions. Our main results highlight that participants recognize their own market power, but they can also recognize the benefits to submit bids which give their opponents market power opportunities to unilaterally end the auction. There are also some trade-offs regarding the level of feedback provided. No feedback reduces average clearing prices and the risk of not achieving the supply target but can also reduce allocative efficiency in certain circumstances. In addition, a downward-sloping demand curve can be designed to eliminate market power opportunities as well as to reduce the ability of participants to tacitly collude.

[3] According to the literature (Sosnick, 1963; Trifunović and Ristić, 2013), ordinary auctions refer to auctions in which a seller puts up an item for sale and the bidders are the potential buyers.

[4] In procurement auctions bidders are the potential sellers. According to Trifunović and Ristić (2013), the theoretical results for the procurement auctions are seen as "mirror image" of those for an ordinary auction.

The remainder of the paper is organized as follows: Section 2 explains the structure of the GB capacity market, defines how market power can arise in this type of auctions, and introduces the elements of capacity auction design to be considered. Section 3 describes the experimental design, the theoretical predictions and the hypotheses used to derive conclusions. Section 4 introduces the data, section 5 presents the results and section 6 concludes.

2 Background

2.1 GB capacity auction

The capacity market is designed to ensure that sufficient reliable capacity is in place to meet demand. The capacity market offers capacity providers a predictable and steady income by remunerating them based on the capacity and the availability of their capacity resource, per kilowatt (£/kW). Capacity providers offer capacity into the capacity auction, and if they are successful, they receive a capacity payment. The capacity payment is thought to encourage sufficient investment in new capacity and provide incentives for existing capacity to remain open. In exchange, capacity providers are committed to providing electricity when they are called upon. Otherwise, they will face penalties (DECC, 2014).

The auction format chosen for the GB's capacity market is a descending-clock, pay-as-clear auction with "intra-rounds" (Ausubel and Cramton, 2006). Bidders are paid the last-accepted bid (LAB).[5] In a pay-as-clear or uniform auction, all the winners in the auction are awarded the same price which is called the clearing price. The clearing price is determined by the LAB which is equal to the bid of the marginal bidder. The auction runs in a descending clock format in a sequence of rounds. This means that the price of the auction starts at a high level, the "price cap", and the auctioneer reduces the price in each round by a set decrement.

Each round has a price cap and a price floor. In each round participants have two choices for each generating unit they have in the auction; either to leave their generating unit in the auction or to exit it from the auction. If a participant wants to exit one of their units from the auction, they need to submit an exit bid for that unit. The exit bid could be any price between the bidding round price cap and the bidding round price floor. As soon as a unit exits, it cannot re-enter the auction. As the price descends in each round and participants submit exit bids, the total capacity remaining in the auction decreases. If participants choose to continue to the next round, it means they are willing to accept a lower price than the price floor of the current round (BEIS, 2014b). Their exit bid is therefore the minimum price at which a participant would accept a capacity agreement for a specific generating unit.

Feedback about excess capacity during the auction is updated at the end of each round and revealed at the beginning of the next round (rounded to the nearest 1 GW). The auction ends when the total capacity remaining in the auction is equal to the capacity demanded by the regulator. In this case, it is said that the market is cleared, and the clearing price is determined by the last unit which clears the market; the LAB. All participants who did not submit an exit bid, as well as all participants who submitted an exit bid below the clearing price, will be successful in the auction and they will be awarded capacity agreements.

As per the capacity market regulations, at the beginning of the auction, participants have information about the demand curve, which is published several months ahead of the auction, the number and the

[5] In auction theory LAB usually stands for lowest-accepted bid but in this paper it refers to the last-accepted bid terminology used for the GB Capacity Market (DECC, 2014).

identity of the participants, how many units each participant has, as well as the type and the capacity of each unit (BEIS, 2014b).[6]

2.2 Market Power: Pivotal Players and Tacit Collusion

There is a significant amount of experimental literature studying the exercise of unilateral market power in double auctions (Davis and Williams, 1991; Friedman and Ostroy, 1995; Holt et al., 1986); posted-offer markets (Davis and Holt, 1994; Davis and Williams, 1991); and sealed-bid auctions (Brandts et al., 2014; Le Coq et al., 2017; Rassenti et al., 2003a, 2003b). However, to date, there has been no work on multi-unit clock auctions. Unilateral market power can arise in multi-unit procurement clock auctions as follows: Say a seller has *n* units and the required supply target set by the regulator can only be met with at least *n-1* of these units. Then this participant is "pivotal" as they have the power to end the auction (and determine the market price) if they submit a high exit bid for one of their units. This then raises the price received by their remaining units in the auction (and for any other units left in the auction for other participants).

Clock auctions are more susceptible to market power opportunities compared to the alternative sealed-bid auctions (Alsemgeest et al., 1998; Burtraw et al., 2009; Engelmann and Grimm, 2009; Kagel and Levin, 2001; Porter and Vragov, 2006). Arguably one reason for this is that unlike double and sealed-bid auctions and posted-offer markets, clock auctions are multi-stage dynamic games. Hence, individual bidding strategies can be a function of past decisions of all participants, increasing the potential that tacit collusion could be sustained. For example, during the auction one of the sellers might bid to exit one of their units to make another player pivotal in the belief they use that power to end the auction at a higher price than would otherwise be the case. Cramton and Schwartz (2000) find empirical evidence consistent with this in the spectrum clock auctions in the US, where bidders appeared able to coordinate their bids by exiting some of their resources at high prices, stopping the auction.

2.3 Capacity auction design: Feedback and Shape of Demand

One fundamental design issue in this type of auction is the feedback given to participants after each round. On the one hand, the feedback after each round helps with price discovery and benefits bidders in a sense they make better estimations of the common value elements of the capacity costs.[7] On the other hand, as it may help support tacit collusion it can be used to facilitate the exercise of market power. Experimental results for clock auctions show that more feedback tends to increase the exploitation of the market power opportunities in single-unit demand (Buchanan et al., 2016; Marshall and Marx, 2009) and multi-unit settings (Kagel and Levin, 2001).

Ausubel et al. (2014), characterises the most common possible options of how much feedback to be revealed after each auction as: a) to show individual supply, i.e. cost and identity of the bidders making the bids is revealed, b) to show aggregate supply, i.e. the number of items still in the auction is revealed and c) not show any information. The feedback policy in the GB capacity auction, updating excess capacity at the end of each round, lies between the extreme of only showing aggregate supply and providing no feedback after each round since excess capacity is revealed rounded to the nearest 1 GW. This feature is intended to provide protection against the probability that a bidder is able to precisely calculate when they may become pivotal and be able to end the auction.

A second design parameter, which is considered particularly important in these types of auctions, is the shape of the demand curve. The few studies which consider the elasticity of demand as a treatment

[6] As is further discussed in 3.3., based on this we made the assumption of complete information when analysing the games used in the experiments.

[7] DECC (2014) recognises capacity costs have some common value elements and this makes the use of clock auction format suitable.

parameter in auction experiments show that it can affect efficiency and price outcomes (Miller and Plott, 1985; Porter et al., 2009). Demand curves used in practical capacity auction design take several forms. The demand curve used in the GB capacity market is a downward sloping demand curve, with a target demand established by the Government in advance of the auction, with allowed variability from the target demand defining the slope of the curve (DECC, 2015).[8] A downward-sloping demand curve is expected to reduce the incentives for capacity withholding because as the demand increases and the price falls, the risks that an individual bidder becomes pivotal during the auction is reduced (Brown, 2018). It also makes the capacity price less sensitive to the volume of capacity offered into the auction (DECC, 2015, 2013). Evidence from the capacity market in ISO-New England and simulation evidence suggests that when the demand curve is vertical, a small movement away from the target can cause an extreme decrease or increase in the capacity price (Battle Group, 2014; ISO New England, 2021, 2014). However, this means that the target demand may not be met and hence, reduce the ability of the market to provide the desired level of energy security (DECC, 2013). UK policy makers are aware of the potential trade-off between efficiency and reliability, with the demand curve used in the auction to be flexibly determined to enable the trade-off between cost and reliability to be automatically determined at the auction (DECC, 2013).

3 Experimental design and theoretical predictions

The above discussion of key issues and elements in the GB capacity auction frames the design of the game and associated treatments considered. Specifically, the experiment was designed to capture the impact of market power opportunities when individual players were (or were not) pivotal at the start of the auction, the effect of the feedback between auction rounds and how the shape of the demand affects outcomes. Theoretical predictions were found for each treatment. This section will first present the game run in the experiment, the different treatments implemented and the experimental procedure. Then, the theoretical predictions for each treatment will be discussed.

3.1 Trading environment

The design of the auction was simplified in several ways relative to the actual GB capacity market auction. A group of three players and five items available for sale represent a market. According to experimental evidences, three market participants are enough to induce competitive outcomes (Abbink and Brandts, 2005; Fonseca and Normann, 2008; Huck et al., 2004).

In every market, two different types of items are to be sold. These are

- three low-cost items, which cost 12 experimental currency (EC) each, to represent technologies that need low-capacity payments, and

- two high-cost items, which cost 32 EC each, to represent technologies that need high-capacity payments.

The cost of each item represents the proportion of the cost of a technology that participants would like to cover with the capacity payment. Items are assumed to be indivisible as in the GB capacity market.

The auction is a descending clock auction: it starts at a high price and the price will decrease through different rounds. While the price decreases, players have to decide if they leave their item(s) in the auction or if they take them out. It was highlighted to participants that their decision for each of their items is independent. Once the number of items left in the auction is less than the desired one, the auction stops.

[8] Currently variability within the GB auction is set at 1.5 GW above and below the target capacity.

Each auction started at the price cap of 60 EC. Each round, the price decreases by the bid decrement of five EC. The auction price drops by 5 EC until enough items exit the market. According to Ausubel and Crampton (2006), the usual range for bid decrements is 5 to 20 % of the whole price range. The parameters for the experimental auction were chosen so the bid decrements are in the price range mentioned above and are close to the actual percentage of the price range in the GB capacity market.[9]

To simplify the experiments for participants, the possibility for intra-rounds bids, which exists in the capacity market, was excluded from the design. Players had to decide for each of their items: either keep or to exit them from the auction at the round price of the auction. How the exclusion of intra-rounds affects our theoretical predictions is discussed in section 3.4.

The pricing rule used is the last-accepted bid (LAB) as in the GB capacity market. Under LAB, winning bidders, who still have items in the auction, receive the amount of the marginal bid. This equals the price at which the marginal bidder exited the auction. For example, suppose 3 items are to be bought in the auction. At 50EC there are still 4 items in the auction, one exits at 45EC. There are 3 items left, the next one to exit will set the price. Let us assume the seller exits this item at 35EC. The auction stops there and the price of the auction will be 35EC paid for that item and for the 2 other items still in the auction. In the event of a tie at the margin, a proportion of the items which have been accepted last in the auction is sold. In our example: if both items 3 and 4 left the auction at 50EC, then they set the price of the auction at 50EC but only 50% of each of them will be bought.[10]

3.2 Treatments

In total six treatments were run to capture the effect of three different features.

- the feedback given to players after each round. With feedback, participants know how many items are left in the market at the end of each round, but they do not know the cost of those items, so this is called “partial feedback”. Without feedback, participants receive no feedback at the end of each round. They only know if the auction keeps going or stops.
- the shape of demand. In some treatments, the demand is inelastic, which means that a set number of items is going to be bought (3 in our experiment). Other treatments have a downward-sloping step demand: the number of items bought will depend on the price.
- the presence of unilateral market power or potential tacit collusion. In some treatments, one player in each group has unilateral market power at the start of the auction. This player is called the pivotal player. In the other treatments, there is no pivotal player at the start of the treatment. In those treatments tacit collusion between the participants is possible.

Even though we test three features in this experiment, we will have only six treatments as when there is a step demand function, players cannot become pivotal. Please see Table 1 below for the details of the treatments characterized by whether a pivotal player is present at the start of the auction, the different levels of feedback, and the shape of demand.

[9] In the actual GB capacity market, the price cap is equal to £75 and the price decrement per round is £5 and thus, the bid decrement is 6.67 per cent of the price range.

