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Emissions Trading with Consignment Auctions

A Lab-In-the-Field Experiment

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Zhi Li, Da Zhang, and Xiliang Zhang*

Abstract

With a unique opportunity of recruiting hundreds of emissions trading system (ETS) participants in a series of lab-in-the-field experiments, we compare a revenue-neutral consignment auction (CA) with free allocation (grandfathering, GF hereafter) and a uniform price auction (UPA) as alternative permit allocation designs. In our setup, firms first receive their permits for free. Then, under the two auction mechanisms, they need to buy back a share of the permits, either with auction revenues returned to the firms in the primary market (CA) or not returned (UPA), followed by a spot (secondary) market for all mechanisms with the continuous double auction. We find that enforced permit transactions in the primary market induce a higher price, facilitating price discovery with lower volatility and more effective trading in the spot market. Both auctions reduce non-compliance compared with GF, because the auctions reduce both permit hoarding and risky over-selling in the spot market. Both CA and UPA help smaller polluting firms lower their profit risks. CA also helps large, cleaner firms increase profits. Our results provide insights on permit allocation designs when introducing an ETS, especially for developing countries that are pondering the balance between market efficiency and firms' cost burden.

Keywords: emissions trading, consignment auction, uniform price auction, grandfathering, spot market, price collar

JEL Codes: C92, D44, Q52, Q54, Q58

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that appear to influence the work reported in this paper.

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1. Introduction

Pricing carbon emissions is recognized as the center of climate mitigation policies. In 2021, the share of global greenhouse gas (GHG) emissions covered by carbon pricing, either in the form of carbon taxes or emissions trading systems (ETS), reached 21.5%, a significant increase compared to 15.1% in 2020 (World Bank, 2021). This increase was largely due to the launch of the world's largest ETS in China in July 2021. Currently, China's national ETS covers the power generation sector only, but this alone accounts for more than 7% of global GHG emissions. The coverage of China's national ETS is expected to expand to more energy-intensive sectors in the next few years, leading the policy practices of carbon pricing in developing countries.

The rules for permit allocation, as a key design feature affecting the acceptance and effectiveness of an ETS, have attracted much attention from policymakers, participating firms, and researchers alike. At the time of this writing, all the permits are allocated for free to participating firms in China's national ETS. This lessens the cost burdens but raises concerns of market trading efficiency due to thin markets or market power (Hahn and Noll, 1982; Hahn and Stavins, 2011). Although economists prefer auctions for their efficiency, revenue-raising capacity, and greater incentives for innovation (Cramton and Kerr, 2002), the higher cost burden on firms makes them less desirable politically, especially for developing countries that place much weight on economic growth. Therefore, a mechanism that can balance market efficiency and cost burden concerns is much needed.

As an extension of the classic uniform price auction (UPA), a hybrid auction mechanism called a consignment auction (CA) has been recently discussed as a promising solution. A consignment auction is a revenue-neutral auction (RNA), in which recipients of free allowances consign the allowances for sale into the market with revenues returning to their original owners. Burtraw and McCormack (2017) summarize the advantages of the consignment auction, which are especially important for newly established emissions trading schemes: it can facilitate price discovery and market liquidity, increase transparency and perceived fairness, and reduce trade barriers. The consignment auction was first used in the US for the sulfur dioxide (SO_2) trading program and is now used for carbon emissions permit trading in California's electricity sector. Busch et al. (2018) argue that the consignment auction could be particularly attractive for China's policymakers because it is aligned with the output-based allocation in China's ETS. As an RNA, it can overcome some legal and institutional barriers and increase auctioned shares over traditional auction approaches.

Hahn and Noll (1982) were the first to propose a revenue-neutral auction (called a zero revenue auction) to design a tradable permits market for sulfur oxides emissions, based on the criteria of incentivizing sufficient transactions to provide a clear price signal, avoiding market power or manipulations, and maintaining political feasibility. However, the theoretical literature on consignment auctions is relatively small. An early study by Güler et al. (1994) discussed a "zero-out" auction with descriptive theoretical models and lab experiments. A growing strand of literature focuses on revenue refunding rules in the context of environmental regulation (Gersbach and Requate, 2004; Montero, 2008; Bandyopadhyay, 2011; Gersbach and Winkler, 2011). The two most recent studies directly focused on consignment auctions are Khezr and MacKenzie (2018) and Liu and Tan (2021). Khezr and MacKenzie (2018) find that firms' equilibrium strategy under CA is to buy back their consigned allocation and that payoffs are independent of the auction clearing price – i.e., no price signal emerges from the CA if firms have a constant marginal value for permits. However, Liu and Tan (2021) find a higher equilibrium price in a consignment auction than in a uniform-price auction when firms have (strictly) decreasing marginal values for permits, but the ex-post efficiency ranking of the two auctions is ambiguous.

In terms of experimental evidence, Franciosi et al. (1993) provide experimental support for the equivalence between the Hahn-Noll RNA and a no-rebate uniform price auction in terms of prices and market efficiencies, but not in the distribution of the gains or the propensity for overbidding. Ledyard and Szakaly-Moore (1994) find that a continuous double-auction (called a multiple-unit double auction) outperforms the RNA by generating higher and stable prices and efficiency levels. In a recent study, Dormady and Healy (2019) compare CA and UPA in a short-run auction experiment where firms cannot adjust pollution outputs or abatements in response to permit prices. They find that CA results in significantly higher auction-clearing prices but inefficient allocations, such that some firms hold excess permits while others with too few permits pay non-compliance penalties. These mixed experimental results could be attributed to their different experimental setup. Franciosi et al. (1993) compare CA and UPA, while Ledyard and Szakaly-Moore (1994) compare CA with the continuous double auction, both of which have a schedule of different permit values induced in their experiments. In Dormady and Healy (2019), marginal values for permits in equilibrium are either 0 for firms with sufficient permits or equal to the non-compliance penalty for firms with permit deficits.

A key element that is present in real-world ETS but missing in the existing literature is the spot market that usually follows the primary market of the initial permit allocation. The spot market allows firms to trade with each other. Note that one of the main motivations for introducing the consignment auction noted by Hahn and Noll (1982) is to initialize the market such that a price signal can be produced to facilitate more frequent and effective trading later on in the spot market. Without including a spot market, the comparison between different mechanisms is incomplete or even biased. Therefore, one key component in our experimental design is incorporating a spot market following the initial allocation of permits.

Our research objective in this paper is two-fold. First, this research aims to fill a gap in the experimental literature by evaluating the overall performance of consignment auctions in terms of price signals and market efficiency, compared to the existing popular mechanisms for initial permit allocation. The second objective is to provide a testbed of ETS with policy implications, especially for developing countries that want to balance market efficiency and cost burden concerns. To achieve the two objectives, we have included the following key features in our experimental design, in addition to incorporating a spot market. First, permit banking is allowed, i.e., unused permits for earlier compliance periods can be used for the next period. As noted by Dormady and Healy (2019), banking and spot markets could mitigate the inefficiencies of consignment in the primary market, but have not been tested in the literature. Second, we include a price collar – a combination of a price floor and a price ceiling. Holt and Shobe (2016) showed experimentally that a price collar is crucial in preserving market stability, and Wang et al. (2021) explored practical issues and potential welfare improvements associated with incorporating price limits through consignment auctions.

Combining the novel features discussed above, we conduct a large-scale lab-in-the-field experiment based on a unique opportunity of recruiting hundreds of potential participants in China's ETS as subjects. The subjects were power plant managers. The experiments were conducted during training for ETS implementation, and the participants were incentivized in the experiments with potential career advancement. We compare the impacts of permit allocation under a consignment auction with grandfathering (GF, free allocation) and UPA. We analyze their performance in terms of price signals, trading volumes and liquidity, firm compliance behavior, and implications for firms' total net profits over trading.

The remainder of the paper is organized as follows: Section 2 introduces the experimental design and procedures. Section 3 discusses the experimental results. Section 4 investigates the underlying mechanisms. Section 5 concludes.

2. Experimental Design and Implementation

2.1 Emissions Permit Trading

A complete emissions permit trading process in our experiment consists of three stages. The first stage is defined as the primary market. In this stage, firms (permit users) initially receive permits for free, based on a benchmark emissions intensity and their outputs. A pre-determined portion of their permits is automatically collected by a third party and pooled together, and then auctioned back to all firms. After the primary market, firms enter a spot market, i.e., the second stage, where they can trade permits directly with each other. The third stage involves compliance, during which permit holdings are compared with total emissions for each firm. Firms need to pay fines (at a pre-determined permit price) for permit deficits if emissions are greater than their permit holdings.

We compare three mechanisms for the allocation of emissions permits in the first stage as different treatments in our experiment: consignment auction (CA), uniform price auction (UPA, or auction), and grandfathering (GF). GF is used as a reference, where firms receive permits for free and then enter the spot market directly; that is, there is no auction in the primary market under GF.

Under CA and UPA, firms need to buy permits through an auction before they can trade in the spot market. The auction used here is the uniform price sealed bid auction, in which firms place a bid by specifying a price and a quantity for permits to buy. When the total demand exceeds the supply, bids are ranked by price in descending order, with the associated quantity accumulated up to the supply of permits to be auctioned, at which the price is the auction clearing price. Permits are then awarded to all the winning bidders at this price. Firms with a higher bidding price have a higher priority to earn the permits until the supply is exhausted. When the total demand is less than the supply, the lowest bidding price is the auction clearing price. The revenue generated by auctioning off these permits is equal to the uniform auction-clearing price multiplied by the quantity of permits awarded.

CA and UPA differ in the allocation of the auction revenue. Under UPA, the revenue goes to the market maker or auctioneer. Firms bear the full cost of buying permits in the primary market, and unsold permits will not be returned to the firms. Under CA, however, the permits collected for auction are consigned by the firms – i.e., they are still owned by the firms in the sense that the revenue generated from the auction belongs to the firms. That is, the auction revenue will be fully returned to the firms. Each firm will receive a share that equals the ratio of their individually consigned permits to the total of consigned permits. If the demand is less than the supply, the unsold consigned permits will be returned to the firms in proportion to their consigned share of the total supply.

