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An Experimental Investigation

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Auction Mechanisms for Allocating Subsidies for Carbon Emissions Reduction: An Experimental Investigation

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Abstract

One method to reduce greenhouse gas emissions is to subsidize emissions-reducing activities. The question is how to allocate such subsidies. Allocation through auctions is an emerging mechanism. In a controlled experimental market setting, we compare the effects of a variety of auction mechanisms for allocating subsidies for carbon emissions reduction in China. Besides the conventional auction mechanisms, we place particular focus on testing the actual performance of the auction mechanism proposed by Erik Maskin (2011). We find that, while the Maskin auction mechanism spends the most from a fixed subsidy budget and leads to the largest emissions reduction, its per-unit emissions reduction cost is higher than that of discriminatory and uniform-price auction mechanisms. Both the Maskin and uniform-price auctions outperform discriminatory auctions in price discovery. Furthermore, from the government's perspective, the Maskin auctions exhibit the strongest improvement tendency with repeated auctions.

Key Words: auctions, subsidy allocation, carbon dioxide, greenhouse gases, emissions reduction

JL Codes: C91, C93, D64

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Auction Mechanisms for Allocating Subsidies for Carbon Emissions Reduction: An Experimental Investigation

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1. Introduction

In order to reduce greenhouse gas emissions (GHG), both developed and developing countries have begun subsidizing emissions-reducing activities. This type of subsidy has been put into practice in the USA, the UK, and several other countries (see, e.g., Smith and Swierzbinski, 2007; Lopomo et al., 2011). Subsidies are also being considered by policy makers from other countries as an alternative to emissions allowance policies because they provide an opportunity to facilitate industrial restructuring[1] with tax transfer payments.

The question in this paper is how best to allocate such subsidies. One emerging mechanism for allocating such subsidies is through auctions. There have been some experiments with other forms of subsidy allocation, such as equal division and grandfathering. However, economic theory, the weight of recent experience, and current policy proposals suggest that auctions can be an important mechanism for selling subsidies for emissions reduction, especially in cases where the government desires to maximize reduction with a limited total subsidy. It is widely recognized that the effects of a given subsidy on total emissions reduction could vary with auction mechanisms, and the performance of different types of auction mechanisms could vary with the specific context. Previous relevant studies focus on sales of emissions allowances and have mainly been conducted in developed countries, such as the US and Europe (see, e.g., Holt et al., 2008; Burtraw et al., 2009; Porter, 2009; Shobe et al., 2010). Therefore, it is important to investigate the performance of various auction designs in the context of GHG emissions reduction subsidy sales, not only theoretically but also empirically, through controlled experimental auction markets. New evidence from developing countries may also supplement the current literature.

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[1] Industrial restructuring refers to, e.g., diminishing or even eliminating production of high emissions firms or increasing the production of low emissions firms.

Auctions to allocate carbon emissions reduction subsidies are essentially procurement auctions. That is, each bidder specifies a price at which he is willing to execute the emissions reduction project. The bidder(s) submitting the lowest bid(s) is (are) assigned the execution of the project in exchange for a payment that equals the bid(s). Although in most cases auctions are an effective way to allocate subsidies, which auction mechanism should be employed remains problematic in both theory and practice. When the primary goal of the subsidy is efficiency, i.e., the government aims to maximize emissions reduction with a given subsidy, various auction formats could be utilized. Among others, discriminatory and uniform-price auction formats are the leading candidates in the case of carbon emissions permits.[2] In a discriminatory price sealed-bid auction for allocating a subsidy, bidders submit their bids and all winning bidders obtain their bid prices for the reduction. In a uniform-price sealed-bid auction, bidders submit their bids and all winning bidders obtain the uniform market-clearing price for the reduction.[3] This study will compare the effects of various auction formats based on sealed bids because previous papers already have explored the differences between first-price-sealed-bids and dynamic-bid designs in multi-unit auctions (Shachat, 2010) and procurement auctions (Goeree et al., 2013), respectively.

In theory, if emitters (e.g., firms) bid their costs, discriminatory auctions can work perfectly (i.e., maximizing the emissions reduction) because subsidies are allocated to the emitters facing the lowest reduction costs. However, if emitters tend to bid above their costs to gain benefits from their emission reduction activities, uniform-price auctions could outperform discriminatory auctions because they provide incentives to bid at cost. Nevertheless, uniform-price auctions are not optimal because they are unable to maintain a budget-binding total subsidy (i.e., not violating or wasting the subsidy). Maskin (2011) developed a new auction mechanism (a “Maskin auction” hereafter) based on a uniform-price auction. By participating in this auction, firms are induced to bid their cost and the total budgeted subsidy can be utilized as much as possible. In other words, the total reduction can be maximized subject to the subsidy budget constraint. The rules of the Maskin auction mechanism appear rather complicated but are essentially simple: each firm should bid its cost, i.e., no strategic behavior needs to be contemplated.

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2 Examples include discriminatory auctions for US sulfur dioxide permits and uniform-price auctions for Virginia nitrogen oxide permits (Lopomo et al., 2011). See, e.g., Cramton and Kerr (2002), Cramton (2007a), and Betz et al. (2010) in support of discriminatory auctions and Holt et al. (2007, 2008) in support of uniform-price auctions. Lopomo et al. (2011) provide a detailed comparison of different types of auctions utilizing the case of carbon emissions permits.

3 In dynamic-bid auctions, an auctioneer begins by calling out a low price and raises the price gradually until sufficient emissions reductions are supplied at the announced price, which consumes the entire subsidy. The winning bidders pay their bid prices in discriminatory-price auctions and a uniform market-clearing price in uniform-price auction, respectively.

In both uniform-price and Maskin auctions, the winning bidders are paid a uniform transaction price equal to or above their bids, and the transaction price is equivalent to the winners' bids in discriminatory auctions. Therefore, for a given subsidy budget, which mechanism is superior depends on (1) how strong is the incentive to bid above cost in a discriminatory auction; (2) how large is the difference between the transaction prices and the bid in uniform-price and Maskin auctions; and (3) how closely the bids can be induced to approach costs in uniform-price and Maskin auctions. In addition, because the auction models require full understanding and rationality, whether agents in the real world could behave in the same or a similar way as theoretically predicted remains unknown, as does the length of the convergence process. Furthermore, the similarities and differences in performance indicators, such as efficiency, total reduction amount, price discovery, and budget spending for different auction mechanisms could also be of interest for policy makers.

By constructing experimental auction markets with a sealed-bid auction design, we compare the performance of three types of auctions in terms of total emissions reduction, efficiency, price discovery, etc., in the context of allocating a carbon emissions reduction subsidy. We also investigate how firms adjust their bidding behavior[4] in a finitely repeated auction game because learning can be an important determinant of dynamic bidding behavior (see, e.g., Isaac and Walker, 1985; Selten and Buchta, 1999; and Güth et al., 2003). To the best of our knowledge, this is the first study that utilizes experiments to test the actual performance of the proposed Maskin auction mechanism, in a first step from theory to application. This study provides evidence to facilitate policy makers' choices among various auction mechanisms for allocating subsidies. Our main findings are that the Maskin auction mechanism spends the most from a fixed subsidy budget and achieves greater total emissions reductions; however, the per-unit emissions reduction cost is higher than that of the other two auction mechanisms. Both Maskin and uniform-price auctions outperform discriminatory auctions in price discovery. Moreover, many indicators of the performance of these mechanisms improve with repeated auctions, and the Maskin auctions demonstrate the strongest tendency for improvement.

The remainder of the paper is organized as follows. Section 2 reviews the literature, and Section 3 provides a theoretical interpretation of the auction mechanisms. Section 4 introduces the experimental design. Section 5 reports the results, and Section 6 presents the conclusions.

[4] For example, the performance (e.g., efficiency and increased emissions reductions) of Maskin auctions might not exceed that of other types of auctions in one-shot auctions; however, its performance can be improved gradually when more auctions are conducted.

2. Literature review

Many environmental regulations are often less costly than anticipated at the time of their adoption. The overestimation of baseline emissions levels and failure to incorporate the emissions-reducing effects of technological change are important factors that contribute to overestimation (Harrington et al., 2000). Periodically held auctions, however, play a role in the effective allocation of emission reduction quotas and in the determination of prices by accounting for the disadvantages of other environmental regulations (Cramton and Kerr, 2002). For example, the US sulfur dioxide emissions trading program, initiated in 1995, was specifically designed to apply an annual revenue-neutral auction. This auction was held in advance of the compliance period and played an important role in the discovery of compliance costs and the associated allowance price that was ultimately obtained in the market (Burtraw, 2000; Carlson et al., 2000). Consequently, low prices, thin trading, and large amounts of allowance banking characterized the early market for SO_2 allowances (Ellerman et al., 2000). The first mandatory emissions control and trading program for GHG emissions in the US, the Regional Greenhouse Gas Initiative (RGGI) for the ten northeastern states from Maryland to Maine, launched its first auction on September 25, 2008. In RGGI, carbon dioxide allowances are sold through quarterly auctions using a uniform-price sealed-bid format.[5] Six Midwestern states, seven Western states and some Canadian provinces developed a similar regional carbon cap-and-trade program, the Western Climate Initiative (WCI). An auction mechanism with penalties was also utilized in the European Union Emissions Trading System (EU ETS), which accounted for more than half of the EU's carbon dioxide emissions. While the initial two phases of the EU ETS relied almost completely on free allocation of allowances to regulated facilities instead of on auctions (Ellerman and Buchner, 2007), the third phase, beginning from 2013, has started to auction 40% of the allowances (Restiani and Betz, 2011) and will expand this approach to most other emissions sources by 2020 (Burtraw et al., 2009).[6]

Auctions have been utilized to allocate carbon emissions reduction subsidies in GHG emissions control programs in the USA, UK and several other countries (e.g., Smith and Swierzbinski, 2007; Lopomo et al., 2011). This type of auction is essentially a procurement auction in which an entity, e.g., the government, procures certain environmentally friendly goods and services with a limited budget to implement environmental policies. Recent empirical studies of procurement auctions observe that demand constraints might influence

[5] For example, in the June 2009 auction, the market-clearing price was $3.23 per ton of carbon dioxide. See www.rggi.org for more details.