[10] This rule is inconsistent with the fact that the items are indivisible, but is a reasonable compromise to avoid potential risk aversion effects. The alternative solution would have been to use a random draw of one of the items (which gives the same prediction in theory as we assume risk neutrality) but it could have affected the behaviour of the players if they were risk averse.

Table 1: Summary of parameters specific for each treatment

	Treatment					
Parameters	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Demand	*Inelastic*	*Inelastic*	*Inelastic*	*Inelastic*	*Step*	*Step*
Pivotal player	Yes	Yes	No	No	No	No
Feedback after each round	*Partial*	*No*	*Partial*	*No*	*Partial*	*No*

As seen in Table 2, in the treatments with unilateral market power (T1 and T2), the pivotal seller, player A, had one high-cost item and two low-cost items, the second seller, player B, had one low-cost item and the third seller, player C, had one high-cost item. In the remaining treatments without a pivotal player, all three sellers had one low-cost item and two sellers, A and B, had one high-cost item.

Table 2: Distribution of items in the market by Treatment

	Treatment					
Sellers	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
A	2 low-cost and 1 high-cost item	2 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item
B	1 low-cost item	1 low-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item	1 low-cost and 1 high-cost item
C	1 high-cost item	1 high-cost item	1 low-cost item	1 low-cost item	1 low-cost item	1 low-cost item

The game-theoretic predictions associated with each of the treatments are discussed in the section 3.4 (with formal derivations provided in Appendix D).

3.3 Experiment procedures

Subjects were fully informed about the market demand and their rivals, as well as the associated cost of their rivals. Experimental evidence shows that the information setting at the beginning of the auction can affect the exercise of market power (Buchanan et al., 2016; Marshall and Marx, 2009). With regards to the cost of each capacity resource, DECC (2014) recognize capacity costs have some common value elements. However, there is often good information regarding the operational and fixed costs for different technologies. This means each auction participant is likely to have a relatively clear idea of the costs that other participants in the auction will be bidding to cover, given they know the different types of capacity they hold (Parsons Brinckerhoff, 2013). Overall, the complete information assumption used here appears reasonable for market demand, the number of participants in the market and the number of items each participant owns keeping in mind that at the beginning of the auction, participants have information about the demand curve, the number of participants, how many units each participant has, as well as the type and the capacity of each unit as per the auction rules (BEIS, 2014a).[11]

In each session, each subject participated in 20 auctions. At the beginning of each session, all subjects were assigned randomly to groups of three by the computer and each participant stayed in the same group throughout the session. Partners design, instead of strangers design, was implemented to capture the annual repetition of the auctions, as well as to allow the participants to gain experience (Altavilla et al., 2006; Orzen, 2008). Each group represented an independent market and subjects kept the same role for the 20 auctions.

At the end of the 20th auction, their real payoff was calculated based on the average experimental profit from 3 auctions picked randomly by the computer. This payment rule was chosen to motivate

[11] See Appendix B for a summary of the parameters held constant in all treatments.

the participants to play well in the experiment from the first until the last auction. This avoids the potential "house money effect", where participants may bid more aggressively initially (Moffatt, 2015).

3.4 Theoretical predictions

In all treatments, sellers are assumed to be trying to maximise their profit. For each treatment, the non-cooperative equilibrium is derived for the auctions with discrete bid space.[12] The full analysis of the games and associated different lemmas used to derive the equilibria can be found in Appendix D. The theoretical predictions determine if there are market power opportunities in each treatment, where "equilibrium market power" is defined to exist if the non-cooperative equilibrium yields prices that exceed the competitive level (Holt, 1989). The actual exercise of market power opportunities and collusion is determined based on the experimental results. We follow the approach used by Davis and Holt (1994) to distinguish between evidence of exercise of market power and tacit collusion in their experiments. When the observed clearing price is above the competitive level but equal to or below the non-cooperative equilibrium then the participants are interpreted as exercising market power opportunities. Tacit collusion is interpreted as occurring when players' strategies lead to observed prices above those predicted by the game equilibrium, i.e. when players behave in more sophisticated ways to coordinate their bidding. As already mentioned, intra-rounds were excluded from the experiment. To reduce the influence of this on the results, the experimental design parameters were chosen so that the market power opportunities and efficiency predicted by theory were identical to whether intra-rounds were included or excluded (see Appendix C).

Pivotal players

In treatments with a pivotal player, at the start of the auction (T1 and T2), seller A owns a high-cost item and two low-cost items, seller B owns a low-cost item and seller C owns a high-cost item, while demand is equal to 3. In these treatments, seller A has unilateral market power since, without their capacity, the supply cannot serve the total demand. In both treatments with a pivotal player, it is beneficial for player A to price out two of their items and benefit from a higher payoff, by selling one item at a high price instead of two items at a lower price.[13] This is true, only when the price is at least 50. If the price falls below 50, then the pivotal seller is better off to sell their two low-cost items instead of stopping the auction and selling only one item.[14]

The equilibrium in the treatments with pivotal players is equal to 55, independent of the feedback policy. Seller A is expected to exit their high-cost item and one of their low-cost items at the price cap and exit their second low-cost item at 55. Another strategy that will result in the same outcome is for seller A to exit their high-cost item at 60 and exit both of their low-cost items at 55. Using these strategies, one low-cost item of seller A, as well as the only item of seller B and seller C is sold in the market. The allocation in these treatments is inefficient since the items sold in the market include the

[12] It is well-known that the theoretical predictions of the auctions with continuous bid space are consistent with those when the bid space becomes discrete (Ausubel and Cramton, 2006; Cramton and Sujarittanonta, 2010; David et al., 2007; Rothkopf and Harstad, 1994; Yu, 1999). As bidding in real world markets can only be multiples of a given currency unit this suggests that the predictions from discrete space may give more realistic predictions.

[13] Let us assume that bidders bid competitively and exit their items just above the cost of each item, as in the case with no pivotal players i.e. seller A and seller C exit their high-cost item at 35 and then seller A and B have a weakly dominant strategy to exit one low-cost item each at 30 (see Appendix D.2, Lemma 6). Thus, the clearing price is equal to 30, and the sellers' payoffs are: $\pi_A = 2 * (30 - 12) = 36$, $\pi_B = 30 - 12 = 18$ and $\pi_C = 0$. It can be seen that this is not an equilibrium, since bidder A is better off by exiting their high-cost item at 60 and then their two low-cost items at 55. In this case, the clearing price is equal to 55 and sellers' payoffs are: $\pi_A = \frac{55-12}{2} + \frac{55-12}{2} = 43$, $\pi_B = 55 - 12 = 43$ and $\pi_C = 55 - 32 = 23$.

[14] Seller's A payoff if they sell only one low-cost item at any price below 50 is less than selling two low-cost items at 30: e.g. at 45 then: $\pi_B = 45 - 12 = 32 < \pi_B = 2 * (30 - 12) = 36$.

high-cost item of seller C. With feedback, this behaviour arises from the fact that sellers owning one item have a weakly dominant strategy not to exit their item at any clock price $\mathrm{P_s}$, where $\mathrm{P_s} \geq \cdots \geq \mathrm{P_{t-1}} > \mathrm{P_t} > \mathrm{c}$ while the number of items in the market is higher than the demand (see Appendix D.2, Lemma 2). Without feedback, this behaviour arises from the fact that sellers with one item have a weakly dominant strategy to stay in the auction until the price reaches just above their cost i.e. they will exit their item at $\mathrm{P_s}$, where $\mathrm{P_s} > \mathrm{c} > \mathrm{P}_{s+1}$.[15] So, in both treatments bidders with one item have no incentive to exit their item at a price higher than 35, except in the case there is feedback and two items have already exited from the auction (see Appendix D.2, Lemma 1). It is implied that seller A's payoff is maximized if they end the auction at price 55.

Although seller A is indifferent between the two strategies mentioned above, exiting only their high-cost item at 60 is a trembling hand perfect equilibrium.[16] If any of the sellers play any strategy off the equilibrium, e.g. seller B or/and seller C exit their items at 60 or 55, seller A benefits by a higher payoff, compared to the case seller A exits two items at the price cap. The optimal strategy is the same independent of the state of the world and the beliefs of the bidders of what happened in previous rounds. The probability of reaching the nodes later in the game is zero. The competitive level is determined by the vertical overlap of the demand and supply functions. Due to the discreteness of the bid space, the competitive level might involve any price from {15,20,25,30}. Since the non-cooperative equilibrium is higher than the competitive level, then as defined the game is described as having market power opportunities.

Inelastic demand and no pivotal player

In the treatment with inelastic demand, no pivotal player and partial feedback (T3), there are multiple Perfect Bayesian equilibria. All sellers have a low-cost item and sellers A and B own also a high-cost item, and demand is equal to 3. If both bidders A and B coordinate their bids and exit their high-cost items at the same clock price and exit their low-cost item during the immediate next round they cannot be better off by unilaterally deviating from this strategy. The optimum strategy for sellers A and B is to coordinate and exit their high-cost item at 60. Then all bidders will observe that two items are out of the auction at the end of round 1. Since 2 items are out of the auction, it is a weakly dominant strategy for all sellers to exit their low-cost items at 55 (see Appendix D.2, Lemma 1). In this case, the two high-cost items are not sold in the market, therefore, the auction outcome is efficient. This equilibrium maximizes the payoffs of the sellers, and it is the focal point because it is the equilibrium which is most compelling for the bidders. If there is one focal point equilibrium in a game, we expect to observe this equilibrium. The optimal strategy is the same, independent of the state of the world and the beliefs of the bidders in previous rounds. The competitive level is the same as in the treatments with pivotal players and it involves any price from {15,20,25,30}. Since the non-cooperative equilibrium is above the competitive level, this again means there are market power opportunities.

In the case of inelastic demand, no pivotal player and no feedback (T4), there are no market power opportunities as the non-cooperative game equilibrium equals the competitive level. Seller A and seller B are indifferent between exiting their high-cost item at any clock price in the set $\{60, 55, \ldots, 35\}$. It is a weakly dominant strategy for all sellers to exit their low-cost item at 30 (see Appendix D.2, Lemma 6).

Although there are no market power opportunities in this game, there are reasons to think that the players may be able to successfully tacitly collude, i.e. to support prices outcomes above the game equilibrium. Seller A and seller B are indifferent between exiting their high-cost item at any clock price in the set $\{60, 55, \ldots, 35\}$, but exiting their high-cost items at $\mathrm{P_1} = 60$ is a trembling hand perfect

[15] The proof for this is similar to the proof of Lemma 5 in Appendix D.2.

[16] A trembling hand perfect equilibrium is an equilibrium that takes the possibility of off-the-equilibrium play into account by assuming that the players, through a "slip of the hand" or tremble, may choose unintended strategies, although with negligible probability.

equilibrium since if any of the sellers play any strategy off the equilibrium, seller A and seller B would benefit with a higher payoff. For example, if seller A and seller B exit their high-cost item at 60 and seller C exits their low-cost item at 50, then the auction ends at 50 and all sellers sell their low-cost item at this price. Thus, player A may gain by submitting an exit bid unilaterally for their high-cost item as this makes B pivotal in the game (if they can assume that their opponent will behave rationally).

Step demand

In the treatments with step demand (T5 and T6) the number of items the auctioneer would like to buy increases as the price decreases. At prices {60,55,50} the auctioneer would like to buy 1 item. At prices {45,40,35} the auctioneer would like to buy 2 items. At prices {30,25,20} the auctioneer would like to buy 3 items. At prices {15,10,5} the auctioneer would like to buy 4 items and at price {0} the auctioneer would like to buy 5 items.

These treatments do not have pivotal players at the start of the auction and have been designed to eliminate the market power associated with the T3 treatment. Plausibly we also argue they reduce the incentives for tacit collusion. With feedback (T5), the clearing price of the auction is predicted to be at the competitive level of 30 with three low-cost items bought by the auctioneer. The previous market power opportunities no longer arise because if both sellers A and B exit their high-cost item at 60, demand remains at 1 item. Therefore, it is no longer a weakly dominant strategy for all participants to exit their low-cost items at the next round; so the auction is predicted to continue. In fact, seller A and seller B are indifferent between exiting their high-cost item at any clock price in the set $\{60, 55, \ldots, 35\}$ (see Appendix D.2, Lemma 6). It is a weakly dominant strategy for all sellers to exit their low-cost item at 30 or after they notice that the number of items still in the auction is equal to the demand of the current round (see Appendix D.2, Lemma 1).