2.2 Experimental Setup

An emissions permit market in our experiment consists of 20 coal-fired power firms of ten types, categorized based on their power generation capacity and emission intensity. There are four levels of generation capacity (50, 300, 600, and 1,000 MW). The 300 MW firms have four levels of emission intensities, and the other three firms have two levels each. There are two identical firms in a market within each capacity-emissions type. Each firm is represented by one participant in the experiment.

The endowment for each firm is given by the product of its capacity, the hours of power generation (5000 hours), and the profit per unit output of electricity (0.1 yuan/kWh). In the experiment, the hours of power generation and the electricity unit profit are fixed and the same for all firms. Therefore, a firm's endowment is determined by its capacity.

The emissions from each firm equal the generated electricity multiplied by the emissions intensity (ton/MWh). The emissions permits initially allocated to firms equal the product of a firm's output and a pre-determined benchmark emissions intensity. Thus, the permit demand of each firm for compliance is equal to the firm's electricity output multiplied by the difference between the firm's emissions intensity and the benchmark intensity. In our setup, firms with smaller capacities of 50 MW and 300 MW have emissions intensities higher than the benchmark, while the larger firms (600 and 1000 MW) have emissions intensities lower than the benchmark. Because of this difference in intensities, the smaller firms are potential buyers of permits and the larger firms are potential sellers.

Each market lasts for three years (periods), with the benchmark intensity decreasing over the years to reflect more stringent policy requirements. In each year, firms go through the complete three-stage emissions permit trading process described above. Firms decide how to use permit trading to increase their total profits at the end of the three year period. Specifically, at the beginning of each year, firms learn their endowment, total emissions, permits received, emissions intensity, benchmark, and permit deficits after the consignment (if relevant). Then, firms enter the primary market to submit their bids under CA or UPA. Each firm can bid only once, and irrevocably. After all the firms place their bids, the market clears, and firms learn the auction clearing price and how many permits they have bought. Then, firms enter the spot market. Note that firms under GF directly enter the spot market without going through the primary market.

The continuous double auction is used for spot markets, where all firms can place buy orders (bids) or sell orders (asks) by specifying a price and a quantity for permits to trade at any time when the spot market is running. Firms can trade with each other by either submitting their own orders or taking orders posted by others. There are two sessions of spot markets with a short time break between them in each year, with each session lasting a fixed length of time. When the time for spot markets runs out, the quantity of permits that is equal to a firm's emissions will be deducted automatically from the firm's permit accounts for compliance. If a firm's permit holdings are insufficient to cover its emissions at this stage, the gap will be filled automatically by buying permits at a pre-determined high price as a fine for non-compliance. If a firm's permit holdings are greater than its emissions, the extra permits will be transferred to the next year. After compliance is ensured by the above method at the end of the third year, any remaining permits that a firm holds will be bought automatically by the auctioneer at a pre-determined price. Note that a price collar is used through all the primary and spot markets. A price collar is a combination of a price floor and a price ceiling, which are respectively the lower and upper bounds of prices that can be used in the uniform price auction and the continuous double auction.

2.3 Experimental Parameters and Implementation

We use a between-subject design to compare CA, UPA, and GF. In each session, subjects are randomly assigned to groups (markets) of 20 subjects. Each session has two rounds of three years (periods). In each round, subjects go through a complete permit trading process in the same market. Subjects are reshuffled among all session subjects over rounds. Before the first year in the first round, a year 0 was introduced as a practice period.

Table 1 provides the main experimental parameters at the firm level. Benchmark emissions intensities in the three years are 1.015, 0.985, and 0.955 ton/MWh, respectively. In each year, 10% of the permits initially allocated to firms are collected by the auctioneer as the supply in the primary market under CA and UPA. The lower and upper bounds of the price collar are 50 yuan/ton and 150 yuan/ton, and the prices posted need to be multiples of 10. The fine for each unit of permit deficits is 100 yuan/ton, and the price to buy back remaining permits at the end of the third year is 50 yuan/ton.

The subjects were mainly power plant managers, recruited from four ETS training sessions organized by the Ministry of Ecology and Environment of China and Tsinghua University in November and December 2019.[1] Participants in the organized training sessions were not paid.

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[1] Our experiment was designed as a session of a training program series organized by the Ministry of Ecology and Environment of China and Tsinghua University. Consent was obtained from all the participants to join all sessions of the training program.

They were incentivized in the experiment by their rankings based on their total earnings in the experimental currency among each of the ten types of firms in a session. Participants received different levels of certificates issued by Tsinghua University according to their ranking. The certificate represented their performance in the training, which could potentially affect their performance evaluations and promotions.

Table 1. Main experimental parameters

Firm type	Same in each year				Initial permits allocated		
	Capacity	Endowment	Emission	Emission intensity	Year 1	Year 2	Year 3
	MW	k-yuan	ton	ton/MWh	ton	ton	ton
1	50	25,000	300,000	1.2	253,750	258,990	251,220
2	50	25,000	275,000	1.1	253,750	258,990	251,220
3	300	150,000	1,650,000	1.1	1,522,500	1,553,940	1,507,322
4	300	150,000	1,575,000	1.05	1,522,500	1,553,940	1,507,322
5	300	150,000	1,500,000	1	1,522,500	1,553,940	1,507,322
6	300	150,000	1,425,000	0.95	1,522,500	1,553,940	1,507,322
7	600	300,000	2,730,000	0.91	3,045,000	2,877,990	2,791,650
8	600	300,000	2,700,000	0.9	3,045,000	2,877,990	2,791,650
9	1,000	500,000	4,400,000	0.88	5,075,000	4,796,650	4,652,751
10	1,000	500,000	4,350,000	0.87	5,075,000	4,796,650	4,652,751

Note: Benchmark emissions intensities in years 1-3 are 1.015, 0.985, and 0.955 ton/MWh, respectively. For each firm, the hours of power generation are 5,000, and the output (electricity) unit profit is 0.1 yuan/kWh.

All observations are over the three-year period. We had 179 participants for 13 market-level observations under CA, 71 participants for 6 market-level observations under UPA, and 72 participants for 6 market-level observations under GF, with a total of 25 markets and 500 observations of market-specific decisions.[2] All the experimental sessions were implemented on

[2] As noted, there were two rounds of three years in each session, within markets of full size of 20 subjects. Because some subjects participated in both rounds while others participated in only one round, the total number of participants is not a multiple of 20. Specifically under CA, among the 179 participating subjects, 98 subjects attended only one round, and 81 attended two rounds, generating 13 market-level observations in total. Under UPA and GF, 71 subjects (49 participating in two rounds and 22 in only one round) and 72 subjects (48 participating in two rounds and 24 in one round) generated another two sets of six market-level observations. Note that only markets that have a full set of 20 subjects are used in our analysis.

mobile phones. A Wechat applet, which is similar to Facebook add-ons, was used as the platform. Each session lasted about 90 minutes. See the Appendix for a sample experimental instruction with screenshots included.

3. Experimental Results

Fig. 1 shows the time series of market prices and trading volumes in three years by treatment. Each panel includes three sub-panels, each for one year with one auction market (denoted at second 0) under the treatments of CA and UPA, and two-session spot markets (spanning from seconds 1 to 330) under all three treatments. In each sub-panel, the lower part shows the average trading volumes across markets (colored bars) for each second with the vertical axis on the right, and the upper part shows the average auction clearing prices (red dots) and the 10-second moving-average quantity-weighted transaction prices (colored lines), overlaid by the highest and lowest prices (grey areas), with the vertical axis on the left. The blue, orange, and green colors are for CA, UPA, and GF, respectively.

Overall, under CA, the transaction prices are higher, and the trading volumes are larger than those under UPA and GF, especially in the first two years. In the auction market, the market-clearing prices are around 70 under CA, which is higher than those under UPA, and the trading volumes are around 400 under both CA and UPA. In the spot market, the transaction prices fluctuate around 80 under CA, which is higher than those under GF (around 70) and UPA (around 60), and the trading volumes under CA and GF are higher than under UPA. Comparing the auction and spot markets, under CA and UPA, the spot market prices look higher than the auction prices, while the trading volume per transaction is higher in the auction market than in the spot market. Under all treatments, the transaction prices decrease toward the end of the third year.