[6] For more information on the draft auction rule of the next phase of the EU ETS, see http://ec.europa.eu/environment/climat/emission/auctioning_en.htm.

entry and bidding behavior in consecutive auctions. For example, Jofre-Bonet and Pesendorfer (2000; 2003) study procurement auctions conducted by the California Department of Transportation between 1994 and 2000 and find that firms that did not win highway paving contracts earlier in a sequence of auctions were more likely to enter subsequent auctions than firms that had already won contracts. Similarly, De Silva et al. (2002) study auctions conducted by the Oklahoma Department of Transportation between 1998 and 2000 and report that firms that failed in morning auctions bid more aggressively in the afternoon than firms that were successful in the morning. However, the majority of the experimental research on auctions focused on selling rather than procuring goods and services (see Kagel (1995), Kagel and Levin (2012), and Kwasnica and Sherstyuk (2013) for extensive surveys). Only a few studies consider procurement auctions. For example, Brosig and Reiß (2007) experimentally compare subjects' entry and bidding behavior in single first-price procurement auctions with their behavior in a game consisting of two subsequent first-price procurement auctions. They find that entry and bidding behavior are crucially affected by the opportunity cost of early bid submission and systematically deviate from the perfect Bayesian equilibrium prediction. Engelbrecht-Wiggans et al. (2007) find that, when suppliers bid at price and the buyer subsequently selects the winner, the procurement official receives significant gains compared to awarding the contract to the lowest bidder. Haruvy and Katok (2008) examine the performance of a buyer-determined winner auction versus a first price auction and find that the latter is superior if suppliers have complete information regarding the quality of other sellers. Shachat and Swarthout (2010) compare the performance between sealed-bid buyer-determined auctions and dynamic-bid price-based auctions with bidding credits when procuring differentiated goods. They find that the former is less efficient than the latter, and both the buyer and seller receive greater surpluses in the latter auction. Shachat (2010) examines the relative performance of an English auction (EA) and a first price sealed-bid auction (FPA) when procuring a single-unit commodity. He finds that the bids and prices in an EA are consistent with game theoretic predictions, while they are not in an FPA, and that the average prices produced by an EA are higher than in a FPA. Previous studies mainly focus on procurement auctions for single goods/services, whereas studies comparing the relative performance of various mechanisms for procuring multiple units of goods are lacking.

Uniform-price auctions may be more suitable than discriminatory auctions for selling subsidies for GHGs emissions, because discriminatory auctions are demonstrated to not be "asymptotically efficient" (Jackson and Kremer, 2007; Lopomo et al., 2011). This result occurs because the dominant strategy in a uniform-price auction is to bid the cost (Cramton and Stoft, 2007), while a discriminatory auction rewards those who can accurately estimate the clearing price and bid based on that guess (Lopomo et al., 2011).[7] Evidence from experimental auction markets suggests that the potential for improved price discovery with discriminatory auctions may not be realized in practice. For example, Cason (1995) considered an inverted version of a discriminatory auction in which buyers face the same incentives as sellers. He finds that, consistent with theoretical predictions, buyers bid above their valuation, auction outcomes are inefficient, and increasing the number of buyers increases bids. Goeree et al. (2013) conduct a multi-unit auction experiment with either discriminatory (sealed-bid) auctions or ascending clock auctions in which bidders were informed when anyone reduced their bid quantities. They find that tacitly coordinated demand reduction and preemptive bidding (forms of strategic bidding) may be more of an issue in clock auctions and tended to stop the clock at low prices, and auction revenues were much higher in discriminatory auctions. A broad review of the recent literature on auction designs for carbon allowance, conducted by Lopomo et al. (2011), suggests that a uniform-price sealed-bid auction with a sensibly chosen price collar is likely to perform its primary function well. However, which of the alternative auction designs is best for allocating subsidies for emissions reduction and how actual performance differs from theoretical predictions remain open questions. Therefore, the experimental testing of auction designs can help answer the aforementioned questions (Lopomo et al., 2011).

Since the first experimental study of alternative auction mechanisms by Smith (1967), several early studies have focused on the performance differences among auction formats in various circumstances (see, e.g., Cox et al., 1985; Miller and Plott, 1985; Cason, 1995; Goswami et al., 1996; and Alsemgeest et al., 1998). Regarding experimental studies of auction mechanisms to facilitate GHG emission reduction, Shobe et al. (2010) investigate the efficiency of auction formats for allocating CO_2 emissions allowances, and find that all auction formats yield efficient allocations of emissions allowances, while aggressive bidding behavior in initial discriminatory auctions yields higher revenues than in other auction formats. However, these differences among the auction types erode over time during a particular auction session. Burtraw et al. (2009) utilize laboratory experiments to test three auction mechanisms – uniform, discriminatory price sealed-bid, and ascending clock auctions

[7] Regarding the use of a sealed-bid or a dynamic-bid auction design, some scholars argue that ascending-bid auctions outperform sealed-bid auctions in price discovery, especially for multiple products or new assets without established prices (see, e.g., Cramton, 1998; 2007b; Cramton and Kerr, 2002; and Betz et al., 2010), whereas others observe that sealed-bid uniform-price auctions achieve price discovery equivalent to simultaneous ascending-bid auctions (Burtraw et al., 2009). It is widely recognized that the dynamic-bid design increases information transparency, although it does not necessary induce more desirable auction outcomes than a sealed-bid design (Burtraw et al., 2011). Additionally, dynamic bidding facilitates collusive bidding (Holt et al., 2007). For example, Alsemgeest et al. (1998) utilize experiments to compare the performance of sealed-bid uniform-price auctions and English clock auctions with both single-unit and two-unit demand for each bidder. Their results suggest that dynamic-bid auctions may be more susceptible to tacit collusion.

– with and without the ability of subjects to communicate explicitly to maximize profits. The authors find that discriminatory and uniform-price auctions generate greater revenues than clock auctions in both cases, and that the effect of explicit communication is to reduce the revenues from both uniform and clock auctions.

However, we have not found previous research that empirically tests the performance of different auction formats in the context of allocating subsidies for emissions reduction. The rankings of different auction mechanisms depend on the specific context. Markets for environmental subsidies are relatively new, and there is little empirical experience with the utilization of auctions for allocating these subsidies. Furthermore, it is particularly interesting to test the actual performance of a new auction mechanism for the allocation of subsidies for emissions reduction designed by Maskin (2011) and to compare its performance with other auction formats.

3. Theoretical interpretation of various auction mechanisms

When the government provides a given subsidy for firms to reduce their carbon emissions, the objective is to maximize the reduction subject to a subsidy budget constraint. Therefore, the social optimum can be achieved if all firms bid their cost of reduction and the government selects the firms with the lowest cost and subsidizes them for implementing the reduction. In this manner, a society can achieve the largest possible carbon emission reduction at a certain total cost. Unfortunately, this social optimum is often not in the firms' best interests. To clarify the theoretical interpretation of different auction formats as much as possible, we utilize a simple example. However, this example can be generalized. Suppose that the government provides a total amount of 100 dollars as a subsidy (S) to reduce carbon emissions as much as possible during a certain period. Six firms participate in an emission reduction subsidy auction and compete for the subsidy with the constant reduction costs $\mathrm{C}_1 = 4.5$ dollar/unit, $\mathrm{C}_2 = 4$ dollar/unit, $\mathrm{C}_3 = 6$ dollar/unit, $\mathrm{C}_4 = 6.5$ dollar/unit, $\mathrm{C}_5 = 7$ dollar/unit, and $\mathrm{C}_6 = 8.5$ dollar/unit. All firms possess the same emission reduction capacity of 10 units within this given period. Two major conventional auction mechanisms can be utilized to auction the subsidy.

The first auction mechanism is a *discriminatory sealed-bid auction* (e.g., Holt, 1980). The auction is regulated by the following rules: each firm i bids (p_i, q_i), where p_i is the price it proposes to be paid for per-unit reduction up to its maximal reduction capacity q_i . Given $p_1 \leq p_2 \leq \cdots \leq p_n$, the number of firms that win the auction is m^*, where m^* solves $max\{m| \sum_{i=1}^{m} p_i q_i \leq S\}$. That is, the firm with the lowest reduction bid will be selected and paid for its reduction capacity first. If any portion of the subsidy remains, then the firm with the second lowest bid will be selected and paid for its reduction capacity, and so on. This selection rule will be applied until m^* firms are selected and the entire subsidy is allocated. In this numerical example, if all six firms bid at their costs, Firm 2 will be selected and paid for its full reduction capacity first, and then firm 1 will be selected and paid for its full reduction capacity. However, Firm 3 will be selected and paid only for part of its reduction capacity (i.e., 2.5 of 10 units) because the subsidy will be allocated before firm 3's reduction capacity is fully compensated. The subsidy allocation will be $C_1 * 10 + C_2 * 10 + C_3 * 2.5 = 100$. Therefore, the total amount of emissions reduction is 22.5 units, and this is the largest possible total reduction under a 100 dollar subsidy budget. However, it is not possible to achieve the maximum total reduction amount under discriminatory auction rules because firms do not face incentives to bid at their costs. For instance, Firm 2 will place a higher bid (e.g., any value between 4 and 4.5 dollar/unit) to gain profits while still winning the auction.