In the treatment with no feedback (T6) if all bidders follow their weakly dominant strategies the non-cooperative equilibrium is the competitive equilibrium.[17] Although higher equilibria compared to the competitive price can be sustained if some bidders play irrationally, without feedback no market power opportunities exist. The optimal strategy for sellers A and B is to exit their high-cost items at any price equal to or above 35 and exit their low-cost items at 30 (see Appendix D.2, Lemma 6). Intuitively, the form of the downward sloping demand curve, may also reduce the opportunities for tacit collusion as A and B no longer gain by unilaterally exiting a high-cost item from the auction as their opponents do not become pivotal as a result.

3.5 Hypothesis

The game-theoretical analysis of the different treatments provides several sets of predictions which can be used to help judge the experimental results. Table 3 provides a summary of the predictions from the theoretical analysis.

Table 3: Summary of theoretical predictions

	Treatment					
	T1	**T2**	**T3**	**T4**	**T5**	**T6**
Non-cooperative equilibrium	*55*	*55*	*55*	*30*	*30*	*30*
Max competitive price	*30*	*30*	*30*	*30*	*30*	*30*
Market power opportunities	*Yes*	*Yes*	*Yes*	*No*	*No*	*No*
Efficient dispatch	*No*	*No*	*Yes*	*Yes*	*Yes*	*Yes*

[17] A full game solution in this case was not possible to derive.

These are used to specify a number of hypotheses, given below, which are useful in evaluating the experimental outcomes relative to the theory. These are grouped into four categories: hypotheses which test a) the observed clearing prices against the theoretical predictions; b) the comparison of relative prices across treatments; c) observed allocative efficiency relative to predicted efficiency; d) the number of items sold in the market against the predicted. The first set of hypotheses captures how well the theoretical predictions capture observed behaviour, the second set of hypotheses on relative prices tests for the impact of the shape of demand and feedback, allowing for the possible impact of non-equilibrium behaviour by some participants. The third and fourth set of hypotheses provides a basis to explore the potential trade-offs between the exercise of market power, efficiency and ability of the market to achieve the desired level of energy security.

a) *Clearing prices – Theoretical predictions*

Hypothesis 1: Pivotal players will exercise unilateral market power, (raising the clearing prices to 55).

Hypothesis 2: Participants should be able to exercise market power when there is partial feedback and inelastic demand (raising the clearing prices to 55).

Hypothesis 3: Where demand is inelastic without a pivotal player, no feedback should restrict the exercise of market power and the outcome should be competitive prices (30).

Hypothesis 4: The downward sloped demand function eliminates all the market power opportunities, and outcomes for prices in all treatments with a step-demand function should be competitive (30).

b) *Clearing prices – Comparison across treatments*

Hypothesis 5: No feedback reduces exploitation of market power and tacit collusion.

i. Without a pivotal player, no feedback should lower clearing prices when demand is inelastic.
ii. Without a pivotal player, no feedback prices should be independent of the shape of the demand.

Hypothesis 6: A downward-sloping demand curve with no pivotal player reduces the impact of feedback on clearing prices.

i. With step demand, clearing prices will be independent of feedback.
ii. With partial feedback, step-demand will lower clearing prices.

c) *Allocative efficiency*[18]

Hypothesis 7: Without pivotal players, the market will be efficient. Pivotal players will lower the efficiency of the auction.

d) *Security of supply: Number of items bought* [19]

Hypothesis 8: With step demand, the number of items sold should always equal the target set (3 items).

4 Data

The experiment was run at the Scottish Experimental Economics Laboratory (SEEL) at the University of Aberdeen. It was programmed and conducted with the software z-Tree (Fischbacher, 2007). A total

[18] The auction is efficient if the lowest cost units are sold and so total generation costs are minimized; otherwise, the auction is inefficient. Hence the level of allocative efficiency is independent of the number of items bought.
[19]This hypothesis is relevant only in treatments with step demand, since when the demand is inelastic the number of items bought is constant and only the clearing price changes.

of 165 subjects participated in the experiments. Participants were recruited using the Online Recruitment System for Economic Experiments (ORSEE) of the University of Aberdeen (Greiner, 2015). Participants were mostly undergraduates. They came from a wide range of schools such as science, computer, mathematics, economics, law, psychology, engineering. Female and male students took part in the experiments in close to equal proportions. No subject participated in more than one session and the between-subjects design was implemented to benefit from shorter sessions and reduced learning effects compared to the within-subjects design (Cramton et al., 2012; Dugar and Mitra, 2016; Goeree et al., 2013; Pagnozzi and Saral, 2017). Each session was completed on average within 2 hours including time for instructions. Table 4 presents the data for each treatment.

Table 4: Data for each treatment

	Treatment					
Parameters	**T1**	**T2**	**T3**	**T4**	**T5**	**T6**
Number of sessions	3	2	2	2	2	2
Number of participants	30	24	27	27	27	30
Number of groups	10	8	9	9	9	10

Each subject upon arrival was provided with a written set of general instructions describing the market. These instructions were the same for all six treatments and they were read aloud to participants. Thereafter, detailed instructions about the experimental setup were presented to them via a PowerPoint presentation. Subjects also had a printed copy of the presentation. A PowerPoint presentation was considered appropriate to deal with the complexity of the rules since the traditionally written instructions would have been too long. At the end of the presentation, any questions were answered, and finally, a questionnaire was given to them to check if participants had understood the rules.[20]

The experimental earnings of the participants, i.e. the average of 3 random auctions, were converted to UK pounds, at the conversion rate of 1 EC= £0.30. Subjects also received a £5 show-up fee. Participants could exit their items at a lower price than the cost of their item, meaning that participants could make a negative profit.[21] If their average profit was negative, the participants received the £5 show-up fee. Table 5 provides a summary of the average, minimum and maximum total payments received by the subjects including the show-up fee as observed in each treatment.

Table 5: Summary of cash payments in each treatment

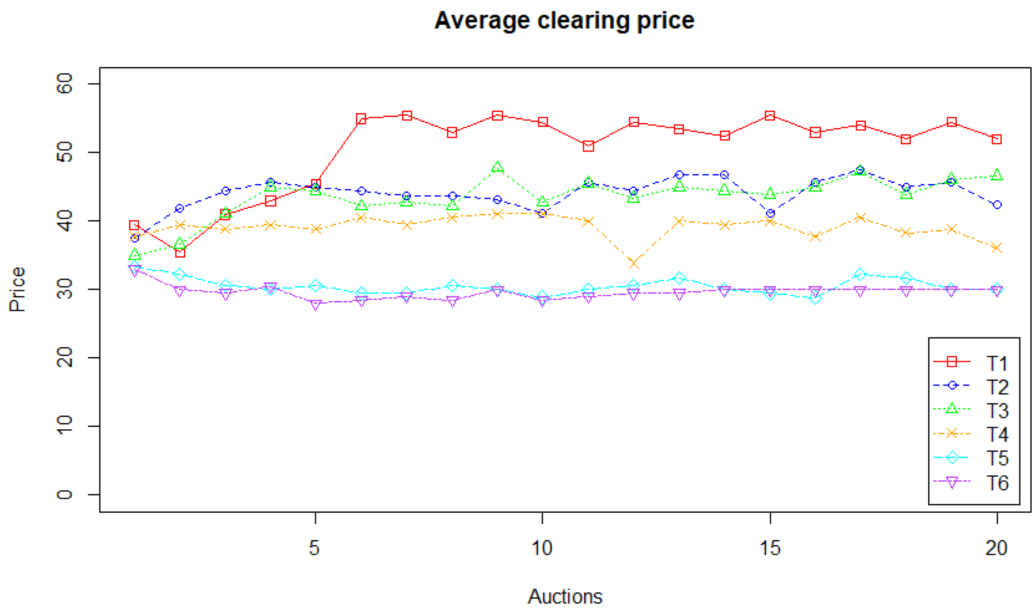
	Treatment					
	T1	**T2**	**T3**	**T4**	**T5**	**T6**
Average payoff	£14.95	£13.95	£14.5	£12	£9.82	£9.85
Minimum payoff	£8	£5	£7	£7.5	£6	£6.5
Maximum payoff	£29	£24	£19	£21	£12.5.	£12.5

[20] The experiment was described without referring to the capacity market or to market power to eliminate biases in the bidding behaviour of the participants if they had in advance any knowledge of the capacity market or the electricity market in general (Dormady, 2014).
[21] A negative average profit was observed once in treatment T2.

5 Results

The section reports the experimental results and hypothesis tests. All analyses were run using R software. As explained in above, subjects participated in 20 auctions. Figure 1 shows the evolution of average prices by treatment for each auction (averaged over all groups within a treatment). The trends of the clearing price for each treatment suggests some learning effects but most particularly in the T1 treatment, with the average clearing prices increasing strongly with the clearing price approaching the predicted value (55) after the 6th auction. In the other treatments, there are smaller adjustments in the first two or three rounds but thereafter no clear pattern is evident. In the inelastic demand treatments (T3 and T4), the initial adjustment appears to be an upward increase in prices whereas in step-demand case (T5 and T6) prices appear to fall after the first two or three rounds.

Figure 1: Evolution of average clearing prices by treatment and each auction (averaged over all groups within a treatment)



5.1 Clearing prices – Theoretical predictions

To allow for learning effects we focus the discussion on the results of the last 10 auctions. For comparison purposes, we also report summaries of the results of the first 10 auctions and overall. For example, the first panel of Table 6 presents disaggregated average clearing prices for each treatment for the last 10 auctions. The second panel in the table reports the average median, standard deviation and range values for the last 10 auctions by treatment and the results of two-tailed one-sample Wilcoxon Signed Rank tests. These non-parametric tests are used to test the null hypothesis that the average clearing prices are equal to the theoretical predictions (hypotheses 1-4). Similar summaries are provided for the first 10 and overall (see Appendix E, Table E-1 and Table E-2 report the underlying data for these cases). For ease of comparison, the predicted clearing price reported in Table 3 is also given in the last row of Table 6.

Table 6: Average Clearing Prices by Treatment

	TREATMENT					
	T1	T2	T3	T4	T5	T6
	Observed Average Clearing Prices last 10 Auctions					
GROUP 1*	37.0	30.5	43.5	46.5	30	30
GROUP 2	58.5	43.0	45.0	33.5	30	30
GROUP 3	55.0	44.5	30.0	32.5	32	30
GROUP 4	54.5	60.0	55.0	50.0	30	30
GROUP 5	52.0	42.0	25.0	30.5	30	28
GROUP 6	53.5	33.5	55.0	33.0	29	30
GROUP 7	55.5	52.0	56.0	32.0	30	30
GROUP 8	55.0	55.5	54.5	33.5	33	30
GROUP 9	55.0	-	42.0	55.0	30	30
GROUP 10***	56.5	-	-	-	-	30
	Last 10 Auctions					
MEAN	53.25	45.13	45.11	38.5	30.4	29.8
MEDIAN	55	43.75	45	33.5	30	30
STANDARD DEVIATION	6	10.3	12.2	9.3	1.2	0.6
RANGE	21.5	29.5	31	24.5	4	2
HYPOTHESIS TESTS**	$p = 0.67$ $V = 11$	$p = 0.055$ $V = 4$	$p = 0.052$ $V = 2$	$p = 0.009$ $V = 45$	$p = 0.42$ $V = 5$	$p = 1$ $V = 0$
	First 10 Auctions					
MEAN	47.8	43.1	42	39.7	30.5	29.6
MEDIAN	50	46	44	40	30	30
STANDARD DEVIATION	5.8	11.9	9.4	6.9	1.9	3.2
RANGE	15.5	32.5	27	17.5	5.5	12.5
HYPOTHESIS TESTS**	$p = 0.0059$ $V = 0$	$p = 0.035$ $V = 2.5$	$p = 0.004$ $V = 0$	$p = 0.009$ $V = 45$	$p = 0.61$ $V = 17.5$	$p = 0.94$ $V = 19$
	All 20 Auctions					
MEAN	50.5	44.1	43.6	39.1	30.5	29.7
MEDIAN	52.13	44.5	45.75	36.75	30	30
STANDARD DEVIATION	4.7	10.6	10.4	7.8	1.3	1.9
RANGE	15.5	30	28.5	20.25	3.75	7.25
HYPOTHESIS TESTS**	$p = 0.008$ $V = 1$****	$p = 0.039$ $V = 3$	$p = 0.0039$ $V = 0$	$p = 0.0039$ $V = 45$	$p = 0.45$ $V = 19$	$p = 0.94$ $V = 19$
THEORETICAL PREDICTION	55	55	55	30	30	30

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for the T1 refers to the first group which was given this treatment, group 1 results for T2 refer to the first (different) group given that treatment etc.