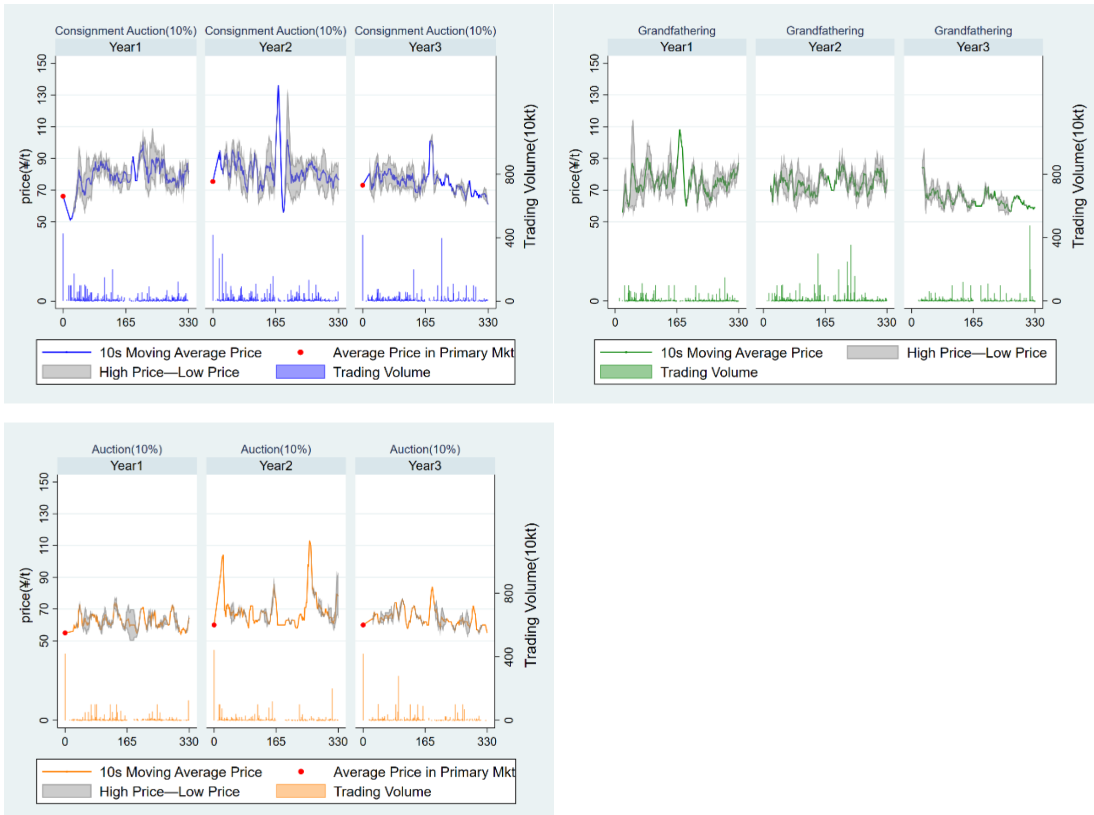

Fig. 1 Time series of market prices and trading volumes by treatment

Each panel includes three sub-panels, each for one year with one auction market (denoted at second 0) under the treatments of CA and UPA, and two-session spot markets (spanning from seconds 1 to 330) under all three treatments. In each sub-panel, the lower part shows the average trading volumes across markets (colored bars) for each second with the vertical axis on the right, and the upper part shows the average auction clearing prices (red dots) and the 10-second-moving-average quantity-weighted transaction prices (colored lines) overlaid by the highest and lowest prices (grey areas) with the vertical axis on the left. The blue, orange, and green colors are for CA, UPA, and GF, respectively.

3.1 Price Patterns

Fig. 2 compares the average auction clearing prices in the primary (auction) markets and the average transaction prices in the spot markets in three years among the three treatments of consignment auction (CA, blue squares), uniform price auction (UPA, orange triangles), and grandfathering (GF, green dots). Primary and spot markets are implemented once and twice a year, respectively.

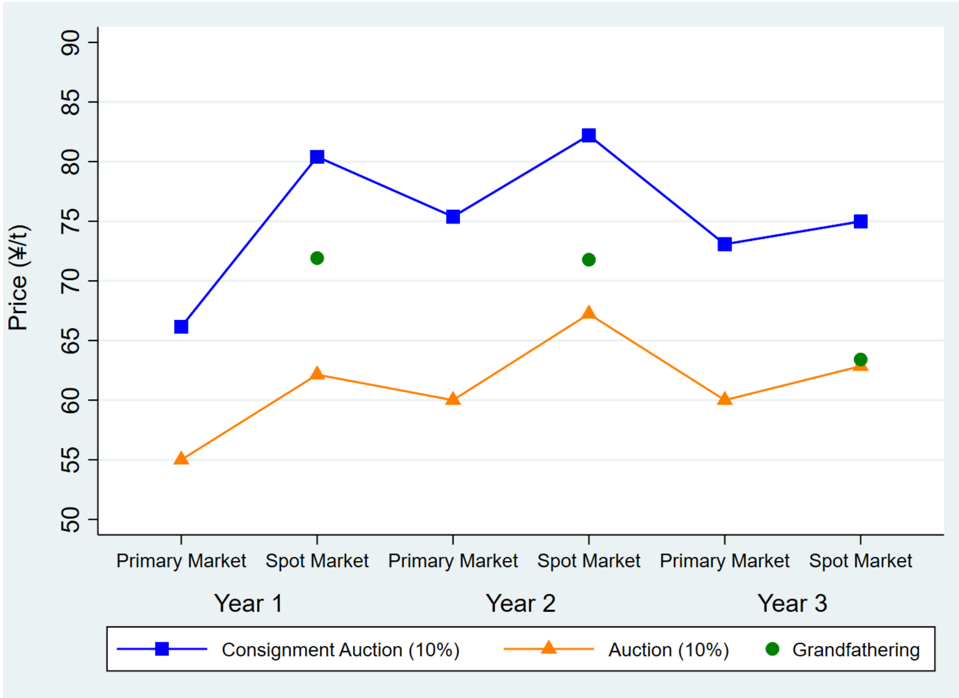

Fig. 2 Average auction clearing prices and spot market transaction prices by treatment

Result 1. In both primary and spot markets, wherever applicable, the consignment auction induces prices significantly higher than grandfathering and the uniform price auction, with the latter resulting in the lowest prices.

Support: The auction clearing price in the primary market under the consignment auction is significantly higher than that under the uniform price auction over all of the three years (by ranksum tests, 72 vs. 58, $p = 0.0070$) and also for each of the first two years (year 1: 66 vs. 55, $p = 0.095$; year 2: 75 vs. 60, $p = 0.064$; year 3: 73 vs. 60, $p = 0.15$).[3]

In the spot markets, the transaction prices are significantly higher under CA than those under UPA and GF (by ranksum tests, CA vs. UPA and GF: 79 vs. 64 and 69, both with $p < 0.01$), with GF significantly higher than UPA (69 vs. 64, $p = 0.037$). The pair-wise comparisons among treatments for each year and overall are all significant at the 5% level except for CA vs. GF in years 1 and 2, with $p = 0.079$ and 0.054, respectively, and GF vs. UPA in years 1 to 3, with $p =$

[3] By *t*-tests, the differences for overall and each of the three years are all significant, with *p*-values of 0.00085, 0.027, 0.056, and 0.085.

0.055, 0.34, and 0.87, respectively. **Fig. A1** in the Appendix compares the 33-second moving average of the spot market transaction prices among the three treatments with the consignment auction, supporting overall higher spot market prices.

Result 2. Consignment auction and uniform price auction form a price signal in the primary market, which leads to significantly higher transaction prices with smaller volatilities in the spot markets.

Support: For both CA and UPA, the market clearing prices in spot markets are significantly higher than those in primary markets overall (by signrank tests, CA: 79 vs. 72, $p = 0.0057$; UPA: 64 vs. 58, $p = 0.0050$). The pair-wise comparisons for the first two years under both CA and UPA are all significant at the 5% level (by signrank tests, CA: 80 vs. 66 in year 1, $p = 0.023$; 82 vs. 75 in year 2, $p = 0.028$; UPA: 62 vs. 55 in year 1, $p = 0.046$; 67 vs. 60 in year 2, $p = 0.046$). In year 3, the differences between the prices in the spot and primary markets are not statistically significant under either CA (75 vs. 73, $p = 0.70$) or UPA (63 vs. 60, $p = 0.35$).

Tables A1 and A2 in the Appendix present results from two-way random effects regressions of the effects of the auction clearing prices in the primary markets on firm-level average transaction prices, bids, and asks in the spot markets. Errors are clustered at market and individual firm levels under CA and UPA, respectively.[4] In each of the two tables, Models 1, 3, and 5 each provide a baseline that includes only year dummies, using year 1 as the base, for transaction prices, bids, and asks, respectively; Models 2, 4, and 6 show the effects of the price signals in the primary markets on the prices in the spot markets after controlling for the other factors that could affect the transaction prices.

[4] The random effects models are based on the following regressions: $p_{ijt} = X_{ijt}\beta + \mu_i + \nu_j + \epsilon_{ijt}$, where p_{ijt} represents the average transaction price (or bids or asks) in the spot market for firm *i* in group *j* in year *t*, with two random effects denoted by μ_i and ν_j, respectively, and X_{ijt} is a set of regressors including year dummies with year =1 as the baseline, the auction clearing prices in the primary markets, a dummy (1 if yes) for whether there exist permit deficits after the consignment before the primary market, permit deficits before the spot market, and the interaction of the latter two. Other specifications with control variables, including the endowment and various combinations of interactions, have been tested but are not statistically significant and hence are not included here. **Table A3** in the Appendix presents models that are similar to those in Tables A1 and A2 for GF, except that the variable of the auction clearing price is dropped since there is no primary market under GF.

Under both CA and UPA, the auction clearing price in the primary market has a significantly positive effect on the transaction price, bids, and asks in the spot market, all at the 1% significance level, except for the transaction price and asks under CA, with a significance of 5%, indicating a significantly positive price signal from the primary market. The effect of the price signal is especially large under UPA, with coefficients between 0.4 and 0.5 in Table A2; that is, an increase of 10 yuan/ton in the price in the primary market may induce an increase of 4 to 5 yuan/ton in the transaction price in the spot market. The corresponding effect under CA is about 1 yuan/ton. Note that the regression constants in the models are generally consistent with the observations in **Fig. 2**.

With a price signal from the primary market, the price volatility in the spot market is also reduced. Price volatility is measured by the natural logarithm of the ratio of the highest price to the lowest price in a given time window (Grossman, 1988). **Fig. 3** shows the price volatilities of the spot markets for each treatment over the three years by a time window of 33 seconds dividing the yearly transaction time into ten segments.[5] The blue, orange, and green lines represent the average price volatilities over the three years for CA, UPA, and GF, respectively. Overall, the price volatilities decrease over time in all treatments, with the greatest volatility under GF followed by CA and UPA, especially in the first two years.

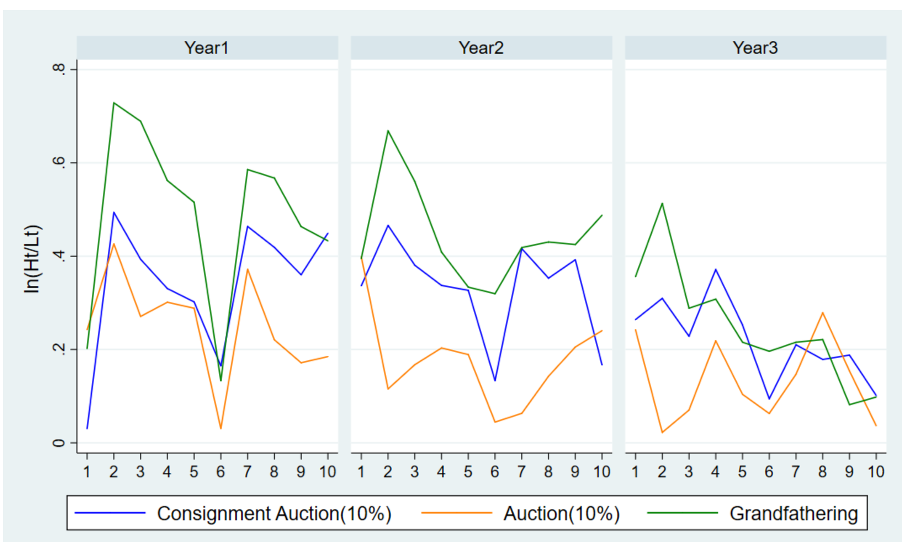

Fig. 3 Price volatilities in spot markets by treatment

[5] In each year, the spot market lasts 330 seconds in two 165-second periods. A time window of 33 seconds is chosen to increase the number of observations while keeping the time long enough for a sufficient number of transactions.