In another auction mechanism, the *uniform-price sealed-bid auction* (e.g., Fabra, 2003), a firm's bid cannot directly determine the price to be paid. This auction is governed by the following rules: each firm *i* bids (p_i, q_i) as before. Let $p = p^*$ be the highest p that solves $p\sum_{i \in I(p)} q_i \leq S$ where $I(p) = \{i | p_i \leq p\}$. Each firm *i* for which $i \in I(p_i \leq p^*)$ is selected and paid p^* for its reduction q_i; other firms are paid nothing. That is, the selected firms are paid the uniform price of the lowest rejected bid. In our numerical example, if all six firms bid at their costs, then only Firm 2 will be selected and paid for its full reduction capacity at the price of the lowest rejected bid. At this point, the subsidy allocation will be $C_1 * 10 \ = 45$. Firm 2 cannot be selected because the subsidy required will exceed the budget; this is because the price to be paid would be C_3, i.e., the total subsidy needed is $C_3 * (10 + 10) \ = 120$ even when $q_3 = 0$. Under these auction rules, a firm has an incentive to bid its cost because the bid does not directly impact the price to be paid, while bidding at cost enables the firm to have the maximal probability of winning the auction. However, as shown in our example, the drawbacks of this auction are that either it may violate the budgeted amount of the subsidy, or much of the budget may be wasted.

Maskin (2011) developed a new auction mechanism that incorporates a uniform-price auction's advantages yet offsets its weaknesses through the following three important features: [1] bidders are induced to bid their costs; [2] the price being paid is no greater than the lowest rejected bid; and [3] total payments do not exceed the budget. That is, this auction maximizes the (expected) emissions reduction (assuming firms are more likely to have low rather than high costs) (see Maskin (2011) for a formal proof of this mechanism). We also interpret this auction's rules utilizing the same numerical example. In a Maskin sealed-bid auction with six competing firms, in which each firm places a bid, the number of firms to be selected and the transaction price to be paid are determined systematically by the following rules: if no more than one firm bids below $(10/2), the bidder with the lowest bid is selected and paid the lower price of \$10 or the second-lowest bid;[8] if more than one firm bids below \$(10/2) but not more than two firms bid below \$(10/3), the two bidders with the lowest bids are selected and paid the lower price of \$(10/2) or the third-lowest bid; and so on. Table 1 provides detailed auction rules, which can be extended to an infinite number of bidders. Essentially, this auction is a modified form of uniform-price auction in which additional limitations on the transaction price and on the number of winners are imposed in addition to the conventional rules in the uniform-price auctions.

To sum up, although the winners' transaction price is equal to their bids, the discriminatory mechanism does not provide an incentive to bid at cost. The uniform-price mechanism provides such an incentive, but a portion of the subsidy is wasted because winners are paid transaction prices, which are usually higher than their bids. The Maskin mechanism incorporates the advantages of both mechanisms, providing an incentive to bid at cost while limiting the transaction prices to no higher than those under a uniform-price auction with the same bid structure. Therefore, the Maskin mechanism reduces subsidy waste and provides the theoretically most efficient manner to utilize a subsidy.

In this study, we will test the following hypotheses in a controlled market environment:

Hypothesis 1: In a uniform-price and Maskin auction, firms' bids gradually converge to the cost of emissions reduction;

Hypothesis 2: Compared to a discriminatory auction, uniform-price and Maskin auctions yield lower average winners' bids and higher total emissions reductions;

Hypothesis 3: A greater portion of the subsidy is spent and greater emissions reductions occur under a Maskin auction than in a uniform-price auction.

4. Experimental design

Auctions for allocating emission reduction subsidies are essentially multi-unit procurement auctions. In this experiment, we focused on two auction formats that have received attention in emissions permit trading programs and one new auction format developed by Maskin (2011), all with sealed-bid designs. That is, our experiment includes three treatments: discriminatory, uniform-price, and Maskin sealed-bid auctions. The experiment utilizes a between-subjects design and consists of nine sessions, three for each treatment. In each session, four auction markets with six subjects in each market were

[8] \$10 is the reserved reduction price, equal to the total \$100 subsidy divided by a single firm's 10 unit reduction capacity.

simultaneously and independently operated. Each subject acted as a firm. Thus, we can investigate the performance differences yielded by different auction formats.

To compare the performance differences across these three auction formats, we designed an experiment with three treatments. In Treatment 1, discriminatory sealed-bid auctions, firms were selected in sequence to win the auction according to their bids from low to high, and the transaction price paid was equal to their own bids. This procedure of winner selection continued until the entire subsidy was allocated. In Treatment 2, uniform-price sealed-bid auctions, firms with the lowest bids won the auction. The same selection procedure as in Treatment 1 was applied; however, the transaction price paid was a uniform price equal to the *lowest rejected bid*. In Treatment 3, Maskin sealed-bid auctions, firms with the lowest bids won the auction. The number of firms and the price paid were determined by pre-established rules that were announced prior to the auction. The specific rules are displayed in Table 1. The currency was converted to Chinese yuan in this experiment.

4.1. Emitters and market background design

In this experiment, we utilized a background design for firm characteristics similar to the design developed by Burtraw et al. (2009).[9] This design captures crucial features of the emitting firms and the structure of the market, while maintaining the simplest experimental setup possible. In each auction market, there were six participating firms (each represented by one subject) competing for subsidies for emissions reduction. This experiment introduced asymmetries by requiring some firms to obtain additional production capacities different than other firms in the same market. Specifically, the subjects were endowed with either 5 or 10 capacity units, which could be utilized to produce identical products sold at a given price (subjects knew that this product price was identical for all firms, and they also knew that all products could be sold to the experimenter at this price). In addition, this experimental design applied an asymmetric emissions structure by creating high emitters and low emitters. High emitters are firms with small production capacity that require two emission units to operate one unit of production capacity, and low emitters are firms with large production capacity that require one emission unit to produce one unit of production. The asymmetric size of the firms reflects the unbalanced structures of real firms, and the asymmetric emissions structure reflects the general picture that cleaner energy is more likely to be used for production by larger firms than by smaller ones (Burtraw et al., 2009).

[9] This background design is commonly utilized in experiments that investigate auction design for carbon emissions reduction programs (see, e.g., Burtraw et al., 2009; Burtraw et al., 2011; and Shobe et al., 2010).

This design did not allow the allocated portion of the subsidy to be banked; therefore, the production profit is equal to the difference between the product price and production cost without the subsidy. The bid for the subsidy is determined by the profit divided by the number of emissions units required to produce a unit of product. For example, at a production cost of 5 and a product price of 11, low emitters will bid for a subsidy greater than six, while high emitters will bid for a subsidy greater than three (= 6/2). The production costs for low emitters, approximately twice as high as for high emitters, reflect the higher costs associated with cleaner energy utilization. Cost asymmetry also acts as an equalizer to counteract the earnings differences across subjects from introducing asymmetric production capacity and per product emission. The costs for low emitters were randomly drawn from the interval [5, 10]; the costs for high emitters were randomly drawn from the interval [2, 6]. The costs are uniformly distributed within the intervals. The same uniform distribution of random cost draws, generated from a series of given random number seeds, was utilized to ensure that the random cost draws were balanced across treatments.

Given a fixed product price and unit product emissions, the distribution of costs determines a range of values for the subsidy for one emissions unit under which firms are indifferent between production and reduction of emission through ceasing production. These indifference values can be seen as firms' costs of emissions reduction. Because low emitters' costs are drawn from the range [5, 10], a product price of 11 will generate a range of indifference values for the subsidy between 1 (= 11 - 10) and 6 (= 11 - 5). High emitters' indifference values for the subsidy are obtained by dividing the marginal benefit by the required number of emissions units (2); the indifference values are distributed evenly between 2.5 [= (11 - 6)/2] and 4.5 [= (11 - 2)/2]. This parameter design maintains the same average indifference values for the subsidy for both the low and high emitters. The total subsidy in each period of auction market is 100, which guarantees a rather tight competitive environment because most firms cannot sell their reduction capacity.[10] Emissions reductions must be achieved in the current period; there was no secondary market for trading the reduction, and communication between bidders was not allowed.

[10] If the highest (lowest) production costs are drawn for both low and high emitters, the total subsidy needed for all firms to sell their emissions reduction at their costs is 105 (315) yuan; therefore, the actual amount is in the interval [105, 315], depending on the revealed production costs. This tight limitation of the available subsidy reflects real budget constraints.