** Two-tailed one sample Wilcoxon Signed Rank test of the null hypothesis that the average price was equal to the theoretical prediction

***A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

****The V-statistic is the sum of ranks assigned to the positive differences between the observed value and the hypothesised value. In this context a zero value indicates that all observed bids were below or equal to the theoretical value. Positive values are consistent with a mix of positive and negative differences. Large positive values arise when the majority of bids are above the theoretical value.

The average results for the last 10 auctions are generally more consistent with the theoretical predictions (relative to the results for the first 10 auctions or overall), which suggests learning effects were important. In the T1 treatment, the average price for the last 10 auctions is close to the predicted value, and the null hypothesis is not rejected at 5% significance. Although still higher than for all other treatments, the average result for all 20 auctions is lower and the null hypothesis of equality with the predicted value can be rejected at 1%.

The results for the T2 treatment suggest some evidence that the players were not able to fully exploit the market power opportunities. While the average prices are well above the competitive level (30), the average value (45.1) is well below the T1 treatment value. The hypothesis that the average is equal to the theoretical prediction (55) can be rejected at 10% significance. Taken together, the columns 2 and 3 provide support for Hypothesis 1 that pivotal players will exploit (at least partially) the market power opportunities presented.

The column 4 results for treatment T3 are similar to the T2 results with average prices (45.1) above the competitive equilibrium but somewhat below the theoretical prediction. Formally, the hypothesis that the average price was effectively equal to the predicted value is not rejected at 10% for the last 10 auctions. Hence, there is some supporting evidence for Hypothesis 2 suggesting that participants will (partially at least) draw on feedback between rounds to exploit market power opportunities. However, it appears that as for the T2 treatment, participants are not able to exploit all the theoretical market power opportunities.

In contrast, the results for treatment T4 in column 5 are not consistent with the theoretical prediction. In this case, the game equilibrium prediction is that the average price should be equal to the competitive level. However, the observed results show that the average price is well above this and the null hypothesis that the observed price equals the predicted value is rejected at 1% significance (thus rejecting Hypothesis 3). This suggests tacit collusion, consistent with the idea that individual players can identify profitable off-equilibrium path strategies, e.g. by exiting a high-cost item to make an opponent pivotal during the auction.

The final two treatments using the step demand function (T5 and T6) provide relatively clear-cut results, with, in both cases, the average prices being very close to the competitive value predicted by theory (columns 6 and 7). In these two treatments, the hypothesis that the average prices are equal to the predicted (competitive) level cannot be rejected either for the last 10 auctions (or the first 10 and overall). This provides supporting evidence for Hypothesis 4 that the downward sloped demand function effectively eliminates the market power opportunities.

5.2 Clearing prices – Comparison across treatments

Table 7 reports the results of various Mann–Whitney–Wilcoxon hypothesis tests. These compare the clearing prices across the treatments and form the basis for exploring the strength of evidence to support Hypotheses 5 and 6.

Hypothesis 5 on the impact of feedback draws on two separate implications of the relative clearing prices predicted by the theory. First, 5i. states that no feedback should lower clearing prices when demand is inelastic (in the absence of a pivotal player). This is considered by testing the null of the equality of clearing prices across treatments T3 and T4 against the alternative that the clearing price is higher in the treatment with partial feedback (T3). The results and p-values are presented in the second column of Table 7. Here the lack of rejection of the null provides evidence against Hypothesis 5. So, although the average clearing prices observed in Table 6 are somewhat higher for treatment T3 (with partial feedback) e.g. 45.1 versus 38.5 for the last 10 auctions, these differences are not found to be statistically significant.

Hypothesis 5ii. that no feedback prices should be independent of the shape of the demand, is considered by testing the equality of the clearing prices across treatment T4 (with inelastic demand)

and T6 (with step demand). The results are reported in columns 4 in Table 7 with the null being rejected in all samples at 1% significance levels. In this case, the rejection of the null provides evidence against the hypothesis. These set of results provide evidence against Hypothesis 5 that in general, no feedback reduces clearing prices when no pivotal player is present.

The final two tests provide evidence on the impact of the shape of the demand function on the clearing prices, testing hypothesis 6i. and 6ii. Columns 6 and 7 report on the null that the clearing prices are equal across the T5 and T6 treatments. The non-rejection of this null supports the claim that a downward sloping demand curve can reduce the impact of feedback. The final test results, given in columns 8 and 9, test the null hypothesis of the equality between the clearing prices in the T3 and T5 treatments against the alternative hypothesis that the prices are higher when demand is inelastic (T3). In this case, the rejection of the null hypothesis provides support for the claim that the step demand function can reduce clearing prices when market power opportunities are present otherwise.

Table 7: Mann–Whitney–Wilcoxon hypothesis test results: Comparison of prices across treatments

Auctions	***Clearing Prices: Alternative hypothesis*** (H_1)							
	5i T3 > T4		**5ii T6≠T4**		**6i: T6 ≠ T5**		**6ii T5<T3**	
	p-value	**W-value**	**p-value**	**W-value**	**p-value**	**W-value**	**p-value**	**W-value**
1-10	*0.201*	50.5	<0.001	2	0.804	48.5	0.007	12
11-20	*0.165*	52	<0.001	0	0.331	54	0.005	11
All	0.218	50	<0.001	0	0.711	50	0.009	14

Overall, the results of Table 6 and Table 7 together, suggest that the role of feedback on clearing prices is not as clear-cut as the theoretical results predict, and does not eliminate the ability of participants to tacitly collude. In contrast, a downward sloping demand does appear to significantly reduce clearing prices and makes feedback less important.

5.3 Allocative efficiency

Table 8 presents the analogous results to Table 6 but now focussing on allocative efficiency. In the first part of the table, the frequency of allocative efficiency for the last 10 auctions is presented. The second panel in the table reports the average frequencies, median values, standard deviation and range for the last 10 auctions by treatment and the results of two-tailed one-sample Wilcoxon Signed Rank tests. These non-parametric tests are used to test the null hypotheses that the observed levels of efficiency are equal to the theoretical predictions of allocative efficiency (given in the last row of the table). As for Table 6, the last two panels of the table provide similar summary values for the first 10 auctions and all 20 auctions for each group (see Appendix E, Table E-3 and Table E-4 for individual results for the first 10 auctions and the 20 auctions).

Table 8: Frequency of allocative efficiency levels by Treatment

	TREATMENT					
	T1	T2	T3	T4	T5	T6
	Observed frequency allocative efficiency last 10 Auctions (%)					
GROUP 1*	50	90	40	0	90	100
GROUP 2	0	10	70	0	100	90
GROUP 3	0	30	90	10	100	100
GROUP 4	0	0	100	70	100	100
GROUP 5	30	20	100	30	100	10
GROUP 6	10	60	100	40	90	90
GROUP 7	10	10	80	60	100	80
GROUP 8	0	0	100	40	100	100
GROUP 9	0	-	10	90	80	100
GROUP 10***	0	-	-	-	-	100
	Last 10 Auctions					
MEAN	10%	27.5%	76.7%	37.8%	95.6%	87%
MEDIAN	0%	15%	90%	40%	100%	100%
STANDARD DEVIATION	17%	32%	32%	31.5%	7.3%	27.9%
RANGE	50%	90%	90%	90%	20%	90%
HYPOTHSIS TESTS**	$p = 0.098$ $V = 10$	$p = 0.036$ $V = 21$	$p = 0.059$ $V = 0$	$p = 0.009$ $V = 0$	$p = 0.174$ $V = 0$	$p = 0.098$ $V = 0$
	First 10 Auctions					
MEAN	27%	27.5%	62.2%	33.3%	83.3%	82%
MEDIAN	20%	15%	70%	30%	90%	80%
STANDARD DEVIATION	26.3%	33.3%	25.4%	32%	18.0%	11.4%
RANGE	90%	90%	70%	100%	50%	40%
HYPOTHSIS TESTS**	$p = 0.009$ $V = 45$	$p = 0.059$ $V = 15$	$p = 0.014$ $V = 0$	$p = 0.014$ $V = 0$	$p = 0.035$ $V = 0$	$p = 0.008$ $V = 0$
	All 20 Auctions					
MEAN	18.5%	27.5%	69.4%	35.6%	89.4	84.5%
MEDIAN	10%	15%	80%	35%	95%	90%
STANDARD DEVIATION	18.4%	32%	25.1%	31.3%	10.1%	18.2%
RANGE	60%	90%	80%	95%	25%	60%
HYPOTHESIS TESTS**	$p = 0.009$ $V = 45$****	$p = 0.036$ $V = 21$	$p = 0.015$ $V = 0$	$p = 0.009$ $V = 0$	$p = 0.021$ $V = 0$	$p = 0.006$ $V = 0$
THEORETICAL PREDICTION	Inefficient (0%)	Inefficient (0%)	Efficient (100%)	Efficient (100%)	Efficient (100%)	Efficient (100%)

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for T1 refers to the first group which was given this treatment, group 1 results for T2 refer to the first (different) group given that treatment etc.

** Two-tailed one sample Wilcoxon Signed Rank test of the null hypothesis that the frequency of allocative efficiency was equal the theoretical prediction

***A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

****The V-statistic is the sum of ranks assigned to the positive differences between the observed value and the hypothesised value. In this context a zero value indicates that all observed bids were below or equal to the theoretical value. Positive values are consistent with a mix of positive and negative differences. Large positive values arise when the majority of bids are above the theoretical value.

Hypothesis 7, that inefficiency should only arise when there are pivotal players (T1 and T2), derives directly from the theoretical predictions. The predicted inefficiency arises as a pivotal player has an incentive to price out their low-cost item and sell their other low-cost item at a higher price. Table 8 reports that behaviour appears consistent with this as the majority of the groups in treatments with pivotal players yielded inefficient outcomes. However, the level of inefficiency is not as low as the theory predicts. Formally, using the data for the last 10 auctions the null hypothesis of no difference between the actual and theoretical efficiency is rejected in treatment T1 at 10% significance ($\mathrm{p} = 0.098$) and also rejected in T2 at 5% ($\mathrm{p} = 0.036$). Using data from all observations, the null hypothesis is rejected in both treatments. This suggests that while the treatments with a pivotal player do lead to inefficiency, the level of efficiency is higher than predicted by the game-theoretic equilibrium.

More surprising results arise in the treatments with no pivotal player and inelastic demand where the theory predicts the outcomes should always be efficient (T3 and T4). However, in these treatments there is evidence of inefficiency. The formal hypothesis tests of equality between the predicted efficiency levels and the outcomes support this. The null of no difference between the actual and theoretical efficiency is rejected in treatment T3 at 10% significance ($\mathrm{p} = 0.059$), and more conclusively in T4 at 1% ($\mathrm{p} < 0.01$).

In the treatments with step demand (T5 and T6), the average efficiency level achieved is much closer to the theoretical full efficiency prediction. However, in the tests of the null hypothesis of no difference between the actual and theoretical efficiency, we do not reject the null in the T5 treatment only ($\mathrm{p} = 0.17$, last 10 auctions). In all other cases there is some evidence that, while higher, full efficiency is not achieved. Furthermore, somewhat surprisingly the evidence suggests that efficiency outcomes are lower in the treatment with no feedback (T6).