In the spot markets, price volatilities under CA are significantly lower than those under GF overall (by ranksum tests, 0.312 vs. 0.400, $p = 0.00057$), which are attributed to the significant differences in the first two years (in year 1: 0.368 vs. 0.488, $p = 0.0016$; in year 2: 0.335 vs. 0.446, $p = 0.010$). In year 3, the differences in price volatilities are not significant between CA and GF (0.230 vs. 0.255, $p = 0.41$). Similar results are obtained by *t*-tests. Noticing that transaction prices in spot markets are higher under CA than those under GF, lower price volatilities under CA also support the role of the auction clearing price in the primary market as a price signal to the spot market.

With the lowest transaction prices in the spot markets, price volatilities under UPA are the lowest among the three treatments, that is, significantly lower than those under GF and CA in all three years, except for the first period in year 1 when compared with CA (0.308 vs. 0.345, $p = 0.77$) and the second period in year 3 when compared with both GF and CA (0.139 vs. 0.160 and 0.153, $p = 0.69$ and 0.92, respectively).

3.2 Market trading volumes and liquidity

Fig. 4 compares average market-level trading volumes by treatment for each year. Striped and solid areas denote the primary and spot markets, respectively. The blue, orange, and green colors are for CA, UPA, and GF, respectively. The trading volume of a market in one year is normalized by the total emissions of all the firms in this year.

Result 3. The trading volumes are significantly larger under CA than those under UPA in the spot markets; the total trading volumes in the primary and spot markets under either CA or UPA are not significantly different from the trading volumes in the spot markets under GF.

Support: Although the auction clearing price under CA is higher than that under UPA in the primary market, the trading volumes are not significantly different between CA and UPA overall (by ranksum tests, $p = 0.99$) and for each year ($p = 0.65$, 0.32, and 0.62 for years 1 to 3), all around 10% of the total emissions. However, the trading volumes under CA are 60% larger than those under UPA in the spot markets overall (by ranksum tests, 16% vs. 10%, $p = 0.012$). This is attributable to the significant difference in year 2 (by ranksum tests, 18% vs. 9%, $p = 0.028$), implying a potential effect of a higher price in the primary market on the trading volume in the spot market. Note that out of the total trading volume in the primary and spot markets, 61% occurs in the spot market under CA, while 49% occurs under UPA. Given similar trading volumes in the primary markets of CA and UPA, the total trading volume under CA is 30% larger than that under UPA.

Since there is no primary market under GF, the trading volume in the spot market represents the total trading volume under GF, which is comparable to the total trading volume under CA and UPA. The total trading volumes in the primary and spot markets under CA or UPA are not significantly different from the trading volumes in the spot markets under GP overall and for each year (by ranksum tests, all with $p > 0.2$).

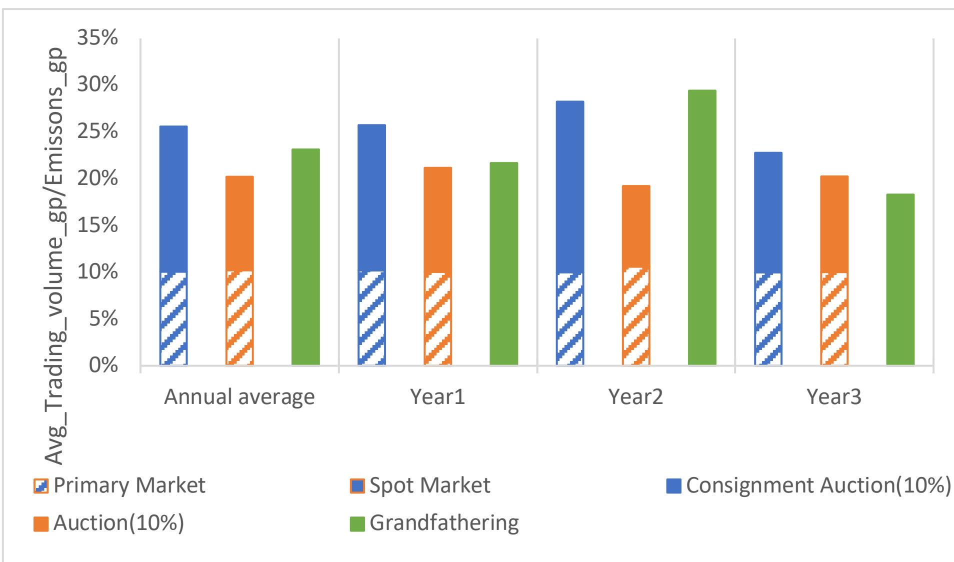

Fig. 4 Market trading volumes by treatment

Next, we compare the liquidity in the spot market by treatment. The relative bid-ask spread, which is the ratio of the difference between the highest traded bid price and the lowest traded ask price to the average of these two prices during a time window, is one of the main measures of liquidity used in the literature (Amihud, 1996; Chordia et al, 2001), including carbon market studies (Ibikunle and Gregoriou, 2018). Since firms could take any bid or ask offers posted, and the highest bids and the lowest asks are not automatically used in our design, we use the average traded bid price and the average traded ask price in a market in a given time period to calculate the relative bid-ask spread, to avoid potential idiosyncratic individual choices. **Fig. A2** presents the average traded bid prices (in blue) and ask prices (in red) in every 33 seconds over the three years, by treatment. Overall, the bid-ask differences are larger under GF than those under CA and UPA, especially for the first two years. **Fig. A3** shows the relative bid-ask spread as defined above over the three years, by treatment. We have the following result:

Result 4. The spot market liquidity is greater under CA and UPA than under GF overall.
Support: The mean of the relative bid-ask spreads over three years is the highest under GF (29%), followed by CA (24%) and then UPA (16%), with all pair-wise comparisons significant at the level of 5% (by ranksum tests, GF vs. CA, $p = 0.017$; GF vs. UPA, $p < 0.0001$; CA vs. UPA, $p = 0.001$). Here, the prices are weighted by trading quantity. The result still holds if the prices are not weighted by quantity or a time interval of 15 seconds is used.

3.3 Firm Compliance

The consignment auction in the primary market is observed to improve emissions permit trading by inducing higher transaction prices with smaller price volatilities in the spot market. However, the total market trading volume under CA is not different from that under GF. To evaluate the effectiveness of the permit trading among treatments, we investigate the non-compliance behaviors, that is, the permit deficits after the market trading periods in each year. A more effective trading scheme is expected to reduce permit deficits.

Fig. 5 compares market-level permit deficits after the trading periods in each year among the three treatments. The market-level permit deficit in one year is normalized by the total emissions of all the firms in this year. Note that permit deficits are counted only for the excess emissions above the permits held by firms. When the permits are sufficient to cover the emissions, permit deficits are zero. The solid, striped, and dotted areas represent years 1 to 3, respectively. The blue, orange, and green colors are for CA, UPA, and GF, respectively. **Fig. 5** shows that permit deficits decrease over the years under all three treatments and drop below 1.5% in the last year. Note that new permits are added into the markets through the compliance process each year, and all excess permits are bought back at the lowest price of 50 at the end of the last year. Therefore, the highest permit supply is expected in the last year, which may minimize the potential differences among treatments, as illustrated in the figure. We will focus on the differences in the first two years to identify the effectiveness of the trading schemes in reducing permit deficits.

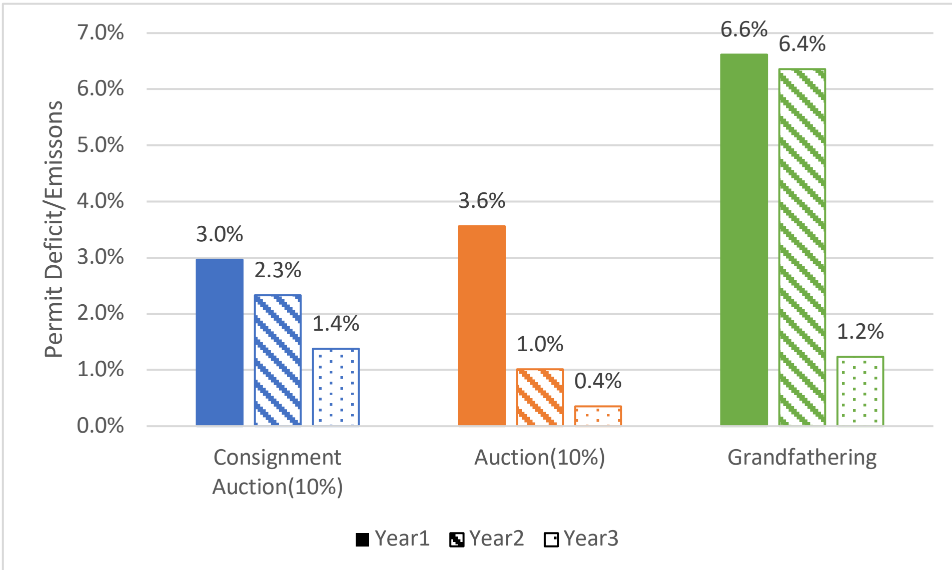

Fig. 5 Permit deficits by year and treatment at the market level

Result 5. Permit deficits at the market level are significantly lower under CA and UPA than those under GF in the first two years, but the differences are not significant in the last year.
Support: In the first two years, the average permit deficits at the market level under CA and UPA are 2.6% and 2.3%, respectively, both of which are significantly lower than the 6.5% level under GF by ranksum tests, with $p = 0.055$ and 0.041, respectively. In year 1, the largest difference among treatments is between CA and GF (by ranksum tests, 3.0% vs. 6.6%, $p = 0.023$); in year 2, the largest difference is between UPA and GF (by ranksum tests, 1.0% vs. 6.4%, $p = 0.097$). In year 3, CA and UPA are not significantly different from GF (1.4% and 0.4% vs. 1.2%, $p =$ 0.15 and 0.85, respectively). CA and UPA are not significantly different in any of the three years, all with $p > 0.1$.