4.2. Procedure

Upon arrival, written instructions for either low or high emitters were randomly disseminated to all subjects. (The instructions are included in the appendix.) The two versions of the instructions differed only in the information about their firms' emission type and production capacity, while all remaining information was identical. Each subject knew only the parameters of his own firm. Subjects were given 15 minutes to read the instructions, and the experimenters were prepared to answer questions. All three treatments followed the same procedures, except for the execution of the auction. The instructions indicated some of the basic strategic considerations inherent in the auctions, and examples of how the auctions functioned were presented. In each auction, subjects had the incentive to sell their reduction capacity for a price no less than their reduction cost. Subjects were given the rational rule that a firm's entire 10 emissions units would be automatically reduced in exchange for the subsidy if the auction was won with a transaction price no less than its indifference value; the production profit would be paid otherwise. That is, each subject's experimental payoff is either the profit from production or the subsidy from selling all emissions units. Given the rules of the Maskin mechanism, if the remaining subsidy is insufficient to pay for the entire 10 emissions units of a firm, it will not be paid to a firm (i.e., this firm's bid will be rejected). We implemented this additional rule for all auctions to maintain comparability across the three auction mechanisms. Bids in all auctions were restricted to not exceed a pre-announced reserve price, 10 yuan, and to multiples of 0.1 currency unit.

After reading the instructions, all subjects were required to solve control questions about their firm's indifference values for the subsidy, the number of winners, the transaction price, the gains from winning an auction compared to continuing production, etc., to ensure full understanding of the auction rules and consequences of their bidding behavior. The formal auction did not begin until all subjects had solved the questions correctly. Subjects then participated in 20 periods of auctions in which they bid for the carbon emissions reduction subsidy.[11] At the end of each period, information about bids, transaction prices, the number of winning firms, and own income were announced without revealing the identities of the bidders.[12] The repetition of a task provides subjects with the opportunity to learn.[13]

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[11] The repeated auction game allows us to discover how the firms learn and adjust their bidding behavior.

[12] As noted by Burtraw et al. (2011), revealing information about others' bids might enhance price discovery and learning, while revealing information about particular bids during the auction could facilitate collusion. From the focus group and pilot studies of this experiment, we found that learning was not easy and collusion was not observed even when information was revealed. This pattern may be due to the limited total subsidy in our context. We thus provided the aforementioned information while maintaining anonymity in our experiment.

[13] However, learning was more difficult with the varying cost across auctions in each session; therefore, compared to constant cost across all auctions in a session, this experiment will present the lower bounds of learned bidding behavior.

The experiment was conducted using z-Tree (Fischbacher, 2007) in the experimental laboratory at Beijing Normal University in 2012. This university, located in the center of Beijing, has approximately 20,000 full-time students. The subjects were recruited via announcements on the bulletin board system (BBS). All subjects were allowed to participate in only one session, and subjects did not know about the treatments in which they did not participate. To maintain anonymity about the outcome of the experiment, subjects were informed at the beginning that they would be paid confidentially and individually. Final earnings from the experiment were the sum of the period payoffs in addition to a show-up fee of 10 yuan. The experiment lasted, on average, approximately 90 minutes. The subjects earned an average of 74 yuan[14] in cash inclusive of the show-up fee. The entire nine-session experiment, as depicted in Table 2, was performed within a three-day period. This short period minimized the potential for shared information among incoming subjects. We also balanced the time of day in which the sessions for each treatment were conducted.

5. Experimental results

5.1. Descriptive statistics

In total, 216 subjects participated voluntarily in this experiment, 72 for each treatment. Table 2 reports the main characteristics of the experiment sessions. Given that every set of six subjects constitutes an auction market for 20 periods, in each treatment, we observed 240 auction markets (12 independent markets for 20 periods) and 1440 bids (6 bids in each auction market).

In the treatments of uniform-price and Maskin auctions, there was a uniform transaction price in each market, while more than one transaction price could exist in discriminatory auctions. We calculate the mean transaction price for each auction market in the discriminatory auctions and obtain 240 uniform transaction prices for the 240 markets in each of the three treatments. For a firm, the indifference price for selling an emissions unit is equal to the difference between the product price and the production cost divided by the number of emissions units needed to produce one unit of product. We construct performance measures for the auction mechanisms from three aspects. First, we include the bid, the transaction price, and some measures based on bid and price, such as the difference between the winner's bid and the winner's indifference price and the difference between the winner's transaction price and the winner's bid. Second, the total subsidy budget spent in each auction and the total emissions reduction from a single auction were included. Third, we considered

[14] $1 = 6.32 yuan at the time of the experiment.

individual firm characteristics, including firm's total profit and the winning firm's extra profit from winning an auction in addition to the profit earned from products sold without emissions reduction. The definition of each performance measure is introduced in Table 3.

In Table 3, we provide the descriptive statistics for various performance variables for each of the three treatments. Because all statistics are calculated utilizing the market means of the variables across all 20 auction periods, as well as across the first 5 and the last 5 periods, there are 12 observations corresponding to 12 markets in each treatment.[15] These statistics indicate that bids are highest and transaction prices are lowest in discriminatory auctions. The emissions reduction volume and total subsidy spent are highest in Maskin auctions. The firms' profits and winners' extra profits are highest in Maskin auctions. Nevertheless, further analysis is needed to verify the significance of these differences.

The following figures compare the trends of some performance variables across periods within and across each treatment. The values of the performance variables are presented on the vertical axis, and the number of periods is presented on the horizontal axis. The left panel of Figure 1 indicates that bids in discriminatory auctions are no lower than those in uniform-price and Maskin auctions in all periods except Period 5, while there is almost no difference in bids between uniform-price and Maskin auctions across periods. The winners' bids (right panel) are apparently highest in discriminatory auctions, while the differences in winners' bids for the remaining two types of auctions are small.

Figure 2 indicates that the differences in the winner's indifference prices and the differences in transaction prices between any two treatments are small; however, the transaction price is highest in Maskin auctions and lowest in discriminatory auctions.[16] Transaction prices are considerably higher than the winner's indifference price in all three treatments, illustrating that bidders earned extra profits by winning the auctions. The transaction price is related to the winner's bid, i.e., it equals the winner's bid in discriminatory auctions, whereas it is no less than the winner's bid in uniform-price and Maskin auctions. These differences can be decomposed into two parts, i.e., the difference between the winner's bid and the winner's indifference price, as well as the difference between the transaction price and the winner's bid. The first part measures the price discovery ability of an auction

[15] Because bidders' bidding behavior depends on the other bidders' bids in previous periods in the same markets, observations based on individual bidders are not independent. Only the observations based on the mean of all bids in one auction market across all periods are independent, and we will utilize this statistic for the nonparametric tests.

[16] The rules in Maskin auctions guarantee transaction prices no higher than those in uniform-price auctions if all bids are the same in both auctions, but we observe higher transaction prices in Maskin auctions. This phenomenon suggests that the function of Maskin auctions in suppressing the transaction price is dominated by its effects on increasing bids.

mechanism, while the second part describes the money paid in addition to the bids to provide the incentive to bid at cost.

The two aforementioned differences over time are reported in Figure 3. We observe from the left panel that the difference between the winner's bids and indifference prices is considerably larger in discriminatory auctions than that in uniform-price and Maskin auctions, and this difference in uniform-price and Maskin auctions declines slightly across periods. The figure indicates that, compared to discriminatory auctions, uniform-price and Maskin auctions play a much stronger role in preventing high bids from winning auctions. Therefore, the winner(s) in uniform-price and Maskin auctions is (are) more likely to have lower costs of emissions reduction than those in discriminatory auctions. The right panel indicates that the transaction price equals the winner's bid in discriminatory auctions, whereas the transaction price is considerably higher than the winner's bid in uniform-price and Maskin auctions. Comparing the two panels in Figure 3 suggests that the effects of uniform-price and Maskin mechanisms on reducing the winner's bid are dominated by the increase that the two mechanisms exert on the transaction price from the winner's bid.

The correlations between firms' indifference price and bid for each mechanism are displayed in Figure 4. The size of the bubble reflects the frequency of the observation that lies in the center of the bubble. Many observations adhere closely to the forty-five degree line, indicating that many subjects bid their cost. Nevertheless, the left panel suggests that a considerable number of bidders with low indifference prices bid above their indifference price in discriminatory auctions. Given that bidders with low indifference prices are likely to win, the left panel provides an interpretation of why the winners' bids in discriminatory auctions deviate from the indifference prices displayed in Figure 3.

The time trends for the total subsidy spent and the total emissions reduction are displayed in Figure 5. Both measures are highest in Maskin auctions, indicating that both budget utilization and total emissions reduction are maximized in Maskin auctions. In all types of auctions, both measures increase slightly over time, which indicates that bidders learned and adjusted their behavior with repeated auctions. Maskin auctions exhibit the strongest increasing trend.

The time trends for firm profits and extra profits are presented in Figure 6. Both variables are lowest in discriminatory auctions, and they are higher in uniform-price and Maskin auctions. However, these differences seem to diminish with repeated auctions. The right panel of Figure 5 and left panel of Figure 6 indicate that the Maskin mechanism produced a win-win situation in which firms received the highest profit and the largest total emissions reduction was achieved within a fixed subsidy budget.

5.2. Nonparametric tests

We conduct nonparametric tests based on a single data point for each market across all periods. Table 4 reports the p-values of the tests for the hypothesis that there is no difference in distributions between any two auction mechanisms for each variable. The unit emissions reduction cost indicated by the transaction price is the highest in Maskin auctions, and the winners' extra profits are equally high in uniform-price and Maskin auctions. Both uniform-price and Maskin mechanisms result in significantly lower winning bids than the discriminatory mechanism. The uniform transaction price is higher than the winner's bid in uniform-price and Maskin auctions, while the transaction price equals the winner's bid in discriminatory auctions. With a fixed 100 yuan total budget for the subsidy, the Maskin mechanism maximizes the budget utilization and reduces the largest total amount of carbon emissions.