Overall, therefore the evidence from Table 8 only partially supports hypothesis 6. The presence of pivotal players clearly reduces efficiency, but there is also evidence that significant inefficiency can also arise in other treatments, and that in the treatments with no feedback the level of observed inefficiency appears to be higher.

5.4 Achieving target supply: Number of items bought

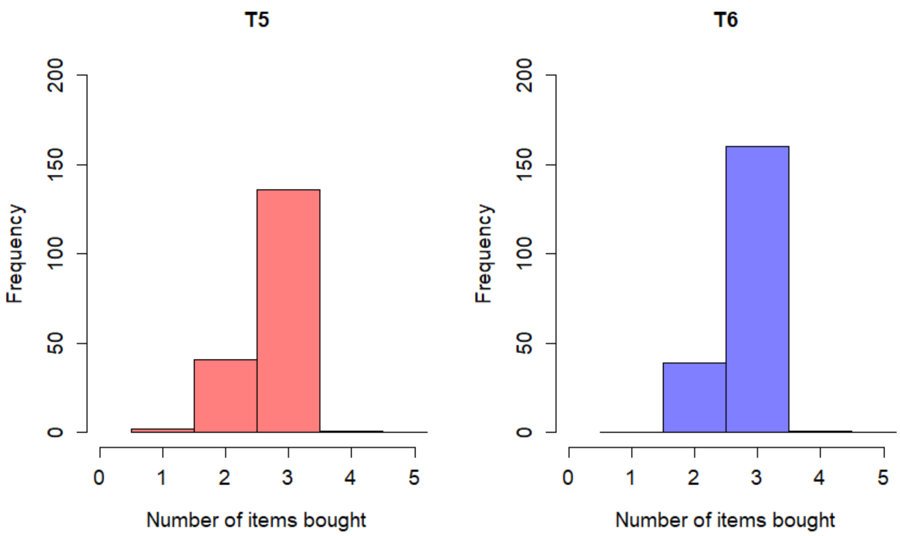
The experiments are designed so that the theoretical prediction is that the target (3 units) should be achieved in all cases. To illustrate the impact of a downward sloping demand curve on the ability of the market to achieve the target capacity and the possible trade-offs with the use of market power and efficiency, Table 9 reports the percentage of times the auctioneer bought fewer items than the demand target (equal to 3 items) across the step demand treatments (T5 and T6). Figure 2 illustrates the frequency distribution for items purchased across these two treatments for all 20 auctions.

Table 9: Percentage (%) of times the auctioneer bought fewer items than the target in treatments with Step Demand

	GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6	GROUP 7	GROUP 8	GROUP 9	GROUP 10	AVERAGE
						T5					
1-10 PERIODS	30	40	70	30	30	30	20	20	10	-	31.1
11-20 PERIODS	10	30	60	0	0	10	0	30	10	-	16.7
1-20 PERIODS	20	35	65	15	15	20	10	25	10	-	23.9
						T6					
1-10 PERIODS	50	70	70	20	20	20	0	0	40	40	33
11-20 PERIODS	0	10	30	0	0	10	0	0	0	10	6
1-20 PERIODS	25	40	50	10	10	15	0	0	20	25	19.5

From Table 9 and Figure 2, we can see that in both treatments the market often fails to achieve the target demand of 3 units. Specifically, in the T5 treatment in the last 10 auctions, the market failed to achieve the target demand 16.7 % of the time (15 observations), and 23.9 % of the time overall (43 observations). In the T6 treatment, the degree to which the target was not achieved was somewhat less in the last 10 auctions (6 %) and was observed 19.5 % of the time overall.

*Figure 2: Frequency distribution of items bought**



*Partial Feedback and Step Demand treatment had in total 180 observations while No Feedback and Step Demand treatment 200 observations.

The observation that the introduction of the step demand does increase the risk that the target is not achieved, is supported more formally. Using a one-sample Wilcoxon Signed Rank test, the null hypothesis that the auctioneer bought exactly three items with probability one is rejected at 5% in all cases in the T5 treatment (e.g. for the last 10 auctions $p = 0.03$).[22] Similarly, in the T6 treatment, the null hypothesis is rejected at 10% significance level in the last 10 auctions ($p = 0.089$).

5.5 Bidding behaviour

From the above discussion, there are several questions which arise concerning the bidding behaviour of the participants. In the treatments with a pivotal player did the players follow the equilibrium strategies predicted or some other approach to achieve the high clearing prices observed? In the other treatments with inelastic demand, is there further evidence from individual strategies of behavior consistent with tacit collusion and what accounted for the higher than expected inefficiency levels observed? For the step-demand treatments what might explain the lower than expected levels of supply relative to the target?

For the treatments with pivotal players, there is evidence that the pivotal participants were able to recognize their position. In treatment T1, seller A, who was pivotal exercised unilateral market power and ended the auction at price 55 or 60 in 114 observations out of 200 (57 %). In treatment T2, this behavior was observed 78 times out of 200 (39 %). However, the null hypothesis that participants followed their equilibrium strategy with a probability of one is rejected for the last 10 auctions (T1: p-value = 0.02; T2 p-value = 0.02). This does suggest that a significant proportion of participants followed a range of non-equilibrium strategies.

In treatment T3 market power opportunities can arise due to feedback, as any bidder can stop the auction as soon as they notice that two items have already dropped out of the auction. In the T3

[22] Against the alternative that the probability is less than one.

treatment, this behaviour is observed in 142 out of 180 observations (78.9 %) with a third item dropping out of the auction immediately after two items are exited. Table 10 illustrates the frequency each group managed to "coordinate" their bids in this way. There also appears to be some learning effects, with a higher average observed during the last 10 auctions. However, as for the previous case, the formal test shows that the ability of the participants to follow this strategy was incomplete. The null hypothesis that the probability equals one, that participants exit their item after two items are out of the auction, is rejected at 5 % significance ($p = 0.03$) (see Appendix D.2, Lemma 1). This perhaps helps explain why, as observed in Table 10, the market power opportunities were not fully exploited.

Table 10: Bidder Behaviour Treatments T3: % time a third item drops out of auction immediately after 2 items exited

	GROUP 1	GROUP 2	GROUP 3	GROUP 4	GROUP 5	GROUP 6	GROUP 7	GROUP 8	GROUP 9
1-10 PERIODS	90	20	70	100	70	70	80	90	40
11-20 PERIODS	80	70	90	100	100	100	80	90	80
1-20 PERIODS	85	45	80	100	85	85	80	90	60

In the T4 treatment, the null hypothesis that with probability one auctions end at the competitive price is rejected ($p < 0.01$) (last 10 auctions). In only 25 observations (13.9 %) do bidders behave as equilibrium theory predicts, while in 132 observations (73 %), the auction ended at a higher price than the predicted price of 30. This supports the suggestion that participants in this treatment managed to tacitly collude. Here there is evidence that either seller A or seller B exited their high-cost item at a high price (above 35) to give their opponent a pivotal position on the assumption that this would lead to a higher price for all (see trembling equilibrium in section 3.1). Specifically, in 114 observations (63%) either seller A or seller B exited their high-cost item making their opponent pivotal and in 64 observations (35.6%) both sellers unilaterally exited their high-cost items at a high price.

Some of the inefficiency in the outcomes observed in Table 8 for these treatments appears to arise from apparent "irrational" behaviour of sellers A and B. In these cases they exited both their high-cost item and low-cost item at the same price rather than exiting first their high-cost item and in subsequent round their low-cost item (see Appendix D.2, Lemma 4). This type of behaviour was observed in 63 observations (35% of the time) and led to higher clearing prices and higher levels of inefficiency.

Finally, turning to the treatments with step demand, in treatment T5 either Seller A or Seller B exited their high-cost item at a high price in 159 observations (88% of the time), while in 110 observations (61%) both sellers exited their high-cost items above 35. In T6 in 125 observations (62.5%) Seller A or Seller B exited their high-cost items above 35. This suggests that, although unsuccessful, sellers were trying to engage in tacit collusion. This also helps explain the lower than predicted observed efficiency and levels of supply in these experiments.

6 Conclusions

This paper explores the design of multi-unit procurement auctions relevant for electricity capacity markets drawing on the structure of the market introduced in Great Britain. It has explored how key elements of the design potentially impact on market outcomes, in terms of whether participants can exploit their market power, the efficiency of the market and its ability to achieve its target supply. The GB capacity market can be interpreted as a multi-unit procurement clock auction, where there are no general theoretical predictions. Here, we use simple games to make predictions about key elements of capacity market design, namely the impact of feedback between rounds of the auction and the downward sloping demand curve. We use the predictions as a set of benchmarks and test these with a series of economic experiments. This approach provides a rigorous framework to evaluate the specifics of the auction design.

The experimental results show that players with unilateral market power (so called pivotal players) will recognize and act on their position raising clearing prices and lowering allocative efficiency in the auction. Reducing feedback does not have a statistically significant effect but does seem to reduce auction clearing prices. When there are no pivotal players at the outset of the auction, the participants are still able to exploit the remaining market power opportunities. Even when the game equilibrium suggests that they should not be able to maintain prices above the competitive level, they appear able to tacitly collude. The non-equilibrium strategies employed include recognizing when by making their opponents pivotal they can also benefit. The level of feedback does impact average auction clearing prices, with no feedback prices lower than when partial feedback is provided. However, no feedback also appears to substantially lower the level of allocative efficiency achieved.

In the experiments using a downward sloping step-demand function designed to eliminate any predicted market power opportunities, there is evidence that this leads to competitive prices no matter what level of feedback is given. However, there are some indications that this does not lead to complete allocative efficiency and there is a significant risk of not achieving the desired target level of supply. This risk does appear reduced when no feedback is provided to participants.

Overall, there are a number of implications for the design for these types of auctions. First, that participants will recognize their own market power, but they can recognize that it can be in their interests to make other participants pivotal during the auction, (even when this is not predicted by theory). There also appear some trade-offs to consider in terms of feedback provided. No feedback reduces average clearing prices and the risk of not achieving the supply target but can reduce allocative efficiency in certain circumstances. A downward-sloping demand curve can be designed to eliminate market power opportunities and when this is the case it also seems to reduce the ability of participants to tacitly collude.

What lessons might this analysis suggest for the design of the GB capacity market in the future? Currently, the GB market has successfully drawn on a surplus of low-cost existing capacity leading to low capacity auction prices over the initial years of the market. However, when the market starts to need to provide incentives for significant new investment in backup generation, the ability of the regulator to achieve desired levels of energy security may be more challenging. New generation is likely to need to cover higher costs and therefore, the differences between low-cost and high-cost units are likely to be larger creating more acute trade-offs between reliability, market power and allocative efficiency.

Currently, limited feedback on excess capacity to the nearest 1 GW is given after each round to reduce the market power opportunities. However, the experimental results show that even when theory suggests limiting feedback should eliminate market power opportunities, participants may still be able to tacitly collude, withholding their own capacity to make their rivals pivotal, leading to higher auctions price for all. Furthermore, as we have seen, limiting feedback in such cases can also significantly reduce the levels of allocative efficiency.

The experimental results suggest that, when it is designed to address potential market power, a downward sloping demand curve can be very effective in combating these types of effects. However, this also increases the risk of not achieving the desired target level of back-up capacity.

This implies that rather than announcing the shape of the demand curve for capacity in advance (BEIS, 2014a), there may be a benefit for the regulator to announce the overall target capacity and then announce the exact shape the demand curve once the prospective bidders are known and analysis of the potential for trade-offs between reliability, market power and allocative efficiency can be assessed.