Fig. 6 compares permit deficits among treatments at the firm level for those with strictly positive deficits by box plots (the left-hand vertical axis and the bottom horizontal axis) and cumulative probabilities (the right-hand vertical axis and the top horizontal axis). The observations are pooled over the three years. The means (medians) of firm-level permit deficits are 33 (11), 53

(21), and 102 (52) in 10 thousand tons for CA, UPA, and GF, respectively; that is, the permit deficit per firm is the lowest under CA and the highest under GF. By ranksum tests, permit deficits at the firm level are significantly lower under CA and UPA than those under GF, both with $p < 0.05$, and the difference between CA and UPA is not significant ($p = 0.13$). The comparisons are similar in terms of cumulative probabilities by Kolmogorov–Smirnov tests. Thus, we have the following result:

Result 6. Permit deficits at the firm level are significantly lower under CA and UPA than those under GF, but the difference between CA and UPA is not significant.

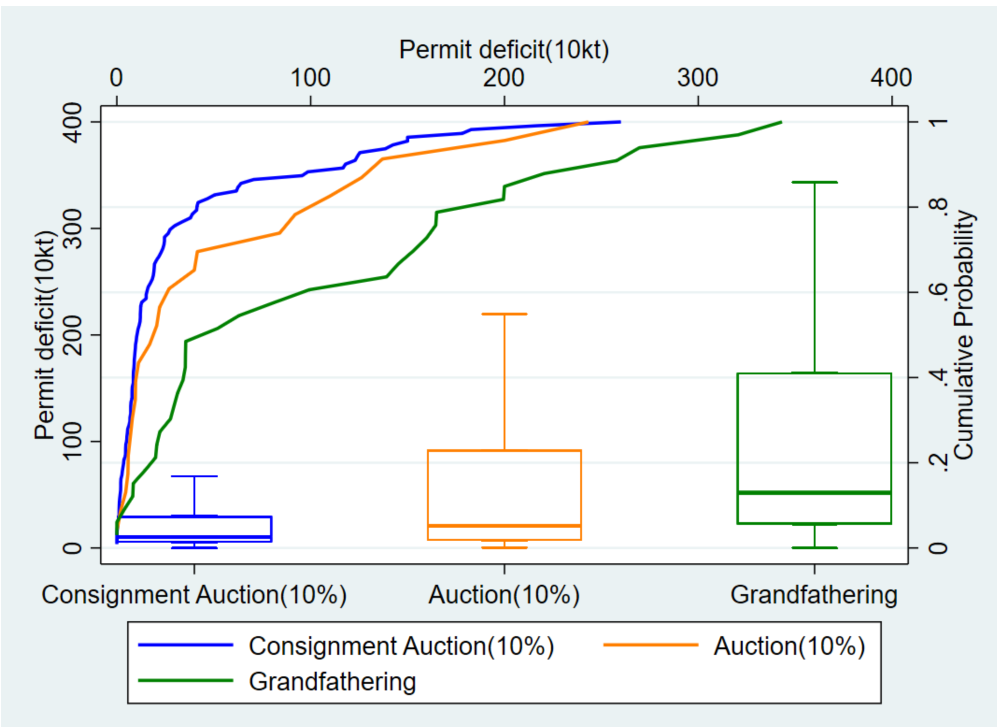

Fig. 6 Permit deficits by treatment at the firm level

4. Underlying Mechanisms and Profit Comparisons by Firm Categories

The experimental results show that the consignment auction induces a significantly higher auction clearing price in the primary market. This acts as a price signal, leading to significantly higher transaction prices with lower volatilities in the spot market. With a primary market, both consignment auction and uniform price auction reduce non-compliance at both the market and individual firm levels compared to the grandfathering treatment without a primary market. However, the total market trading volumes are not different among the three treatments. The results imply more effective transactions under a trading scheme with both primary and spot markets.

We explore the underlying mechanisms for the treatment effects in this section. Specifically, we investigate the reasons for the price differences between CA and UPA in the primary market, and why the permit deficits are significantly different between CA/UPA and GF although they have similar trading volumes. Then, we look into the total net profits through the trading process for welfare comparisons among treatments.

4.1 Price differences between CA and UPA in the primary market

Fig. 7 summarizes the observed market demand and transactions in the primary market by treatment over the three years. In the sub-panel for each year, the vertical red line represents the market supply of permits, which is the consigned 10% of the total permits from all the firms; the solid blue line and the orange dashed line represent the observed market demand averaged over all markets under CA and UPA, respectively. In each market, the demand curve is the cumulative bidding quantity at each given bidding price from above, that is, the total quantity demanded at each given price and higher prices. The small hollow blue triangles and orange circles are observed market-clearing transactions under CA and UPA, respectively, and their averages are respectively denoted by the large solid blue triangles and orange circles. Under CA, firms' net payment depends on the extra permits bought over the consigned ones, while firms need to pay for all the permits under UPA. To be comparable with UPA, the total extra permits over the consigned ones from firms who buy more than their consigned permits are defined as the net market-clearing quantity under CA, represented by the hollow blue circles in the figure, with the large solid blue circle denoting the average. The hollow triangles and circles are staggered to avoid overlapping.

First, the observed market demand curves under CA and UPA are both downward sloping. The shape of these demand curves is not induced in the experimental design but is fully based on subjects' own choices in the experiment. Second, the following findings are consistent with Results 1 and 4 in the following respects: the market demand curve for CA lies above the curve for UPA; the market-clearing prices under CA are higher than those under UPA in each year;

and, most of the time, the total demand is greater than the supply and hence the market clears, indicated by the blue triangles and the orange circles lying along the supply curves.

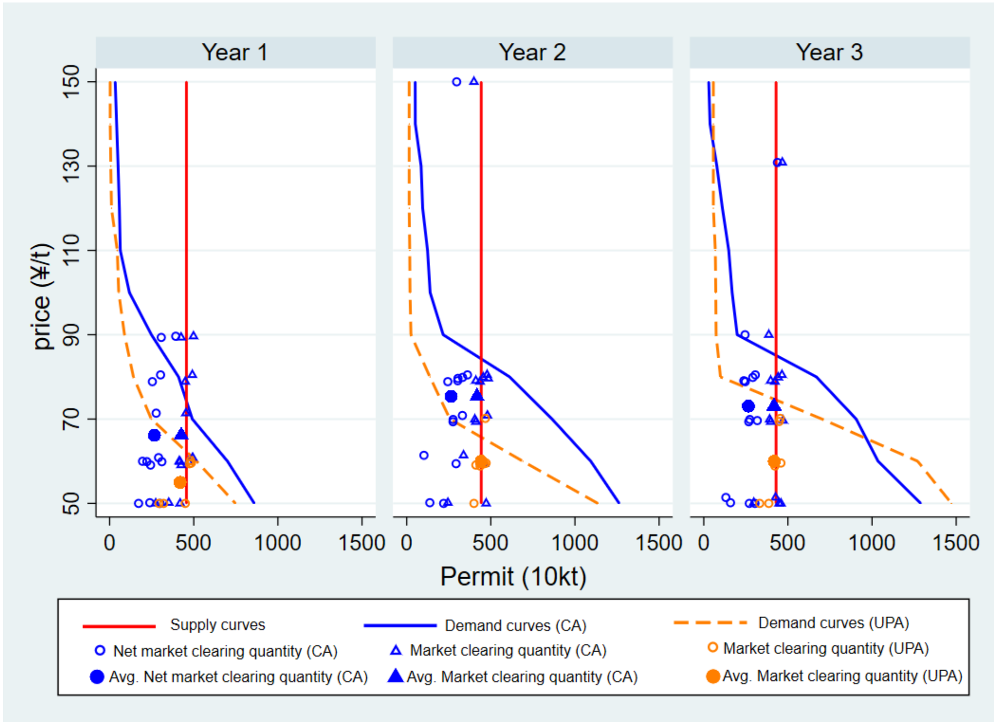

Fig. 7 Market demand and transactions in the primary market by treatment

Third, and most importantly, the solid blue circle lies to the upper left of the solid orange circle, meaning that the net market-clearing quantity under CA is less than the market-clearing quantity under UPA; the difference is significant (by ranksum tests, 265 vs. 427, p <0.0001). Interestingly, we note that the solid blue circles are closer to the orange dashed lines compared to their distances to the blue lines.[6] Combined with the observation that the solid orange circles are also close to the orange dashed lines, this implies that the demand for permits that firms must purchase at full price follows the observed demand curve under UPA, whether they are from the CA treatment or the UPA treatment. In that case, an empirical explanation of the price differences between CA and UPA in the primary market is that the consignment essentially "magnifies" the net market-clearing demand, resulting in a higher auction clearing price compared with that under UPA.

[6] We calculate the distances from the hollow blue circles to fitted linear lines based on the market demand curves, and find that the average distance from the blue circles to the orange dashed line in each year is significantly less than the distance from the blue circles to the blue line, all with $p < 0.01$ by ranksum tests.

The discussions above are summarized in the following observation:

Observation 1. In the primary market:

a) the observed market demand curves under CA and UPA are both downward sloping, with the UPA curve lying above the CA curve;

b) the demand for permits that firms must purchase at full price follows the UPA demand curve more closely than the CA demand curve, under both CA and UPA;

c) the consignment under CA "magnifies" the net market-clearing demand, resulting in a higher auction clearing price compared with that under UPA.