We then investigate the dynamics of auction performance by testing for significant differences in performance variables between earlier and later periods. Table 5 reports the results of the nonparametric tests for the hypothesis that the distributions are the same for the first five and last five periods for each mechanism and each variable. From the government's perspective, all performance indicators improve with repeated auctions. On the one hand, the bid, the winner's bid, the transaction price, the difference between winner's transaction price and winner's bid, the firm profit, and the winner's extra profit decline over time; on the other hand, the total subsidy spent and total emissions reduction increase over time. Compared to other auctions, most performance indicators for Maskin auctions exhibit the strongest tendency for improvement across periods.

The differences in performance indicators between high and low emitters are investigated in Table 6. Consistent and significant differences in winners' bids and transaction prices exist between high and low emitters in each mechanism, indicating that high emitters who win auctions gain more revenue than do low emission winners for all auctions. This gain narrows the overall profitability gap between the two types of firms, although low emitters continue to earn greater total profit and extra profits than do high emitters. Moreover, a larger proportion of low emitters win auctions in both discriminatory and uniform-price auctions; this advantage disappears in Maskin auctions. Significant differences in bids between the two types of firms can be observed in discriminatory and Maskin auctions; this difference disappears in uniform-price auctions.

5.3. Regression results

We further run random effects panel data regressions to consider that bidding behavior and auction outcomes in the same session are clustered at the market level with six bidders. We control for firm characteristics, such as emission type and emission reduction cost, and for the average learning effect across the 20 periods by introducing a period variable with values in the range 1-20.[17] Table 7 displays the regression results.

Compared to discriminatory auctions, both uniform-price and Maskin auctions have similar and significant effects on many performance indicators: these mechanisms reduce the bid, the winner’s bid, and the difference between the winner's bid and the winner's indifference price, while the transaction price, the difference between winner's transaction price and winner’s bid, and firm’s total and extra profit are increased. However, uniform-price auctions spend less of the subsidy budget and reduce fewer total emissions than do discriminatory auctions. Maskin auctions spend more of the subsidy budget than do discriminatory auctions and reduce total emissions as much as discriminatory auctions. These results together indicate that, compared to discriminatory mechanisms, both uniform-price and Maskin mechanisms outperform in price discovery but lead to higher emissions reduction costs. Comparing the results of the fourth and fifth regressions illustrates that the reduction in winner’s bids in uniform-price and Maskin mechanisms is dominated by the even larger increase in the transaction price of the winner’s bid. This result partially explains why the transaction prices in uniform-price and Maskin auctions are higher than the discriminatory auction price. The coefficients for “period” are highly significant across regressions, which suggests that all performance variables vary toward a particular direction as the auctions are repeated. This stable alteration tendency is due to bidder learning with repetition. The coefficients for firms’ indifference prices (the reduction cost) and emissions type are significant in most cases, which indicates that firms’ bidding behavior changes systematically with their characteristics.

We then examine the difference in all performance variables between uniform-price and Maskin auctions. The differences are caused by imposing an additional limitation on the conventional uniform-price transaction prices in the latter auctions. Table 8 reports the Wald test results. Compared to uniform-price auctions, Maskin auctions spend a greater portion of the subsidy budget and achieve higher total emissions reductions; however, this auction produces higher bids, winner’s bids and prices of emissions reduction, and pays more subsidies to winning firms. All these effects are significant and consistent with the results of the nonparametric tests.

[17] We also include an interaction of treatment variables by period in each of the models. However, this analysis does not support the existence of interaction effects.

6. Conclusions

The allocation of government-provided subsidies based on auctions in emissions reduction programs is an important alternative market instrument to manage greenhouse gas emissions reduction, in addition to auctioning tradable allowances, grandfathering (Burtraw and Palmer, 2008) and carbon taxes (Pearce, 1991; Metcalf, 2009). This type of instrument has been utilized in several countries, including the USA and UK, and has attracted increasing attention from policy makers in many other countries. Identifying and designing the most efficient auction mechanism that reduces the most emissions with a fixed subsidy budget is of interest to policy makers. Moreover, other performance indicators for the auction mechanisms, such as the cost of emissions reduction, the role in price discovery, and the dynamic alteration of performance for different mechanisms in the long run, are also important from the government's perspective.

Previous research mainly focuses on tradable emissions allowances, and these studies suggest that bidding behavior, transaction prices, and the amount of revenue raised under various auction mechanisms can be significantly different. In this paper, we compare the performance of discriminatory, uniform-price auction mechanisms and the mechanism recently proposed by Maskin (2011) in an experiment allocating a fixed subsidy for emissions reduction. Consistent with previous studies, our experiment provides a clear demonstration that the performance of different mechanisms differs significantly depending on institutional setting (see, e.g., Binmore and Klemperer, 2002; Shachat and Swarthout, 2010). Specifically, compared to the discriminatory mechanism, both uniform-price and Maskin mechanisms perform better in terms of price discovery, but they lead to a higher cost per unit of emissions reduction. Moreover, the Maskin mechanism allocates a greater proportion of the subsidy budget and achieves greater total emissions reductions, but leads to higher bids and transaction prices of emissions reduction than does the uniform-price mechanism. Discriminatory and Maskin mechanisms achieve higher total emissions reductions than the uniform-price mechanism. For all mechanisms, many performance indicators gradually improve with repetition of the auctions, and the strongest improvement tendency is observed in the Maskin mechanism.

For the sake of simplicity, our experiment applied a constant marginal production cost for each firm; therefore, it is reasonable for a firm to cease production upon winning the auction to sell all its emissions with a higher value than that of production. Other situations, such as increasing marginal production costs or firms that sell only part of their emissions units, are worthy of future research.

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Tables and Figures

Table 1. Winner and transaction price determination rules in a Maskin auction

Case	Bid interval	Number of firms that bid in the interval	Number of firms selected to be paid	Payoff
1	[0, 10/2)	≤1	1	Min(10, 2nd-lowest bid)
2	[10/3, 10/2]	>1	2	Min(10/2, 3rd-lowest bid)
	[0, 10/3)	≤2		
3	[10/4, 10/3]	>2	3	Min(10/3, 4th-lowest bid)
	[0, 10/4)	≤3		
4	[10/5, 10/4]	>3	4	Min(10/4, 5th-lowest bid)
	[0, 10/5)	≤4		
5	[10/6, 10/5]	>4	5	Min(10/5, 6th-lowest bid)
	[0, 10/6)	≤5		
6	[10/7, 10/6]	>5	6	Min(10/6, 7th-lowest bid)
	[0, 10/7)	≤6		

Note：It is impossible to have more than five winners in each experimental market given the parameters imposed in this numerical example.

Table 2. Summary of experimental sessions

session	treatment	number of subjects	periods	maximum earnings	minimum earnings
1	discriminatory	24	20	89.28	66.16
2	uniform-price	24	20	88.88	65.84
3	Maskin	24	20	91.41	67.92
4	Maskin	24	20	82.32	67.15
5	discriminatory	24	20	80.08	65.44
6	uniform-price	24	20	81.04	65.44
7	uniform-price	24	20	82.16	68.24
8	Maskin	24	20	83.01	68.19
9	discriminatory	24	20	80.64	66.64

Table 3. Descriptive statistics of performance variables across various periods for each treatment (N=12 Obs.)

Performance variable	Description	Treatment	All 20 periods		The first 5 periods		The last 5 periods	
			Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Bid	= subject's bid in each auction (yuan)	*Discriminatory*	4.16	0.17	4.30	0.20	4.05	0.23
		Uniform-price	3.83	0.20	3.99	0.24	3.76	0.27
		Maskin	3.93	0.18	4.23	0.32	3.79	0.20
Winner's bid	= subject's bid that won each auction (yuan)	*Discriminatory*	3.34	0.09	3.42	0.18	3.29	0.08
		Uniform-price	2.56	0.15	2.71	0.31	2.51	0.23
		Maskin	2.72	0.14	2.88	0.31	2.66	0.13
Transaction price	= the mean or uniform transaction price in each auction (yuan)	*Discriminatory*	3.34	0.09	3.42	0.18	3.29	0.08
		Uniform-price	3.44	0.10	3.67	0.17	3.32	0.12
		Maskin	3.57	0.14	3.79	0.25	3.45	0.13
Difference between winner's bid and winner's indifference price [a]	= the difference between winner's bid and winner's indifference price (yuan)	*Discriminatory*	0.92	0.13	0.90	0.23	0.90	0.20
		Uniform-price	0.25	0.14	0.31	0.19	0.21	0.17
		Maskin	0.32	0.11	0.42	0.23	0.27	0.10
Difference between winner's transaction price and winner's bid	= the difference between winner's transaction price and winner's bid (yuan)	*Discriminatory*	0	0	0	0	0	0
		Uniform-price	0.89	0.15	0.96	0.26	0.80	0.22
		Maskin	0.85	0.21	0.91	0.24	0.80	0.19
Total subsidy spent	= the total amount spent by the government to purchase the total reduction volume in each auction (yuan)	*Discriminatory*	81.80	5.37	76.98	7.04	85.81	7.33
		Uniform-price	77.18	3.19	76.20	5.20	77.98	5.95
		Maskin	88.21	3.80	84.78	6.46	89.75	6.46
Total emissions reduction	= the total emissions reduction in each auction (unit)	*Discriminatory*	24.68	2.25	22.67	2.74	26.20	2.66
		Uniform-price	22.75	1.40	20.91	1.34	23.80	1.84
		Maskin	25.21	1.60	22.74	2.39	26.41	2.46
Firm's profit	= firm's net benefit from either selling its products or winning an auction (yuan)	*Discriminatory*	38.72	1.24	39.63	2.10	38.27	1.60
		Uniform-price	39.26	1.19	40.71	1.90	38.42	1.36
		Maskin	39.81	1.45	41.23	2.10	39.00	1.62
Winner's extra profit	= winner's mean extra profit in addition to production profit from winning the auction (yuan)	*Discriminatory*	9.17	1.29	8.99	2.32	8.97	2.00
		Uniform-price	11.32	1.35	12.67	2.64	10.17	2.05
		Maskin	11.69	1.58	13.27	2.05	10.64	1.94

Note: [a] The indifference price for selling an emissions reduction unit is equal to the difference between the product price and the production cost of the output reduced due to the reduction, divided by the number of emissions units needed for one unit of output.