Declarations of interest: none

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7 Appendix

Appendix A Main Capacity Auction results

Table A-1: Results for four years ahead (T-4) auction

Auction	Delivery	Clearing price	Adjusted Capacity Cleared Price for inflation	Capacity awarded	New build generation
2014 T-4	1 October 2018 to 30 September 2019	£19.40/ kW/year (2012 prices)	£23.03/ kW/year	49.26 GW	2.62GW (5.32%)
2015 T-4	1 October 2019 to 30 September 2020	£18 /kW/year (2014/15 prices)	£20.9/ kW/year	46.35 GW	1.93 GW (4.18%)
2016 T-4	1 October 2020 to 30 September 2021	£22.5 kW/year (2015/16 prices)	£26.05/ kW/year	52.43 GW	3.412 GW (4.47%)
2017 T-4	1 October 2021 to 30 September 2022	£8.40/ kW/year (2016/17 prices)	£9.54/ kW/year	50.42GW	0.768 GW (1.52%)
2019 T-3[23]	1 October 2022 to 30 September 2023	£6.44/kW/year (2018/19 prices)	£7.12/ kW/year	45.1GW	2.98GW (6.6%)
2019 T-4	1 October 2023 to 30 September 2024	£15.97/KW/Yr (2018/19 prices)	-	43.7GW	1.8 GW (4.11%)
2020 T-4	1 October 2024 to 30 September 2025	£18/kW/year (2019/20 prices)	-	40.8GW	1.7GW (4.17%)
2021 T-4	1 October 2025 to 30 September 2026	£30.59/kW/year (2020/21 prices)	-	42.4GW	1.9GW (4.48%)

Appendix B Trading environment

Table B-1: Summary of main parameters held constant in all treatments

Parameters	**Value/Description**
Trading environment	Procurement discrete descending clock auction
Number of sellers	3
Supply	5 items
Number of low-cost items	3
Number of high-cost items	2
Cost of high-cost item	32 EC
Cost of low-cost item	12 EC
Price cap	60 EC
Bid decrement	5 EC
Pricing rule	Last-accepted bid (LAB)
Information setting	Complete information

Appendix C Theoretical predictions of the game with intra-round bidding

We present here the theoretical predictions of the auction of the experiments **with intra-rounds** bidding. All the other parameters of the experiments are the same as presented in section 3.1 and 3.2

As mentioned previously, the auction is a descending clock auction: it starts at a high price and the price will decrease through different rounds. While the price decreases, players have to decide if they leave their item(s) in the auction or if they take them out. Each auction starts at the price cap of 60 EC. Each round, the price decreases by the bid decrement of five EC.

In the experiment, players had to decide for each of their items: either keep or to exit them from the auction at the round price of the auction. In an auction with intra-rounds, players have to submit a bid to exit the auction. That bid has to be

[23] 2018 T-4 Auction the capacity market suspended. Replacement by T-3 Auction held January 2020

comprise between the floor and the ceiling of the current round. It represents the minimum price the seller is happy to receive for that item.

Suppose the auction reached the round 45-40. Sellers will have to decide if they keep their items in, so they are happy with a price lower than 40EC or if they exit their item at the current round. If they decide to exit an item, they will have to submit a bid between 40 and 45EC.

All the other rules of the auction are the same as the one used in the experiments: items are independent and indivisible, items cannot re-enter the market, pricing rule via LAB.

Table C-1 provides the summary of the theoretical predictions for each treatment when there is intra-round bidding. The predictions of the game without intra-round bidding are also presented in the table for comparison.

Table C-1: Summary of theoretical predictions of the game with intra-rounds and without intra-rounds

Treatment	Prediction with intra-rounds			Predictions without intra-rounds		
	Clearing Price	**Market power**	**Efficiency**	**Clearing Price**	**Market Power**	**Efficiency**
T1	$60-\varepsilon$*	Yes	No	55	Yes	No
T2	$60-\varepsilon$	Yes	No	55	Yes	No
T3	55	Yes	Yes	55	Yes	Yes
T4	$32-\varepsilon$	No	Yes	30	No	Yes
T5	30	No	Yes	30	No	Yes
T6	30	No	Yes	30	No	Yes

**where 0<ε<<1; It captures the fact that with intra-rounds bidding bidders can change their bids marginally*

The predictions are identical for T3, T5 and T6. For T1, T2 and T4, the clearing prices with or without intra-round are very close, but not identical. However, the market outcomes are the same for the criteria we consider, i.e. market power and efficiency.

Appendix D Theoretical predictions

Appendix D.1 General model

There are three risk-neutral bidders/sellers indexed by $i = A, B, C$. Each bidder might own several items, with the size of the items normalized to be one. Assume that the items are indexed by k where $k = 1,2,..,k_i$ and k_i is the maximum number of items bidder i owns, where $1 \leq k_i \leq 3$. Bidder i's costs for the items is given by a vector $c_i = (c_{i1}, c_{i2}, \dots, c_{ik_i})$. It is assumed that the costs are increasing in the number of items so that $c_{i1} \leq c_{i2} \leq \dots \leq c_{ik_i}$. For this analysis complete information is considered, where payoffs and strategies of each bidder are common knowledge. Seller i's profit if they sell k_i item(s) at price p is $\sum_{j=1}^{k_i} p - c_{ij}$ and 0 if they do not sell any of their item(s). In case of a tie at the margin a proportion of the items which have been accepted last in the auction is sold. In total there are five items in the market, three low-cost items which cost $c_{ik} = L = 12$ and two high-cost items which cost $c_{ik} = H = 32$. The buyer wants to buy D_t items in round t at the lowest possible price, where $D_t < 5$, i.e. the available items for sale are more than the number of items the buyer would like to buy.

Before the auction starts the market demand, the number of sellers in the market, the number of items each seller owns as well as the cost associated with each item are made known to all participants. A vector of bid levels evenly spaced $P = (P_1, P_2, \dots P_T, P_{T+1})$ is also announced, where $P_t = \frac{T-(t-1)}{T}$ is the clock price at round t for $t = 1, 2, \dots, T, T+1$ and $(T+1) = 13$ is the number of bid levels. The auction begins in round 1 at the price cap $P_1 = 60$ and the price is reduced in each round by $\frac{1}{T} = 5$ such that $P_1 > P_2 > \dots > P_{12} > P_{13}$, where $P_{13} = 0$. In each round t, bidder i chooses for each item they own either to leave the item in the auction, $q_{ik}^t = 1$, or exit the item, $q_{ik}^t = 0$. In other words, the sellers can choose to exit each one of their items at any price in the set $\{60,55,50,\dots,10,5,0\}$. The price at which a bidder decides to exit their item is the minimum price they are willing to accept to sell the specific item. Once a bidder exits one item in round t, the item is out of the market permanently. Let $Q_t = \sum_{i=A}^{N} \sum_{k=1}^{k_i,} q_{ik}^t$ be the total supply at the end of round t. If there is excess supply at the end of round t, $Q_t \geq D_t$, the auction proceeds to the next round and the price is lowered. The auction stops when $Q_t < D_t$, according to the LAB the pricing rule. In general, $60 = P_1 > \dots > P_6 > H = 32 > P_7 > \dots > P_{10} > L = 12 > P_{11} > \dots > P_{13} = 0$.

Appendix D.2 Lemmas

LEMMA 1: *When there is partial feedback, it is a weakly dominant strategy for all the sellers to exit one of their items, or their only item at the current round* $(t+1)$ *if they observed that the number of items currently in the market equals the demand (*$Q_t = D_t \geq D_{t+1}$*), where* Q_t *the number of items still in the auction at the end of round* t*. This item(s) will determine the auction clearing price which will be* $p = P_{t+1}$*. This lemma applies for* $i \geq 2$ *(more than 2 bidders) and* $k_i \geq 1$ *(each bidder owns at least one item).*

PROOF OF LEMMA 1: Consider bidder i owning only one item which costs $P_{s-1} \geq c_i > P_s$ and let p be the clearing price of the auction. Suppose that $\bar{b}$ is the lowest price at which a bidder have chosen to exit their item from the auction other than bidder i, i.e. $\bar{b} = \min_{j \neq i} b_j$. Let at the end of round t, $Q_t = D_t$, where $t+1 < s-1$, meaning that $P_t > P_{t+1} > P_{s-1} \geq c_i$. During the next round, any bidder can choose either to exit or not their item at the clock price P_{t+1}. Assume for simplicity that $D_t = M, \forall t \geq 1$.

It is shown that it is a weakly dominant strategy for any bidder still in the auction to exit their only item during round $t+1$ at P_{t+1}.

Let's assume $b_i < P_{t+1}$

a) If $b_i < P_{t+1} = \bar{b}$ then the auction stops since $Q_{t+1} < M$ and the clearing price is equal to $= \bar{b} = P_{t+1}$. Bidder i is selling their item and receives a positive payoff $P_{t+1} - c_i$. So, in this case bidder i is indifferent between exiting or not their item at P_{t+1}.
b) If $b_i < \bar{b} < P_{t+1}$ and let . $\bar{b} = P_{t+2}$ and $b_i = P_{t+3}$, then the auction stops since $Q_{t+2} < M$ and the clearing price is equal to $p = \bar{b} = P_{t+2} < P_{t+1}$. Bidder i is selling their item while another bidder sets the clearing price and bidder i receives a positive payoff equal to $b_i - c_i < P_{t+1} - c_i$. Bidder i is better off if they were to submit an exit bid above $\bar{b}$ at P_{t+1}, since in this case $p = b_i = P_{t+1}$ and bidder i, as well as all bidders still in the auction would have benefitted from a higher payoff.

Hence, if $Q_t = M$ at the end of round t, then any bidder cannot be better off by exiting their item at a clock price less than P_{t+1}. For the proof the information setting (complete or incomplete information) has not been used, showing that the high final price of the clock auction with LAB pricing rule comes from the feedback provided to bidders after each round and not from the information setting regarding the cost of the items. This lemma applies also for multiunit auctions. The only difference is that in multiunit auctions if a bidder has more than one item in the market $Q_t = M$, they has a weakly dominant strategy to exit one of their items in round $t+1$. Q.E.D.

LEMMA 2*: When there is partial feedback, it is a weakly dominant strategy for bidders owning only one item not to exit their only item at any clock price* P_s*, where* $P_s \geq \cdots \geq P_{t-1} > P_t > c$ *while* $Q_{s-1} > D_s$*. This lemma applies also to the low-cost items of the players who own more than one item in the games with no pivotal players.*

PROOF OF LEMMA 2: Let p be the clearing price of the auction. It will be shown that it is a weakly dominant strategy for any bidder not to exit their only item at any clock price P_s, *where* $P_s \geq \cdots \geq P_{t+1} > P_t > c$ while $Q_{s-1} > D_s \ \forall s \geq 1$ and $s < t$. Let's assume that bidder C exits their only item in round s. The same proof applies for bidders A and B since $c_C = c_A = c_B = L$ for the treatments with no pivotal player. The only difference is that bidder C has only one item, but bidders A and B have two items and their payoff depends on the sales of both items.

If $Q_{s-1} > D_s$ then bidder C is making a positive payoff only if $Q_s < D_s$ meaning at least x number of items, where $x \geq 1$, in addition to the item of bidder C are exited from the auction.

a) Let $Q_{s-1} = D_s - 1$ and assume that in round s, $x = 1$ number of items, in addition to the item of bidder C is exited from the auction. Therefore, $Q_s < D_s$, the auction stops and $p = P_s$. The payoff of seller C in this case is $\pi_C = \frac{P_s - c_C}{2}$. Bidder C is better off not to exit their item in round s, since then $Q_s = D_s$ and according to Lemma 1, it is a weakly dominant strategy for bidder C (and any bidder) to exit one of their item at P_{s+1} and stop the auction. In this case $p' = P_{s+1}$. The payoff of seller C is $\pi_C' = P_{s+1} - c_C$. It can be easily seen that $P_{s+1} - c_C > \frac{P_s - c_C}{2}$
$$\Rightarrow 2P_{s+1} - 2c_C > P_s - c_C$$
$$\Rightarrow P_s - P_{s+1} - P_{s+1} < -c_C$$
$$\Rightarrow P_{s+1} - \frac{1}{T} > c_C$$
$$P_s > c_C$$
The last inequality is always true since $P_s \geq \cdots \geq P_{t-1} > P_t > c \ \ \forall s \leq t-1$.
b) Let $Q_{s-1} = D_s - 1$ and assume that in round s, $x > 1$ number of items, in addition to the item of bidder C is exited from the auction and thus, $Q_s < D_s$. Then, the auction stops and $p = P_s$. The payoff of seller C in this case is $\pi_C = \frac{P_s - c_C}{a}$, where $a > 1$ is the proportion of the item sold and it is related to the number of items exited at the margin.