4.2 The effectiveness of trading on the reduction of permit deficits (demand)

We use the total reduction of permit deficits as a percentage of market trading volume in each year to measure the effectiveness of trading (**Fig. 8**).[7] Over the three years, the average reductions of permit deficits are 46%, 36%, and 24% of the market trading volumes under UPA, CA, and GF, respectively, with the first two not significantly different from each other (by ranksum tests, $p = 0.16$), but both significantly greater than GF ($p = 0.0024$ and 0.0013). This is attributable to the significant differences in years 2 and 3 (UPA and CA vs. GF: 32% and 36% vs. 12% in year 2, 58% and 43% vs. 27% in year 3, all with $p < 0.05$ except for 58% vs. 27% with $p = 0.055$). We summarize this observation as follows:

Observation 2. CA and UPA are more effective in reducing permit deficits than GF, given the same trading volume.

Fig. 8 shows that more than 50% of the trading volume is not used for the reduction of permit deficits. To understand how trading is related to the reduction of permit deficits, we categorize firms' behaviors by their permit deficits (i.e., demand) before and after the market trading processes into two types, each with three sub-types, i.e., Types 1a to 1c, and Types 2a to 2c. After the consignment of the free allocated permits and before trading, Type 1 firms have extra permits while Type 2 firms have permit deficits. Within each type, sub-types differ in permit

[7] Permit deficits for a firm in a year are the difference between its annual emissions and the allocated permits after consignment, if any. The market trading volume is the total transactions in the primary (if any) and the spot markets.

deficits after the trading processes. Specifically, Type 1a firms over-sell their extra permits, resulting in permit deficits after trading. Type 1b firms sell extra permits but still keep a sufficient amount for emissions. Type 1c firms have extra permits but buy more permits through trading, i.e., they are permit hoarders. Type 2a firms reduce their permit deficits by buying permits on the market, leading to no net deficits. Type firms 2b also buy permits, leading smaller but still positive deficits. Type 2c firms have permit deficits but choose to sell in the markets, resulting in more deficits. **Table 2** gives the definitions of each type.

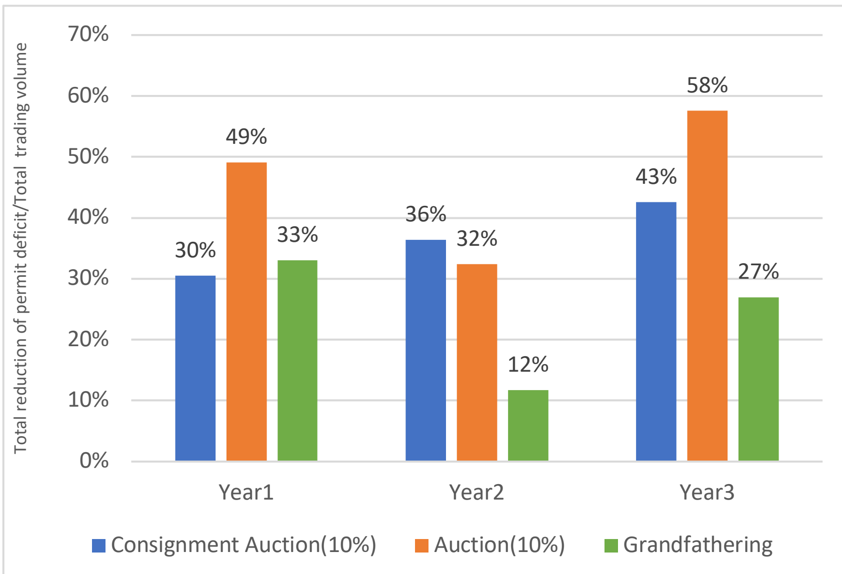

Fig. 8 Reduction of permit deficits in the percentage of trading volumes by treatment

Note that there are two kinds of trading behavior that may curtail the reduction of permit deficits. In one situation, firms buy more permits than they need to cover their deficits.[8] In another, firms sell so many permits that they have deficits. By definition, Type 1c firms have a surplus. Types 1b and 2a may also have a surplus if they keep or buy more than needed. Types 1a, 2b, and 2c have deficits. **Table 3** summarizes permit deficits by firm types as defined in **Table 2**. These are normalized by the total permit deficits in year 1 under GF in percentages.

[8] It has been observed that firms participating in China's national ETS tend to be cautious when they made decisions about selling permits, causing low liquidity and a shortage of permit supply. We speculate that reasons for hoarding could include expected price increases in later compliance cycles, or miscalculation.

Table 2. Firm types by the change of permit deficits after trading

Permit deficits	Type 1			Type 2		
	Type 1a	Type 1b	Type 1c	Type 2a	Type 2b	Type 2c
After consignment	--	--	--	++	++	++
After trading	+	-	---	-	+	+++

Note: The plus sign "+" means that firms have permit deficits, i.e., their permit holdings are less than their emissions; the minus sign "-" means firms have extra or sufficient permits, i.e., their permit holdings are greater than or equal to their emissions. To capture the change in permit holdings, the initial state for each type is either "--" or "++", and the state after trading is represented by either a different sign or the same sign as before, but with the number of the signs adjusted. Taking the example of Type 1 firms, a Type 1a firm has extra permits (--) before trading but permit deficits (+) after trading, while a Type 1b firm still has extra permits (-) after trading but less than before (--). The number of signs only indicates the change within a type, which is not comparable with other types (columns).

Table 3. Permit deficits by firm types based on permit changes after trading

Treatment	Year	Total permit deficits	Total extra permits	Type 1a	Type 1b	Type 1c	Type 2a	Type 2b	Type 2c
CA	1	47%	194%	22%	-4%	-126%	-63%	3%	22%
	2	37%	324%	23%	-20%	-188%	-116%	5%	9%
	3	22%	391%	5%	-64%	-230%	-97%	6%	11%
UPA	1	56%	192%	29%	-6%	-108%	-78%	0%	27%
	2	16%	305%	4%	-41%	-221%	-43%	2%	10%
	3	6%	356%	5%	-84%	-129%	-143%	0%	0%
GF	1	100%	240%	66%	-49%	-105%	-87%	0%	33%
	2	95%	424%	78%	-86%	-290%	-47%	0%	16%
	3	18%	481%	18%	-205%	-234%	-42%	0%	0%

Note: The total permit deficits (the 3rd column) are the sum of permit deficits with only positive numbers among all firm types. The total extra permits (the 4th column) are the absolute value of the sum of permit deficits with only negative numbers. All permit deficits here are normalized by the total permit deficits in year 1 under GF in percent.

First, note that the total permit deficits under CA and UPA are significantly lower than those under GF in the first two years, consistent with **Result 5**. Notably, Type 1a firms under GF contribute the most to the total permit deficits in two respects. Compared with firms of Types 2b and 2c under GF, Type 1a firms contribute the most to the permit deficits in each year (year 1: 66% vs. 0% and 33%; year 2: 78% vs. 0% and 16%; year 3: 18% vs. 0% and 0%). Compared with Type 1a firms under the other two treatments, the permit deficits from Type 1a firms under GF are significantly greater than those under both CA and UPA (by ranksum tests, $p = 0.074$ and 0.026) over the three years, especially in the first two years. Therefore, one reason for the larger permit deficits under GF is that firms with extra permits over-sell too much, i.e., sell more than they can afford for compliance.

Second, the total extra permits in the markets (the 4th column) are much greater than the total permit deficits under all treatments in each year (the 3rd column), indicating that all potential permit deficits could be eliminated through more effective trading processes. Note that the total extra permits under CA and UPA are both significantly lower than those under GF over the three years (by ranksum tests, $p = 0.089$ and 0.054). Moreover, Type 1c firms (i.e., permit hoarders) contribute the most to the total extra permits in each year under all treatments; except that, in year 3 under UPA, Type 1c is only slightly lower than Type 2a (129% vs. 143%). Thus, another reason that GF results in less effective trading and less reduction of permit deficits is that firms under GF buy more than they need, especially due to the permit hoarders.[9]

We summarize the above discussions in the following observation:[10]

Observation 3. There are two main reasons that trading is less effective in reducing permit deficits under GF:

a) under GF, firms with extra permits sell more than they can afford for compliance, and sell significantly more than firms under CA and UPA;

b) firms buy more than they need under GF, especially for those with extra permits; that is, permit hoarding is more severe under GF than under CA and UPA.

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[9] As noted in the previous footnote, permit hoarding is also observed empirically in China's ETS where GF is currently used. When a primary market with permit auctioning (such as CA and UPA) was introduced, firms are forced to submit some proportion of permits for sale, which may alleviate the hoarding.

[10] Based on the feedback from subjects in our subsequent experiments using a within-subject design, the primary market under CA and UPA provides an opportunity for firms to adjust their permit holdings before trading in the subsequent spot market, and is also helpful for firms to form reasonable beliefs about the prices of permits and to be better prepared in the spot market. This results in more effective trading in the sense of reducing permit deficits overall. More direct evidence can be collected to investigate the underlying mechanisms of Observation 3 in future work.

4.3 Total net profits over trading by firm categories

Since the firms in our setup have different initial endowments due to different capacities for power generation, the net profits (i.e., the increased total experimental payoffs) through the trading processes are used to measure their overall performance for comparisons among treatments.

We group the ten types of firms (**Table 1**) in a market into five categories: 5, 30-High, 30-Low, 60, and 100, based on their initial endowments and emission intensities, as shown in **Table A4** in the Appendix. First, firms in each category have the same initial endowments. In addition, given the benchmark emission intensities for initial permit allocations in each year (year 1: 1.015; year 2: 0.985; year 3: 0.955; the unit is tons/MWh), firms have similar properties in terms of permit deficits (demand) in each category. In the categories of 5 and 30-High, firms have permit deficits before the 10% of free allocated permits are consigned in all three years, representing the major buyers in the market. In the categories of 60 and 100, firms have extra permits before the 10% of free allocated permits are consigned in all three years, representing the major sellers in the market. In the category of 30-Low, firms have permit deficits after the 10% of free allocated permits are consigned in all three years, but they may have extra permits before the consignment in some years, and their permit deficits after the consignment are relatively small in the first two years compared with the other categories, representing the minor buyers.