Table 4. Results of nonparametric tests for differences between treatments over all periods

Performance variable	Differences in mean & test	Discriminatory vs. Uniform-price (T1-T2)	Discriminatory vs. Maskin (T1-T3)	Uniform-price vs. Maskin (T2-T3)
Bid	Differences in mean	0.32	0.23	-0.10
	Wilcoxon rank-sum test (p-value)	0.002***	0.008***	0.204
Winner's bid	Differences in mean	0.78	0.62	-0.16
	Wilcoxon rank-sum test (p-value)	<0.001***	<0.001***	0.013**
Transaction price	Differences in mean	-0.10	-0.23	-0.13
	Wilcoxon rank-sum test (p-value)	0.028**	<0.001***	0.028**
Difference between winner's bid and winner's indifference price	Differences in mean	0.67	0.60	-0.07
	Wilcoxon rank-sum test (p-value)	<0.001***	<0.001***	0.166
Difference between winner's transaction price and winner's bid	Differences in mean	-0.89	-0.85	0.03
	Wilcoxon rank-sum test (p-value)	<0.001***	<0.001***	0.488
Total subsidy spent	Differences in mean	4.62	-6.41	-11.03
	Wilcoxon rank-sum test (p-value)	0.024**	0.004***	<0.001***
Total emissions reduction	Differences in mean	1.93	-0.52	-2.45
	Wilcoxon rank-sum test (p-value)	0.024**	0.561	0.001***
Emission reduction per unit subsidy	Differences in mean	0.004	0.02	0.01
	Wilcoxon rank-sum test (p-value)	0.299	0.001***	0.008***
Winner's subsidy	Differences in mean	-1.02	-2.29	-1.27
	Wilcoxon rank-sum test (p-value)	0.028**	<0.001***	0.028**
Firm's profit	Differences in mean	-0.54	-1.09	-0.55
	Wilcoxon rank-sum test (p-value)	0.326	0.094*	0.453
Winner's extra profit	Differences in mean	-2.15	-2.53	-0.38
	Wilcoxon rank-sum test (p-value)	0.002***	<0.001***	0.419

Note: *** p<0.01, ** p<0.05, * p<0.1.

Table 5. Results of nonparametric tests for differences between the first and last 5 periods

Performance variable	Treatment	Difference in mean	Wilcoxon signed rank test (p-value)
Bid	*Discriminatory*	0.24	0.002***
	Uniform-price	0.23	0.010**
	Maskin	0.45	0.003***
Winner's bid	*Discriminatory*	0.13	0.028**
	Uniform-price	0.20	0.071*
	Maskin	0.22	0.034**
Transaction price	*Discriminatory*	0.13	0.028**
	Uniform-price	0.35	0.002***
	Maskin	0.34	0.002***
Difference between winner's bid and winner's indifference price	*Discriminatory*	0.00	0.844
	Uniform-price	0.09	0.084*
	Maskin	0.15	0.060*
Difference between winner's transaction price and winner's bid	*Discriminatory*	0.00	1.000
	Uniform-price	0.16	0.158
	Maskin	0.11	0.050*
Total subsidy spent	*Discriminatory*	-8.83	0.008***
	Uniform-price	-1.78	0.480
	Maskin	-4.97	0.117
Total emissions reduction	*Discriminatory*	-3.53	0.003***
	Uniform-price	-2.89	0.004***
	Maskin	-3.68	0.007***
Firm's profit	*Discriminatory*	1.36	0.034**
	Uniform-price	2.29	0.002***
	Maskin	2.22	0.004***
Winner's extra profit	*Discriminatory*	0.02	0.844
	Uniform-price	2.50	0.008***
	Maskin	2.62	0.008***

Note: *** p<0.01, ** p<0.05, * p<0.1.

Table 6. Descriptive statistics of performance variables for high and low emitters

Performance variable	High emitter			Low emitter			Difference in mean	Wilcoxon rank-sum test (P-value)
	Obs	Mean	Std. Dev.	Obs	Mean	Std. Dev.		
Treatment 1 (Discriminatory)								
Bid	720	3.98	0.85	720	4.33	1.27	-0.35	0.046**
Winner's bid	266	3.42	0.31	307	3.25	0.27	0.17	<0.001***
Transaction price	266	3.42	0.31	307	3.25	0.27	0.17	<0.001***
Firm's profit	720	37.01	5.38	720	40.43	12.20	-3.42	0.003***
Winner's extra profit	266	4.86	2.83	307	12.74	7.74	-7.88	<0.001***
Proportion of winners[a]	720	0.37	0.48	720	0.43	0.49	-0.06	0.027**
Treatment 2 (Uniform-price)								
Bid	720	3.77	1.06	720	3.89	1.85	-0.12	0.783
Winner's bid	232	3.00	0.50	297	2.20	0.78	0.80	<0.001***
Transaction price	232	3.56	0.55	297	3.34	0.47	0.21	<0.001***
Firm's profit	720	37.33	5.82	720	41.20	11.50	-3.87	<0.001***
Winner's extra profit	232	6.55	4.98	297	15.02	8.16	-8.48	<0.001***
Proportion of winners	720	0.32	0.47	720	0.41	0.49	-0.09	<0.001***
Treatment 3 (Maskin)								
Bid	720	3.75	0.90	720	4.11	1.92	-0.36	0.018
Winner's bid	284	3.05	0.48	299	2.40	0.77	0.65	<0.001***
Transaction price	284	3.62	0.49	299	3.51	0.42	0.12	0.012**
Firm's profit	720	38.04	5.25	720	41.58	11.49	-3.54	<0.001***
Winner's extra profit	284	7.16	4.90	299	15.86	8.33	-8.70	<0.001***
Proportion of winners	720	0.39	0.49	720	0.42	0.49	-0.02	0.421

Notes: [a] The proportion of winners is equal to the number of winners divided by the number of bidders.
*** p<0.01, ** p<0.05, * p<0.1.

Table 7. Results for random effect OLS regressions for various performance variables

Dependent Variable	Bid	Winner's bid	Transaction price	Difference between winner's bid and winner's indifference price	Difference between winner's transaction price and winner's bid	Total subsidy spent	Total emissions reduction	Firm's profit	Winner's extra profit
Treatment2 (Uniform-price)	-0.324***	-0.694***	0.126***	-0.694***	0.821***	-4.724***	-2.093***	0.540**	1.265***
	(0.0545)	(0.0442)	(0.0383)	(0.0442)	(0.0357)	(1.752)	(0.738)	(0.224)	(0.383)
Treatment3 (Maskin)	-0.225***	-0.575***	0.235***	-0.575***	0.811***	6.281***	0.458	1.091***	2.354***
	(0.0422)	(0.0432)	(0.0476)	(0.0432)	(0.0524)	(1.847)	(0.781)	(0.261)	(0.476)
Period	-0.00888***	-0.00752***	-0.0143***	-0.00752***	-0.00700***	0.300***	0.188***	-0.0413***	-0.143***
	(0.00206)	(0.00201)	(0.00221)	(0.00201)	(0.00238)	(0.0942)	(0.0288)	(0.0107)	(0.0221)
Indifference price	0.875***	0.586***	0.222***	-0.414***	-0.364***	0.129	-1.116***	6.027***	-7.779***
	(0.0300)	(0.0528)	(0.0160)	(0.0528)	(0.0494)	(0.360)	(0.103)	(0.0900)	(0.160)
Firm with low emissions	0.295***	0.0665**	0.0609**	0.0665**	-0.00531			3.742***	0.609**
	(0.0465)	(0.0290)	(0.0251)	(0.0290)	(0.0348)			(0.148)	(0.251)
Constant	1.029***	1.956***	2.918***	1.956***	0.966***	78.52***	25.47***	16.12***	29.18***
	(0.108)	(0.137)	(0.0551)	(0.137)	(0.135)	(1.949)	(0.773)	(0.356)	(0.551)
Observations	4,320	1,685	1,685	1,685	1,685	1,685	1,685	4,320	1,685
Number of subjects	216	216	216	216	216	216	216	216	216
R-square	0.719	0.670	0.239	0.571	0.520	0.125	0.128	0.771	0.763
F test	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Notes: 1. Standard errors in parentheses; 2. *** p<0.01, ** p<0.05, * p<0.1.