Bidder C is better off not to exit their item in round s, since then still $Q_s < D_s$, $p' = P_s$ and the payoff of seller C is $\pi_C' = P_s - c_C$. It can be easily seen that $P_s - c_C > \frac{P_s - c_C}{a}$, where $a > 1$.

c) Let $Q_{s-1} > D_s - 1$ and assume that in round s, $x > 1$ number of items, in addition to the item of bidder C is exited from the auction such that $Q_s < D_s$. In this case, the auction stops and $p = P_s$. The payoff of seller C in this case is $\pi_C = \frac{P_s - c_C}{a}$, where $a > 1$ is the proportion of the item sold and it is related to the number of items exited at the margin. Bidder C is better off not to exit their item in round s, since then either $Q_s < D_s$ and $p' = P_s$. the payoff of seller C is $\pi_C' = P_s - c_C$. It can be easily seen that $P_s - c_C > \frac{P_s - c_C}{a}$, where $a > 1$.

d) Let $Q_{s-1} > D_s - 1$ and assume that in round s, $x = 1$ number of items, as well as the item of bidder C is exited from the auction such that $Q_s > D_s$. In this case, the auction continues, and seller C payoff is $\pi_C = 0$. Bidder C is better off not to exit their item in round s, and stay in the auction either until $Q_{z-1} < D_z$ or until the round price reaches P_t. If bidder C stays in the auction they might either still get 0 or get a positive payoff.

e) Let $Q_{s-1} > D_s - 1$ and assume that in round s, $x = 1$ number of items, as well as the item of bidder C is exited from the auction such that $Q_s > D_s$. In this case, the auction continues, and seller C payoff is $\pi_C = 0$. Bidder C is better off not to exit their item in round s, and stay in the auction and exit their item at a lower clock price. Exiting the item at a lower price above the cost of the item could either result in a payoff equal to 0 or positive.

Hence, it is a weakly dominant strategy for bidder C not to exit their item in any clock price P_s, where $P_s \geq \cdots \geq P_{t-1} > P_t > c$ while $Q_{s-1} > D_s$. For the proof the information setting (complete or incomplete information) has not been used, showing that the high final price of the clock auction with LAB pricing rule comes from the feedback provided to bidders after each round and not from the information setting regarding the cost of the items. Q.E.D.

LEMMA 3*: I*t is a weakly dominated strategy for bidders owning two items to exit their low-cost item which costs c_L before exiting their high-cost item which costs c_H while $P_{t-1} > P_t > c_H > P_{t+1} > \cdots > P_{t+m} > c_L > P_{t+m+1} \geq \cdots \geq P_{T+1}$ and $m > 1$ and $s > 1$.

PROOF OF LEMMA 3: Without loss of generality let us consider bidder i owning two items c_H and c_L such that $P_t > c_H > c_L$. If at any round $s \leq t$ seller i exits his low-cost item, then:

a) If $Q_{s-1} = D_s$, the auction stops, $p = P_s$ and bidder i sells both items in the market and their payoff is $\pi_i = 2P_s - c_H - c_L$. In this case bidder i is indifferent between exiting their low-cost item first.

b) If $Q_{s-1} > D_s$ and if $Q_s = D_s$, then according to lemma 1 it is a weakly dominant strategy for all sellers to exit one of their items at P_{s+1}. In this case $p = P_{s+1}$ and bidder i sells his high-cost item in the market and their payoff is $\pi_i = P_{s+1} - c_H$. Bidder i is better off selling their low-cost item instead of their high-cost item because $P_{s+1} - c_L > P_{s+1} - c_H$. In this case bidder i is better off to exit their high-cost item first.

c) If $Q_{s-1} > D_s$ and if $Q_s < D_s$, then $p = P_s$ and according to the tie rule, a proportion of the items will be sold and seller i's payoff is $\pi_i = (P_s - c_H)/a$ where a proportion of the items on tie. In this case the payoff of bidder i is less compared to the case they exited their high-cost item first and they was selling their low-cost item instead: $\pi_i = (P_s - c_L)/a > (P_s - c_H)/a$. Bidder i is better off to exit their high-cost item first.

d) If $Q_{s-1} > D_s$ and if $Q_s > D_s$, , then the low-cost item is out of the auction and the seller continuous in the auction only with their high-cost item. If $Q_{s+b} < D_{s+b}$, where $b \geq 1$

   a. If seller i sells their high-cost item, then seller i's payoff is $\pi_i = (P_{s+b} - c_H)/a$ where a proportion of the items on tie and it is related with the number of items on tie. In this case the payoff of bidder i which is less compared to the case they exited their high-cost item first and they was selling their low-cost item $\pi_i = (P_{s+b} - c_L)/a > (P_{s+b} - c_H)/a$. They is better off by exiting their low-cost item before their low-cost item.

   b. if seller i does not sell their high-cost item, then seller i is indifferent between exiting first their low-cost item or their high-cost item.

It is shown that exiting the low-cost items before the high-cost items is a weakly dominated strategy. For this proof the feedback policy is not used, therefore the proof applies either if there is partial or no feedback available after each round. Q.E.D.

LEMMA 4: *It is a weakly dominated strategy for bidders owning two items to exit their low-cost item and their high-cost items at the same clock price* $s \leq t$ *while* $P_{t-1} > P_t > c_H > P_{t+1} > \cdots > P_{t+m} > c_L > P_{t+m+1} \geq \cdots \geq P_{T+1}$ *and* $m > 1$ *and* $t > 1$*, when there is no pivotal player.*

PROOF OF LEMMA 4: Let us consider bidder i owning two items c_H and c_L such that $P_t > c_H > P_{t+1} > \cdots > P_{t+m} > c_L > P_{t+m+1} \geq \cdots \geq P_{T+1}$ *and* $m > 1$ *and* $t > 1$.

If at any round $s \leq t$ seller i exits both their items, then:

a) If $Q_{s-1} = D_s$, bidder i wins the auction with both items and their payoff is $\pi_i = 2P_s - c_L - c_H$. In this case bidder i is indifferent between exiting both their item at the same clock price.

b) If $Q_{s-1} > D_s$ and if $Q_s = D_s$, then according to lemma 1 it is a weakly dominant strategy for all sellers to exit one of their items at P_{s+1}. Thus, the clearing price is equal to $p = P_{s+1}$ and the payoff of bidder i is zero and they are better off by not exiting both their items in round s and be able to earn positive payoff.

c) If $Q_{s-1} > D_s$ and if $Q_s < D_s - 1$, then the clearing price is equal to $p = P_s$. According to the tie rule, bidder i sells a proportion of both their items in the market and their expected payoff is $\pi_i = (2P_s - c_L - c_H)/a$ where $a > 1$ is the proportion of each item sold and it is related with the number of items on tie. Bidder i is better off if they exited only their high-cost item in round s and then $Q_s \leq D_s - 1$. The clearing price would still be equal to $p' = P_s$ and $\pi_i = (P_s - c_H)/b + P_s - c_L > (2P_s - c_H - c_L)/a$ where $a > b > 1$.

d) If $Q_{s-1} = D_s + 1$ and if $Q_s = D_s - 1$, the clearing price is equal to $p = P_s$ and bidder i sells both items in the market. According to the tie rule, the expected payoff of bidder i is $\pi_i = (2P_s - c_H - c_L)/2$. It is a weakly dominant strategy for bidder i to exit only their high-cost item in round s. Then $Q_s = D_s$ and thus, according to lemma 1 it will be a weakly dominant for bidder i (and all bidders) to exit their low-cost item at P_{s+1} and stop the auction. In this case the clearing price would be equal to $p' = P_{s+1}$ and bidder i sells their low-cost item and their payoff is $\pi_i = P_{s+1} - c_L$. It can be shown that:

$$P_{s+1} - c_L > (2P_s - c_L - c_H)/2$$

$$\Rightarrow 2P_{s+1} - 2c_L > 2P_s - c_L - c_H$$

$$\Rightarrow 2(P_s - P_{s+1}) < c_H - c_L$$

$$\Rightarrow \frac{2}{T} < c_H - c_L$$

The last inequality is always true since $P_s > c_H > P_{s+1} > \cdots > P_{s+m} > c_L > P_{s+m+1} \geq \cdots \geq P_{T+1}$ and $m > 1$ and $s > 1$. It is shown that exiting the low-cost items at the same clock price as the high-cost item is a weakly dominated strategy. Q.E.D.

LEMMA 5: *Since* $P_t > H > P_{t+1} \geq \cdots \geq P_{t+m} > L > P_{t+m+1}$ and $m > 1$ and $t > 1$, *if during round* s, *bidders A and B have their high-cost items in the auction, then it is an equilibrium strategy to exit their high-cost items at* P_t.

PROOF OF LEMMA 5: Let for simplicity $D_t = M > 1, \forall\, t \geq 1$, then exiting an item at a clock price equal to or above the cost of the item is not always a dominant strategy. It will be proven that it is a weakly dominated strategy to exit their high-cost item below cost. For the proof, bidder A is considered. The proof applies for bidder B as well since the two bidders are symmetric. Assume bidder A leaves their high-cost item in the auction in round t. It is beneficial for seller A not to exit their item in round t only at the end of round t, 3 items are out of the auction and thus, the auction clears at P_t. Different cases are analysed, and it is proved that this is not an equilibrium. Similar proof applies for the case with step demand. This also applies in the game with a pivotal player.

a) Let us assume that $Q_{t-1} = 5$, then during round s bidder A needs to decide regarding both their items. Bidder A benefits from not exiting their high-cost item in round t only when $Q_t < 3$. Assume that the 3 items exited are the two items of seller B and the only item of seller C. Bidders' payoff is $\pi_A = 2P_t - H - L$, $\pi_B = \frac{2P_t - H - L}{3}$, $\pi_C = \frac{P_t - L}{3}$. This is not an equilibrium since bidder B and bidder C have an incentive to unilaterally deviate from this strategy and exit their low-cost item in round $(t + 1)$. Assume bidder C deviates then $Q_t = 3$ and then the auction moves to the next round. According to lemma 1 it is a weakly dominant strategy for seller A and seller C to exit their item in round $(s + 1)$. Then bidders' payoffs are: $\pi_A = 2P_{t+1} - H - L$, $\pi_B = 0$ and $\pi_C = P_{t+1} - L$. Seller C is better off since $P_{t+1} - L > \frac{P_t - L}{3}$ and $P_{t+1} + P_t > 2c_C$. Seller A is worse off since $P_{t+1} - H < 0$. Thus, Seller A is better off exiting their high-cost item in round t and if seller B exits their two items as initially stated, then bidder A yields a payoff off: $\pi_A = \frac{P_t - H}{3} + P_t - L > 2P_{t+1} - H - L$. Even if the auction does not stop at round t, bidder A is better off not selling their high-cost item and earn zero, than selling their item at a lower price and earn a negative payoff.

b) Let's assume that $Q_{s-1} = 4$. It will be shown that bidder A is better off to exit their high-cost item in round t, independent of which item was exited in previous rounds. Bidder A benefits from not exiting his/he high-cost item in round s only when $Q_t < 3$.

  a. If bidder C, exited their item at a previous round, seller A will be better off to stay in the auction if bidder B exits both of their items in round t. Bidders' payoff: $\pi_A = 2P_t - H - L$, $\pi_B = \frac{2P_t - H - L}{2}$, $\pi_C = 0$. This is not an equilibrium since bidders B have an incentive to unilaterally deviate from this strategy. Let's assume that seller B deviates and exits their high-cost item at P_{t+1} and $Q_t = 3$. According to Lemma 1, it is a weakly dominant strategy for seller A and seller B to exit their item in round $(t + 1)$. Bidders' payoffs are: $\pi_A = 2P_{t+1} - H - L$, $\pi_B = P_{t+1} - L$ and $\pi_C = 0$. Seller B is better off since $P_{t+1} - L > \frac{2P_t - H - L}{2}$ and $P_{t+1} + P_t > 2L$. As before, seller A is worse off since $P_{t+1} - H < 0$. Bidder A is better off to exit their item in round s.