Table 4. Permit deficits before and after the consignment for each category of firms

Firm category	Permit deficits (y 1)		Permit deficits (y 2)		Permit deficits (y 3)	
	Before	After	Before	After	Before	After
5	46,250	71,625	53,862	78,476	61,247	85,122
	21,250	46,625	28,862	53,476	36,247	60,122
30-High	127,500	279,750	173,175	320,857	217,480	360,732
	52,500	204,750	98,175	245,857	142,480	285,732
30-Low	-22,500	129,750	23,175	170,857	67,480	210,732
	-97,500	54,750	-51,825	95,857	-7,520	135,732
60	-315,000	-10,500	-223,650	71,715	-135,041	151,463
	-345,000	-40,500	-253,650	41,715	-165,041	121,463
100	-675,000	-167,500	-522,750	-30,475	-375,068	102,439
	-725,000	-217,500	-572,750	-80,475	-425,068	52,439

Note: The numbers in red indicate permit deficits, and those in green indicate extra permits.

Table 4 summarizes the permit deficits before and after the consignment for each category of firms. Note that firms in the categories of 30-High and 100 have the greatest permit demand and supply, respectively.

Table 5 provides summary statistics of total net profits by treatment and category in the percentage of total endowments in each category. We compare the mean and variance of the net profits in each category among the three treatments.

Table 5. Summary statistics of net profits by treatment and category (in % of endowments)

Firm category	CA (10%)			UPA (10%)			GF		
	mean	median	sd	mean	median	sd	mean	median	sd
5	-16	-14	21	-24	-20	18	-24	-16	27
30-High	-14	-8	15	-19	-15	10	-22	-12	25
30-Low	-10	-2	24	-16	-10	20	-4	-1	12
60	-3	5	22	-4	-2	7	-4	4	20
100	5	8	9	-2	0	6	2	4	7
N		52			24			24	

Note: The numbers in red indicate negative profits, and those in green indicate positive profits.

First, note that the averages of total net profits are negative under all treatments in all categories except for the category 100 under CA and GF, and the medians are all negative except for the categories of 60 and 100 under CA and GF and the category of 100 under UPA. That is, only firms in the categories of 60 and 100 (especially in the latter) that have extra permits even after the consignment in the first two years, i.e., the main sellers of permits, could make positive profits. Firms in the categories of 5, 30-High, and 30-Low, as the main buyers of permits, all make negative profits, especially for 5 and 30-High. Notably, the averages and medians of the net profits increase from category 5 to 30-High, 30-Low, 60, and 100 in the percentage of their total endowments, consistent with the reverse ranking of their emission intensities.

Among the three treatments, UPA has the lowest net profits. By ranksum tests, the averages of total net profits under CA and GF are both significantly greater than that under UPA in all categories, all with $p < 0.01$, except for GF in the categories of 5 ($p = 0.28$) and 30-High ($p = 0.20$). This is as expected because firms under UPA bear the full cost to buy back the consigned permits, while the 10% consigned permits bring revenues to firms under CA, and all permits are free under GF.[11] Interestingly, however, firms in the categories of 5 and 30-High, i.e., those with large permit deficits, do not have significantly different net profits under UPA and GF, even though firms under UPA have 10% fewer permits initially. This implies that UPA is more efficient than GF in reducing permit deficits.

Although **Table 5** shows that CA has larger mean and median net profits than GF in all categories except for category 30-Low, CA and GF are not significantly different from each other at the 10% level, except in the category of 100 with $p = 0.0011$, where firms with extra permits under GF oversell significantly more and hence lose more than those under CA.[12] However, the variances of net profits under CA are significantly less than those under GF in categories of firms with permit deficits, 5 (sd: 21 vs. 27, $p = 0.024$) and 30-High (sd: 15 vs. 25, $p = 0.037$), but are not significantly different from those under GF in categories of firms with extra permits, i.e., 60 and 100 both with $p > 0.5$, all by robustness tests for equality of variances.[13] Therefore, CA improves upon GF in two respects: CA induces the same profits with lower risks (variances) for firms with permit deficits and induces larger profits with the same risks for firms with extra permits. Furthermore, CA and UPA are not significantly different from each other in variances in all categories (all with $p > 0.19$) except for 60 (sd: 22 vs. 7, $p = 0.012$). Combined with their relationships in the averages, CA improves upon UPA overall by inducing larger profits with the same risks.

[11] Here we focus on the welfare effects of the three mechanisms on different categories of firms (i.e., net profits) instead of the social welfare effects, and hence the revenue from the primary market under UPA is not considered. Although the revenue from UPA can be used from the societal perspective, how to allocate the revenue is beyond the scope of this paper. The consignment auction provides one allocation rule of the revenue generated in the primary market and is compared here with the grandfathering approach. An alternative calculation to compare CA and UPA is to exclude the revenue, based on which we find the net profits are not significantly different between CA and UPA, except for the firm category 100, where CA results in higher profits by our side analysis (in terms of the percentage of the endowments, CA vs. UPA: -1 vs. -2, $p = 0.085$ by ranksum tests.).

[12] By *t*-tests, CA has net profits significantly greater than GF in categories of 100, 30-Low and 30-High respectively, with one-sided $p = 0.037$, 0.074, and 0.082.

[13] Fig. A4 in the Appendix compares the cumulative distributions of the total net profits among treatments by the five categories of firms. Since the distributions are quite skewed, we use robustness tests for equality of variances. The corresponding violin plots are provided as Fig. A5 in the Appendix.

Table 6 summarizes the relationships of net profits among the three treatments by the significances of pair-wise comparisons in mean and variance.[14] For each pair (i.e., two) of the three treatments, we compare the mean and variance of their total net profits together in each of the five categories. The treatments are colored in green to indicate that they are better than the uncolored treatments in the same cells due to generating the same net profits with smaller variances or larger net profits with the same variances. When neither mean nor variances are significantly different between the pair of treatments in one cell, or one treatment has both the mean and the variance significantly greater than the other treatment, neither of the treatments is colored.

Table 6. Relationships of net profits among the three treatments in mean and variance

		Firms with	Firms with	Other types of firms	
		5 and 30-High	100	30-Low	60
CA	mean	CA = GF	CA > GF	CA = GF	CA = GF
vs. GF	sd	CA < GF	CA = GF	CA > GF	CA = GF
CA	mean	CA > UPA	CA > UPA	CA > UPA	CA > UPA
vs. UPA	sd	CA = UPA	CA = UPA	CA = UPA	CA > UPA
UPA	mean	UPA = GF	UPA < GF	UPA < GF	UPA < GF
vs. GF	sd	UPA < GF	UPA = GF	UPA = GF	UPA < GF

Note: Treatments are colored in green to indicate that they generate either the same net profits with smaller variances or larger net profits with the same variances compared with the treatments in the same cells.

We summarize the observations from **Table 6** as follows.

Observation 4. In terms of total net profits,

a) CA improves upon GF in two aspects:

a-1) for firms with permit deficits, CA induces the same profits with lower risks;

a-2) for firms with extra permits, CA induces larger profits with the same risks;

b) CA improves upon UPA overall by inducing larger profits with the same risks;

c) UPA performs better than GF for firms with permit deficits by inducing the same profits with lower risks;

d) GF performs better than UPA for firms with extra permits by inducing larger profits with the same risks.

[14] **Table A5** in the Appendix provides the relationships of net profits among the three treatments in mean and variance with *p*-values.

5. Conclusions

Emissions permit allocation designs are critical for the success of an emissions trading system. In this study, we investigate three emissions permit allocation schemes that have been implemented in the real world – grandfathering (GF), uniform price auction (UPA), and consignment auction (CA) – with a series of lab-in-the-field experiments in China. The fact that our experimental subject were real market participants (power generation managers, who were motivated by potential career rewards) is a first in the literature. A key feature of our setup is combining the primary market of permits allocation with a subsequent spot market for emissions trading. The three mechanisms are compared regarding their price discovery, trading volumes, market liquidity, and firm compliance behavior. The underlying mechanisms for their different performances and the resulting effects on firms' profits are also investigated.

Our experimental results show that CA (as a hybrid mechanism of UPA and GF) performs better than GF, and at least as well as UPA, in inducing more efficient permits allocations. In addition, CA imposes a lower cost burden on firms than UPA. Specifically, compared to GF with a spot market only, under either auction mechanism, the auction clearing price in the primary market plays the role of a price signal, leading to higher transaction prices with smaller volatilities and more effective trading in the spot market. Therefore, under both CA and UPA, lower non-compliance was achieved. Furthermore, CA improves upon both UPA and GF in terms of firms' profits. Compared with GF, CA lowers the profit risks (variance) due to permit deficits for smaller polluting firms and increases average profits for larger, cleaner firms by stabilizing the markets with less severe permit hoarding and risky over-selling. Firms under CA earn significantly more than those under UPA, because auction revenues are returned to firms under CA.

The results in our experiment contrast sharply with the theoretical predictions in Khezr and MacKenzie (2018), who demonstrate the no-trading equilibrium with arbitrary auction clearing prices under CA. However, our results reinforce the findings in Dormady and Healy (2019) that CA results in significantly higher auction-clearing prices than UPA. The permit misallocation due to over-bidding of prices and quantities by net sellers, identified in Dormady and Healy

(2019), is less severe in the primary market in our setup and is further solved through the spot market.[15] As conjectured by Dormady and Healy (2019) and confirmed by our experimental results, spot markets and banking may mitigate the potential inefficiency that has been discussed for CA in the literature. The key insight is that the effects of the price signal in the primary market on improving permit reallocation in the spot market dominate the initial inefficiency, due to higher transaction prices and trading volumes later on, which results in an overall more efficient and effective allocation.

Note that our experimental design takes a short-run point of view in the sense that firms undertake no production decisions or emissions abatement in response to permit prices or holdings. This highlights the practical applicability of a pure trading environment for firms with different permit demands or surpluses, as in Dormady and Healy (2019). Given the short time period in this study, and the compressed nature of the mechanisms tested in a lab-in-the-field sessions, the advantage of this first testbed is to facilitate the discovery of potential differences in trading properties among mechanisms. Production and abatement decisions will be incorporated as a natural extension for future studies. Also, the effects of the percentage of initially allocated permits for consignment and whether to allow different percentages of consignment among firms should be further investigated. These future studies will provide more insights on how to induce an effective price signal through the primary market of an ETS.