Table 8. P-value of Wald tests for the performance differences between uniform-price and Maskin auctions based on regression results

Performance variable	P-value (H_0: Uniform-price = Maskin)
Bid	0.066*
Winner's bid	0.012**
Transaction price	0.022**
Difference between winner's bid and winner's indifference price	0.012**
Difference between winner's transaction price and winner's bid	0.883
Total subsidy spent	<0.001***
Total emissions reduction	<0.001***
Firm's profit	0.040**
Winner's extra profit	0.022**

Notes: *** p<0.01, ** p<0.05, * p<0.1.

Figure 1. Bids and winners' bids across periods

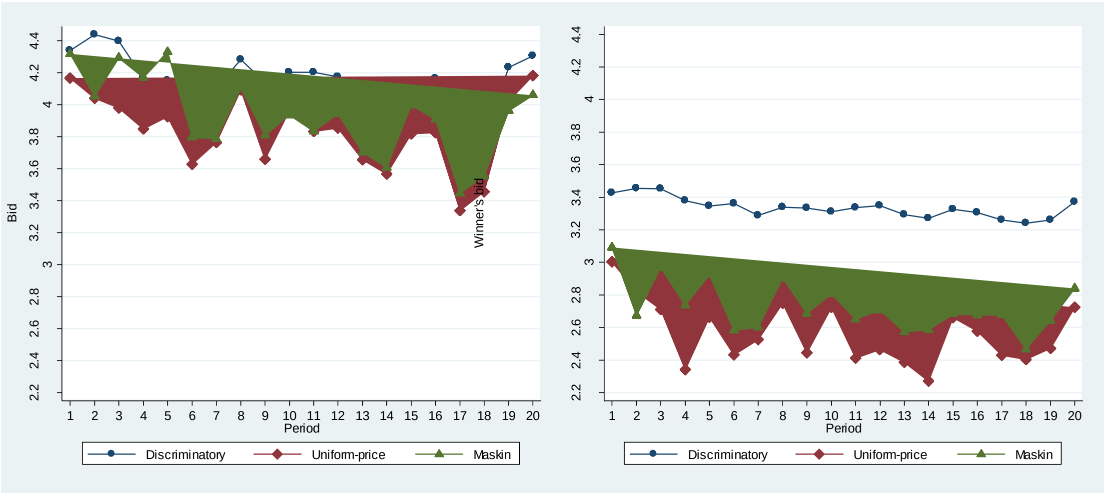


Figure 2. Winner's indifference price and transaction price

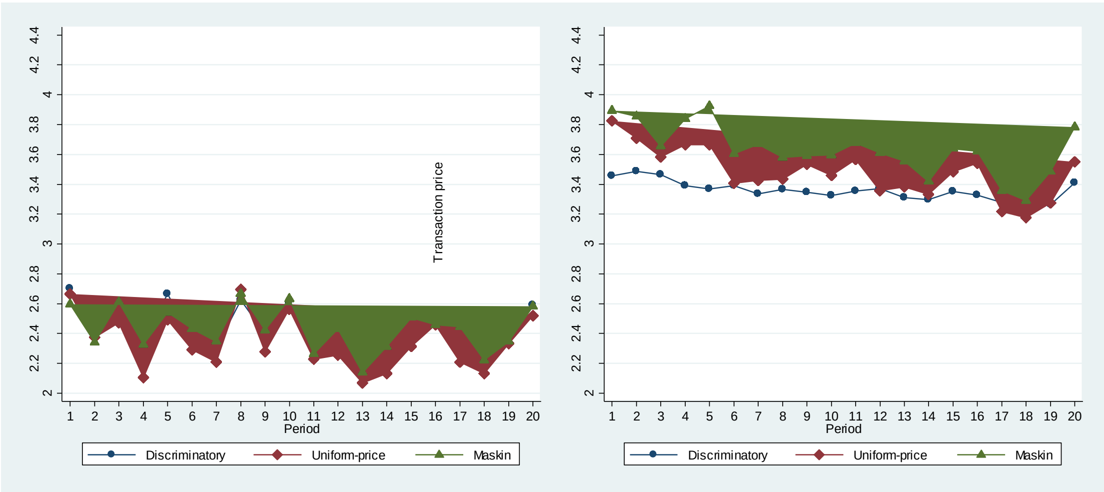


Figure 3. Differences between the winner's indifference prices, bids and transaction prices across periods

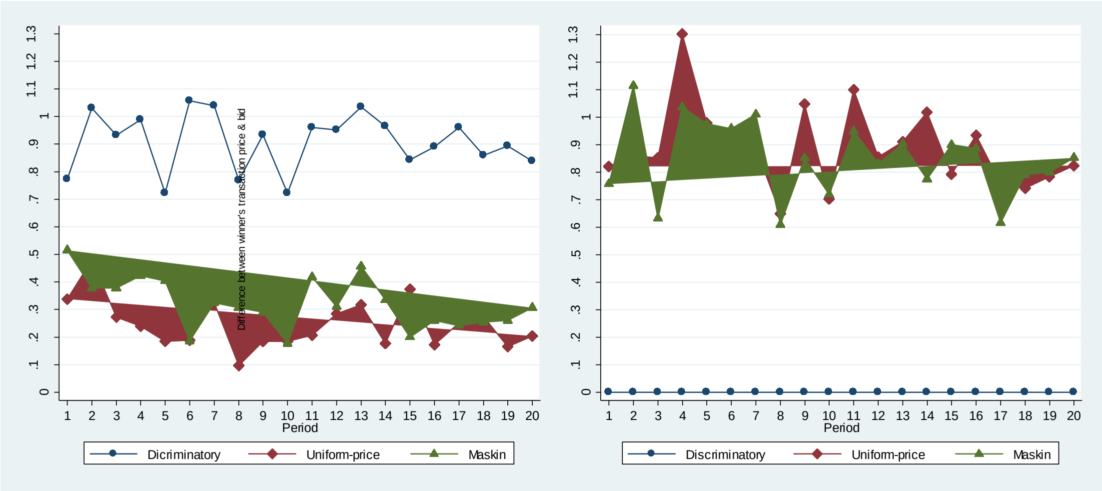


Figure 4. Correlations between firm's indifference price and bid

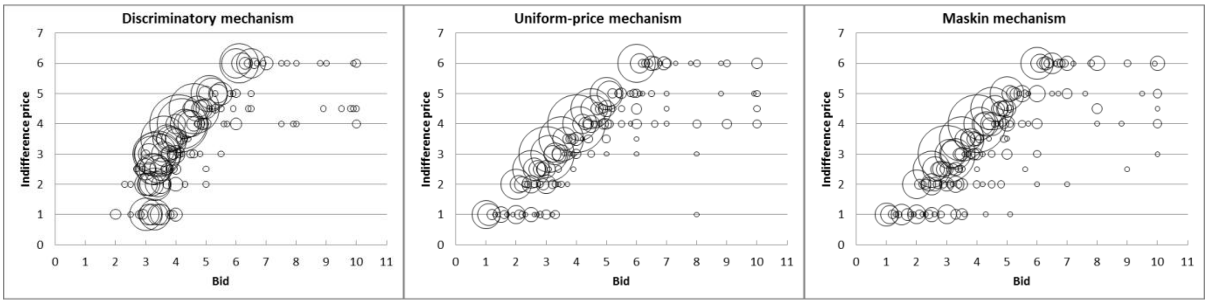


Figure 5. Total subsidy spent and total emissions reduction across periods

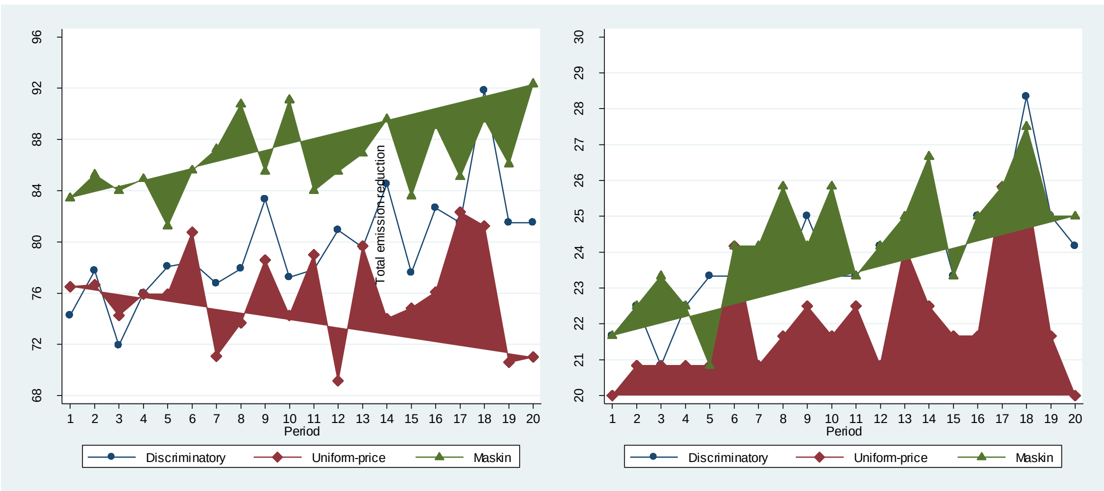
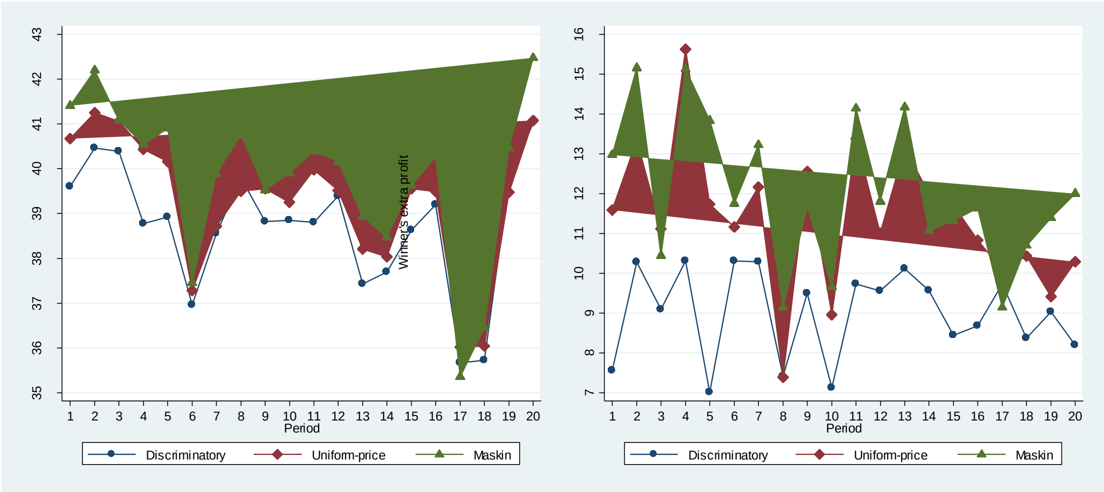


Figure 6. Firms' profits and winners' extra profits across periods



Appendix: Instructions

You seat number is ______. Please sit at the corresponding desk.