  b. If bidder B, exited their high-cost item at a previous round, seller A will be better off to stay in the auction if bidders B and C exit their low-cost item in round s. Bidders' payoff: $\pi_A = 2P_t - H - L$, $\pi_B = \frac{P_t - L}{2}$, $\pi_C = \frac{P_t - L}{2}$. This is not an equilibrium since bidders B and C have an incentive to unilaterally deviate from this strategy and exit their low-cost items at P_t. Assume that seller B deviates and exits their low-cost item at

P_{t+1}, then bidders payoff is: $\pi_A = 2P_{t+1} - H - L$, $\pi_B = P_{t+1} - L$ and $\pi_C = P_{s+1} - L$. Seller B is better off since $P_{t+1} - L > \frac{P_t - L}{2}$ because $P_t > L$. As before, seller A is worse off since $P_{t+1} - H < 0$. In this case, Seller A is better off exiting their high-cost item at round s where they earn $\pi_A = \frac{P_t - H}{3} + P_t - L$.

c. If bidder B, exited their low-cost item at a previous round, seller A will be better off to stay in the auction if bidders B exits their high-cost item and C exit their low-cost item in round t. Bidders' payoff: $\pi_A = 2P_t - H - L$, $\pi_B = \frac{P_t - H}{2}$, $\pi_C = \frac{P_t - L}{2}$. This is not an equilibrium since seller C have an incentive to unilaterally deviate from this strategy. Let us assume that seller C deviates and exits their item at P_{t+1}, then according to Lemma 1 it is a weakly dominant strategy for sellers still in the auction to exit their item in round $(t+1)$. Bidders' payoff: $\pi_A = 2P_{t+1} - H - L$, $\pi_B = 0$ and $\pi_C = P_{t+1} - L$. Seller B is better off since $P_{t+1} - L > \frac{P_t - L}{2}$ because $P_{t+2} > L$. As before, seller A is worse off since $P_{t+1} - H < 0$. In this case, Seller A is better off exiting their high-cost item at round s.

d. If bidder A, exited their low-cost item at a previous round, then seller A will be better off to stay in the auction if bidders B exits their high-cost item and C exit their low-cost item in round s. Bidders' payoff: $\pi_A = P_t - H$, $\pi_B = \frac{P_t - H}{2} + P_t - H$, $\pi_C = \frac{P_t - L}{2}$. This is not an equilibrium since seller C have an incentive to unilaterally deviate from this strategy. Assume that seller C deviates and exits their item at P_{t+1}, then according to Lemma 1 it is a weakly dominant strategy for seller A to exit their item in round $(t+1)$. Bidders' payoff: $\pi_A = P_{t+1} - H$, $\pi_B = P_{t+1} - L$ and $\pi_C = P_{t+1} - L$. Seller C is better off since $P_{t+1} - L > \frac{P_t - L}{2}$ because $P_{t+2} > L$. As before, seller A is worse off since $P_{t+1} - H < 0$. Seller A is better off exiting their high-cost item at round t.

c) Let us assume that $Q_{t-1} = 3$. Then it is a weakly dominant strategy for seller A to exit their high-cost item in round s (Lemma 1).

Therefore, bidders A and B cannot be better off by exiting their items below cost. Q.E.D.

LEMMA 6*: in the treatments with no pivotal player, if* $P_t > H > P_{t+1} \geq \cdots \geq P_{t+m} > L > P_{t+m+1}$*, and no feedback is provided after each round, sellers' A and B optimal strategy is to exit their high-cost item at any round* $s \leq t$ *and exit their low-cost item in round* $t+1$*. No feedback after each round eliminates market power opportunities in treatment with inelastic demand and no pivotal player. This applies also in the case of step demand and partial feedback.*

PROOF OF LEMMA 6: In this section, the optimal strategy of sellers A and B will be analysed. It will be shown that the no-feedback strategy after each round eliminates market power opportunities. For example, as in the case of partial feedback, if sellers A and B exit their high-cost item at P_1 and seller A exit their low-cost item at P_2 to stop the auction then $\pi_A = P_2 - L = \pi_B$. However, this is not an equilibrium when there is no feedback since seller B has an incentive not to exit their high-cost item at P_1 but at P_3. By undercutting their rival, seller B sells both their items at a lower price and benefits from a higher payoff. In this case $\pi'_A = 0$, $\pi'_B = P_3 - L + P_3 - H$. It is beneficial for seller B to undercut seller A if $2P_3 - L - H > P_2 - L \Rightarrow P_3 + P_3 - P_2 > H \Rightarrow P_3 - \frac{1}{T} > H \Rightarrow P_2 > H$. This inequality is always true since $P_2 >..> P_s > H \; \forall \, s \leq t$ and $P_t > H$. In this case, seller A makes zero profit and they have an incentive to exit their low-cost item at P_4 and earn positive payoff: $\pi_A = P_4 - L = \pi_B$. Again, seller B has an incentive to undercut seller A and exit their high-cost item at P_5. Then, the payoffs of sellers A and B are $\pi'_A = 0$, $\pi'_B = P_5 - L + P_5 - H$. It is beneficial for seller B to undercut seller A if $2P_5 - L - H > P_4 - L \Rightarrow P_5 + P_5 - P_4 > H \Rightarrow P_5 - \frac{1}{T} > H \Rightarrow P_4 > H$. This inequality is always true for $P_4 >..> P_s > H$

In general, if seller A and seller B exit their high-cost item at any clock price in the set $\{P_1, P_2, .., P_{s-1}\}$ and seller A exits their low-cost item at P_s, where $s+1 < t$ and $P_t > H > P_{t+1}$, then seller B has an incentive to undercut seller A and exit their high-cost item during the next round, $s+1$. In this way seller A benefits by a higher profit while selling both their items at a lower price if $2P_{s+1} - L - H > P_s - L \Rightarrow P_{s+1} - H > P_s - P_{s+1} \Rightarrow P_{s+1} - H > \frac{1}{T}$.

On the other hand, if $2P_{s+1} - L - H < P_s - L \Rightarrow P_{s+1} - H < \frac{1}{T}$ and if seller A and seller B exit their high-cost item at any clock price in the set $\{P_1, P_2, .., P_{s-1}\}$ and seller A exits their low-cost item at P_s, then their payoffs are: $\pi_A = P_s - L = \pi_B$. Since $P_t > H > P_{t+1} \geq \cdots \geq P_{t+m} > L$, the inequality $P_{s+1} - H < \frac{1}{T}$ is true $\forall \, (s+1) \geq t$. Seller B has no incentive to deviate and exit their high-cost item in round $(t+1)$ since $2P_{t+1} - L - H < P_t - L \Rightarrow P_{t+1} - H < \frac{1}{T}$. However, seller B has an incentive to deviate from the strategy and exit their high-cost item at P_t and benefit by a higher payoff by selling their low-cost item and half of their high-cost item: Sellers' payoff: $\pi_B = \frac{P_t - H}{2} + P_t - L$ and $\pi_A = \frac{P_t - L}{2}$.

Therefore, it is proven that it is not an equilibrium if seller A and seller B exit their high-cost item at any clock price in the set $\{P_1, P_2, .., P_{s-2}\}$ to exit their low-cost item in round $(s-1)$.

Let us see if exiting the low-cost item in round s, while high-cost items were exited at any clock price in the set $\{P_{1,}P_2, .., P_{s-1}\}$ is an equilibrium. Assume seller A and seller B exit their high-cost item at any clock price in the set $\{P_{1,}P_2, .., P_{s-1}\}$ and seller A exits their low-cost item at P_s, then their payoffs are: $\pi_A = P_s - L = \pi_B$. Seller B has an incentive to deviate from this strategy and exit their high-cost item at P_s and benefit from a higher payoff by selling their low-cost item and half of their high-cost item: Sellers' payoff: $\pi_B = \frac{P_s - H}{2} + P_s - L$ and $\pi_A = \frac{P_s - L}{2}$. Thus, it is proven that it is not an equilibrium for seller A and seller B to exit their low-cost item in round s.

According to Lemma 5 if seller A and/or seller B have their high-cost items in the auction during round t while $P_t > H > P_{t+1}$, then it is an equilibrium strategy to exit their high-cost items at P_t. Therefore, sellers A and B optimal strategy is to exit their high-cost item at any clock price $P_s \geq P_t$ and exit their low-cost item in round P_{t+1}. Bidders' payoff: $\pi_A = P_{t+1} - L = \pi_B = \pi_C$. None of the sellers can benefit from a unilateral deviation.

It has been shown that there are no market power opportunities in treatment without feedback and inelastic demand since the non-cooperative equilibrium is equal to the competitive level. No feedback after each round eliminates market power opportunities in the games with inelastic demand. Q.E.D.

Appendix E Results

Table E-1: Observed clearing prices per treatment averaged over the first 10 auctions

	T1	T2	T3	T4	T5	T6
GROUP 1*	42.5	29.5	41.5	49.5	30	29.5
GROUP 2	52	50	46.5	41	31	33.5
GROUP 3	52	27.5	33	32.5	33.5	31.5
GROUP 4	38	60	50.5	44	28	30.5
GROUP 5	53	43	25	34	33.5	21
GROUP 6	51.5	33	52	35	29.5	29.5
GROUP 7	53.5	49	48	32	30	30
GROUP 8	47.5	52.5	37.5	40	30.5	30
GROUP 9	48.5	-	44	49.5	28.5	29.5
GROUP 10**	39.5	-	-	-		30.5

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for the Pivotal + Partial feedback treatment refers to the first group which was given this treatment, group 1 results for Pivotal and No feedback refer to the first (different) group which given that treatment etc.

**A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

Table E-2: Observed clearing prices per treatment averaged over the 20 auctions

	T1	T2	T3	T4	T5	T6
GROUP 1*	39.75	30	42.5	48	30	29.75
GROUP 2	55.25	46.5	45.75	37.25	30.5	31.75
GROUP 3	53.5	36	31.5	32.5	32.75	30.75
GROUP 4	46.25	60	52.75	47	29	30.25
GROUP 5	52.5	42.5	25	32.25	31.75	24.5
GROUP 6	52.5	33.25	53.5	34	29.25	29.75
GROUP 7	54.4	50.5	52	32	30	30
GROUP 8	51.25	54	46	36.75	31.75	30
GROUP 9	51.75	-	43	52.25	29.25	29.75
GROUP 10**	48	-	-	-	-	30.25

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for the Pivotal + Partial feedback treatment refers to the first group which was given this treatment, group 1 results for Pivotal and No feedback refer to the first (different) group which given that treatment etc.

**A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

Table E-3: Frequency of allocative efficiency levels in each group for each treatment over the first 10 auctions

	T1	T2	T3	T4	T5	T6
GROUP 1*	30	90	30	0	60	90
GROUP 2	20	10	50	0	50	80
GROUP 3	0	60	40	10	80	70
GROUP 4	50	0	100	60	90	80
GROUP 5	90	20	70	40	90	60
GROUP 6	10	40	80	20	100	100
GROUP 7	10	0	80	40	100	80
GROUP 8	20	0	80	30	100	90
GROUP 9	10	-	30	100	80	90
GROUP 10**	30	-	-	-		80

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for the Pivotal + Partial feedback treatment refers to the first group which was given this treatment, group 1 results for Pivotal and No feedback refer to the first (different) group which given that treatment etc.
**A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

Table E-4: Frequency of allocative efficiency levels in each group for each treatment over the 20 auctions

	T1	T2	T3	T4	T5	T6
GROUP 1*	40	90	35	0	75	95
GROUP 2	10	10	60	0	75	85
GROUP 3	0	45	65	10	90	85
GROUP 4	25	0	100	65	95	90
GROUP 5	60	20	85	35	95	35
GROUP 6	10	50	90	30	95	95
GROUP 7	10	5	80	50	100	80
GROUP 8	10	0	90	35	100	95
GROUP 9	5	-	20	95	80	95
GROUP 10**	15	-	-	-	-	90

*Each group was given one treatment so group 1 does not refer to the same individuals across treatments. Rather the group numbers refer to the order in which a treatment was received, i.e. group 1 results for the Pivotal + Partial feedback treatment refers to the first group which was given this treatment, group 1 results for Pivotal and No feedback refer to the first (different) group which given that treatment etc.
**A minimum number of eight groups was planned and implemented for all treatments. The testing adjusts for the slightly different number of groups run across treatments.

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