Instructions

(Originally in Chinese)

In this experiment, a given amount of government-provided subsidies will be allocated to firms via auctioning. There will be 6 production firms taking part in the auction market. You will act as a decision-maker of one of the firms, and you will bid for the subsidy. You may earn a significant amount of money if you understand these instructions and make good bidding decisions. How much you can earn depends on both your and other participants' decisions. There will be multiple rounds of auctions.

Background information of the firms

Production capacity: Your firm will be given a number of capacity units. Each capacity unit can be transferred to one unit of the product via production, and the product can be sold to obtain profit. The price of the product and its production cost will be revealed later, and the product's profit will be the price of the product minus its cost.

Therefore, the lowest payoff you can obtain is the product's profit from operating the capacity to produce the product. (You can always obtain a payoff from selling the products to the experimenters at a certain price)

Product price: All firms produce identical products and the price of all products is identical.

Randomly assigned product cost: Product costs are randomly determined in a certain range, and the costs differ from one firm to another. New random costs are determined for each firm at the beginning of each new auction.

Product-emission unit: Production will generate carbon dioxide emissions ("carbon emissions" hereafter). You will know the emission unit that your firm will generate from producing one product.

Carbon-emission-reduction subsidy: To reduce carbon emissions, the government will provide a given amount of budget to subsidize firms that reduce their carbon emissions. Each firm can reduce its carbon emissions by reducing its product outputs such that it can obtain the government-provided subsidy by selling its emission-reduction units.

Auction markets for allocating carbon emission reduction subsidies:

Total subsidy budget: There is a budget of 100 yuan of government-provided subsidies that will be used to purchase firms' carbon-emission-reduction units. Each firm will participate as one bidder in an auction market for the allocation of subsidies. In this auction market, the government will purchase all carbon-reduction units from bidders based on their bids (bids are the price at which firms are willing to sell their reduction units) from low to high, until the 100-yuan budget is depleted.

Types of firms: In total, there are six firms, including your firm, participating in each auction market; where three firms are high emitters requiring two emission units to operate each capacity unit, and the other three firms are low emitters requiring one emission unit to operate each capacity unit. The total emission capacity of a firm is the product of product emission units and production capacity.

Rules for bidding: Each bidder can bid only for a single price for all its emission units. The price for selling an emission unit should be no lower than the unit emission value (the "unit emission value" is equal to the profit from selling products that are produced using one emission unit) such that you can obtain a higher profit from winning the auction than from producing and selling products. You may lose money when winning if you bid for selling emission units at prices that are lower than the unit emission value. In contrast, you may not be able to win an auction if you bid too high. The minimum increment for your bid is 0.1 yuan.

Bid limits: The upper bidding limit for an emission unit is 10 yuan; thus, you cannot bid higher than this bid limit.

Experimental payoff:

1. If you win an auction with a bid no lower than the unit emission value, you will earn a higher profit than from producing and selling products. Thus, you must completely stop production to reduce all your emissions and earn the maximum payoff. When winning an auction, your experimental payoff is specified as follows:

   Profit of winning an auction = Transaction price × Total emission capacity

2. If you do not win an auction with a bid no lower than the unit emission value, you will not need to reduce emissions. Thus, you must produce products using all your production capacity to earn the maximum payoff. When not winning an auction, your experimental payoff is specified as follows:

   Profit of not winning an auction = (Product price - Product cost) × Production capacity

Notes: Your bid for emission units will affect whether you can win an auction and how much subsidy payoff you can obtain from the auction market. If you win an auction, you will have to stop production and sell all your emission units. Thus, as a winning bidder, you have to give up the profit from production to obtain the payoff from selling all your emission units in the auction market. <u>If you bid properly, you can always guarantee that your payoff from winning an auction is no lower than your profit from producing and selling products; therefore, you may obtain extra payoff by participating in an auction.</u>

<u>Detailed information about your firm</u>[18]

Your firm is a ***high/low* emitter** with the information below.

1. Your firm has *5/10* production capacities;
2. Each production capacity can produce one product, and the product price is 11 yuan;
3. The product cost is the same for all your products, and you will be informed about the randomly determined new product cost at the beginning of each auction.
4. The production of one product generates *2/1* units of carbon emission.
5. Thus, the unit emission value is equal to the product price minus product cost and then divided by carbon emission units per product; that is,
   Unit emission value = (product price - product cost) ÷ carbon emission units per product

Example:
Suppose that your firm's product cost is randomly determined as 3 yuan, and each product generated by each capacity unit can be sold at a price of 11 yuan; thus, the product profit is 8 yuan. If you are a high emitter, the production of one product generates two units of carbon emission; therefore, the production profit lost from reducing one unit of carbon emission is four yuan. That is, your firm's unit emission value is four yuan.

If you cannot sell your emission units in the subsidy auction market, you can use these units to produce products and obtain production profit. However, if you can sell your emission units at a price no lower than four yuan, you may obtain a higher profit by stopping production. The difference between the selling price of one emission reduction unit in the auction market and the unit emission value is the extra payoff you can obtain.

18 In this part, each type of firm was only able to see the parameters of their own type, which are in *italics* in the instructions.

Auction rules

Winner and transaction price determination: When all bids are collected and ranked from low to high, the specific rules for determining the winner(s) and the transaction price are shown in the table below. The winner(s) will be the one bidder or a few of the bidders with the lowest bid(s). When using the rules to determine the winner(s) and the transaction price, one should compare the actual situation of bids and number of bidders with the conditions stated in the five scenarios shown in the table with the order from Scenario 1 to Scenario 5. Any actual situation will satisfy one and only one of the five scenarios. The winner(s) and the transaction price will then be determined by the conditions stated in that scenario.

Winner and transaction price determination rules in Maskin auction

Scenario	Condition	Number of winners	Transaction price
1	More than 0 bid belong to [0, ￥10] & no more than 1 bid belongs to [0, ￥5]	1	$min\{￥10, 2nd\ lowest\ price\}$
2	More than 1 bid belong to [0, ￥5] & no more than 2 bids belong to [0, ￥3.3]	2	$min\{￥5, 3rd\ lowest\ price\}$
3	More than 2 bids belong to [0, ￥3.3] & no more than 3 bids belong to [0, ￥2.5]	3	$min\{￥3.3, 4th\ lowest\ price\}$
4	More than 3 bids belong to [0, ￥2.5] & no more than 4 bids belong to [0, ￥2]	4	$min\{￥2.5, 5th\ lowest\ price\}$
5	More than 4 bids belong to [0, ￥2] & no more than 5 bids belong to [0, ￥1.7]	5	$min\{￥2, 6th\ lowest\ price\}$

Please note that all winner(s) have to sell their emission units at the uniform transaction price specified by the scenario into which the actual situation falls. This price will be no lower than the winning bid(s).

Other rules:

1. In an auction market, each bidder can bid only once, and all bidders submit bids simultaneously. Thus, all bidders make their bids without knowing others' bids.
2. If two or more bidders bid at the same price but the subsidy budget is not enough for purchasing emission units from all of the bidders, only some of the bidders will be selected by a random device as the winner(s). The unused subsidy budget will be withdrawn.
3. Uniform price: emissions from all winners in an auction will be purchased at the same price determined in one of the aforementioned scenarios. That is, there is no difference between the transaction prices of different winners.

Information about participating in multiple rounds of auction markets

The experiment consists of multiple rounds of the aforementioned auction markets. The round of auctions will not be announced in advance. The six bidders in each auction market will remain the same throughout all rounds. However, it is not possible to identify each other. Moreover, if you obtain a subsidy from the auction market, you must reduce your emission units immediately. The emission units cannot be "banked" from one round to the next. That is, to exchange subsidies in the auction market, you can reduce production only up to your production capacity in **each** round of auction.

Important earnings announcement

Your experimental payoff in each round is either a carbon emission reduction subsidy or a production profit. Your total payoff will be the accumulated payoff from all rounds. **Please note that your cash earnings will be 8% of your total payoff.** At the end of the experiment, your cash earnings plus the 10 yuan show-up fee will be immediately paid to you in cash in private in another room.