[15] For example, we find that overall net sellers' bid prices are lower than those of net buyers under CA, that the bidding quantities are not significantly different between CA and UPA in the primary market, and that the net total profits under CA are the same as those under UPA with the consignment auction revenues excluded.

Appendix

Table A1. Random effects models of firm-level average transaction prices under CA

VARIABLES	(1) Avg.price	(2) Avg.price	(3) Bid	(4) Bid	(5) Ask	(6) Ask
Year 2	0.728	-0.060	1.141	0.296	-1.458	-2.469*
	(1.115)	(1.157)	(1.124)	(1.164)	(1.319)	(1.372)
Year 3	-3.478***	-3.812***	3.742***	3.194***	-7.640***	-8.776***
	(1.137)	(1.184)	(1.166)	(1.195)	(1.316)	(1.374)
Auction price		0.061**		0.093***		0.094**
		(0.031)		(0.029)		(0.037)
Firm with deficits after consign.		-2.630**		0.978		1.885
		(1.175)		(1.509)		(1.512)
Permit demand after primary mkt		0.003		0.009		-0.011
		(0.007)		(0.008)		(0.009)
Firm with deficits * Permit demand		-0.034		0.018		0.002
		(0.021)		(0.026)		(0.029)
Constant	80.320***	77.899***	67.274***	60.556***	95.757***	88.306***
	(2.049)	(2.882)	(2.087)	(2.972)	(2.608)	(3.497)
Observations	673	673	447	447	601	601
Number of groups	13	13	13	13	13	13

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A2. Random effects models of firm-level average transaction prices under UPA

VARIABLES	(1) Avg.price	(3) Avg.price	(4) Bid	(6) Bid	(7) Ask	(9) Ask
Year 2	3.994***	1.632	4.280***	1.730	-1.581	-3.895**
	(1.081)	(1.265)	(1.005)	(1.163)	(1.661)	(1.892)
Year 3	0.668	-1.706	5.660***	2.037	-8.366***	-10.746***
	(1.101)	(1.299)	(1.107)	(1.390)	(1.657)	(1.907)
Auction price		0.439***		0.464***		0.519***
		(0.131)		(0.119)		(0.190)
Firm with deficits after consign.		-0.868		2.419*		-0.113
		(1.050)		(1.253)		(1.833)
Permit demand after primary mkt		-0.004		-0.005		0.009
		(0.006)		(0.008)		(0.011)
Firm with deficits * Permit demand		-0.006		0.052*		-0.036
		(0.018)		(0.027)		(0.026)
Constant	62.615***	38.908***	54.194***	27.240***	77.767***	49.251***
	(2.619)	(7.428)	(1.929)	(6.635)	(2.678)	(10.689)
Observations	304	304	159	159	302	302
Number of groups	6	6	6	6	6	6

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table A3. Random effects models of firm-level average transaction prices under GF

VARIABLES	(1) Avg.price	(2) Avg.price	(3) Bid	(4) Bid	(5) Ask	(6) Ask
Year 2	-1.809	-2.415*	0.352	0.439	-3.453**	-3.587**
	(1.240)	(1.260)	(1.281)	(1.285)	(1.724)	(1.749)
Year 3	-12.300***	-13.314***	-3.252**	-2.936*	-18.067***	-18.635***
	(1.245)	(1.295)	(1.486)	(1.553)	(1.699)	(1.787)
Firm with deficits after consign.		-5.489***		-0.057		-3.193
		(2.089)		(2.178)		(3.094)
Permit demand after primary mkt		-0.007		0.007		-0.007
		(0.010)		(0.011)		(0.012)
Firm with deficits * Permit demand		0.365*		-0.074		0.491
		(0.220)		(0.230)		(0.340)
Constant	75.680***	76.796***	60.441***	60.771***	92.487***	92.398***
	(2.948)	(2.999)	(1.398)	(1.642)	(3.747)	(3.879)
Observations	331	331	172	172	317	317
Number of groups	6	6	6	6	6	6

Standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.1

Table A4. Firm categories based on initial endowments and emission intensities

Firm category	Power generation (MWh)	Endowment (million yuan)	Emission intensity (ton/MWh)	Marginal Benefit of Permit (yuan/ton)
5	250,000	25	1.20	83
	250,000	25	1.10	91
30-High	1,500,000	150	1.10	91
	1,500,000	150	1.05	95
30-Low	1,500,000	150	1.00	100
	1,500,000	150	0.95	105
60	3,000,000	300	0.91	110
	3,000,000	300	0.90	111
100	5,000,000	500	0.88	114
	5,000,000	500	0.87	115

Table A5. Relationships of profits among treatments in mean and variance with *p*-values

		Firms with permit deficits		Firms with extra permits	Other types of firms	
		5	30-High	100	30-Low	60
CA vs. GF	mean	CA = GF ($p = 0.461$)	CA = GF ($p = 0.176$)	CA > GF ($p = 0.001$)	CA = GF ($p = 0.299$)	CA = GF ($p = 0.203$)
	sd	CA < GF ($p = 0.024$)	CA < GF ($p = 0.037$)	CA = GF ($p = 0.566$)	CA > GF ($p = 0.019$)	CA = GF ($p = 0.742$)
CA vs. UPA	mean	CA > UPA ($p = 0.002$)	CA > UPA ($p < 0.001$)	CA > UPA ($p < 0.001$)	CA > UPA ($p = 0.007$)	CA > UPA ($p < 0.001$)
	sd	CA = UPA ($p = 0.671$)	CA = UPA ($p = 0.192$)	CA = UPA ($p = 0.318$)	CA = UPA ($p = 0.301$)	CA > UPA ($p = 0.012$)
UPA vs. GF	mean	UPA = GF ($p = 0.284$)	UPA = GF ($p = 0.201$)	UPA < GF ($p < 0.001$)	UPA < GF ($p < 0.001$)	UPA < GF ($p = 0.009$)
	sd	UPA < GF ($p = 0.015$)	UPA < GF ($p = 0.015$)	UPA = GF ($p = 0.656$)	UPA = GF ($p = 0.227$)	UPA < GF ($p = 0.017$)

Note: Treatments are colored in green to indicate that they generate either the same net profits with smaller variances or larger net profits with the same variances compared with the treatments in the same cells. The related *p*-values are in parentheses.

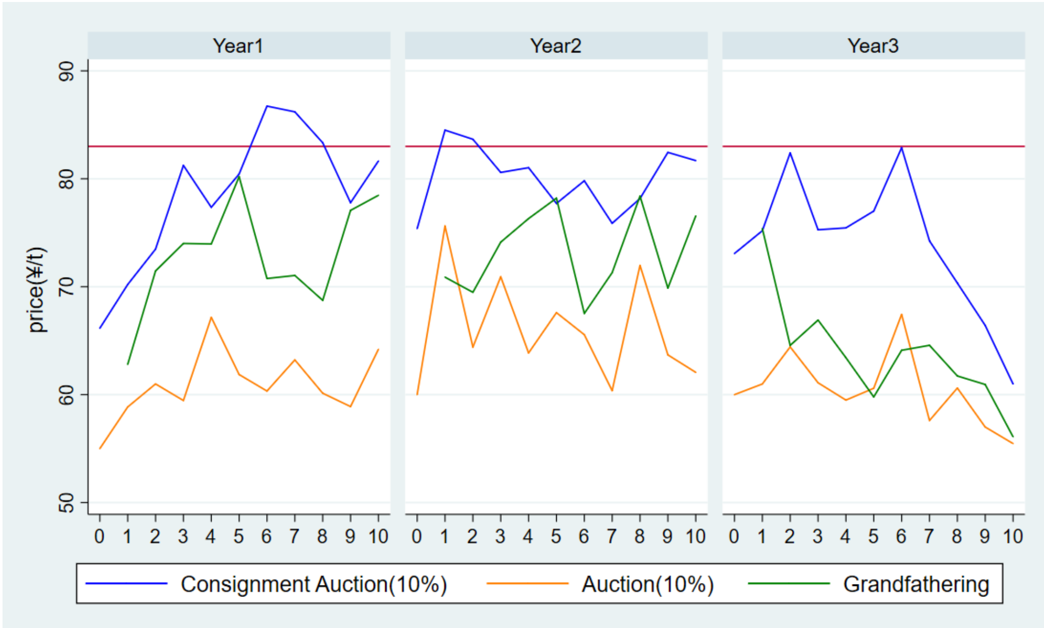

Fig. A1 The 33-second moving average of spot market transaction prices by treatment

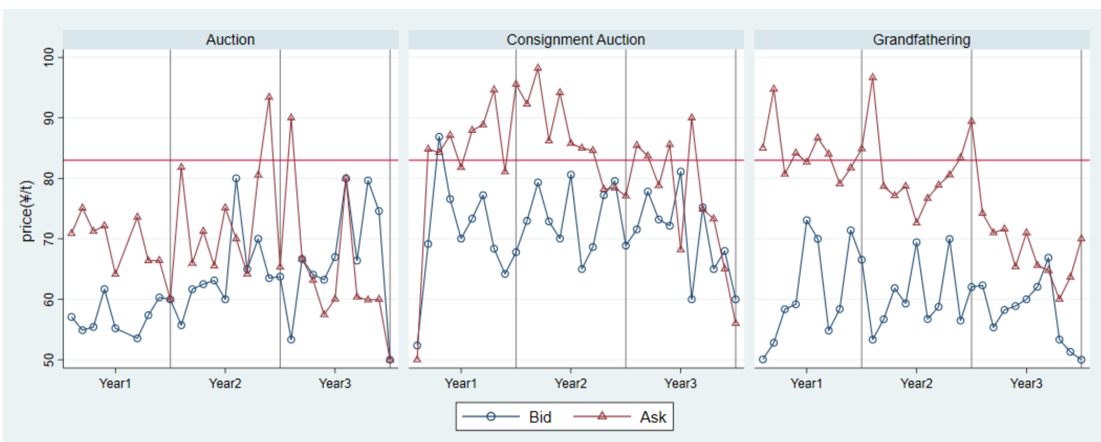

Fig. A2 The traded bid and ask prices averaged in every 33 seconds by treatment

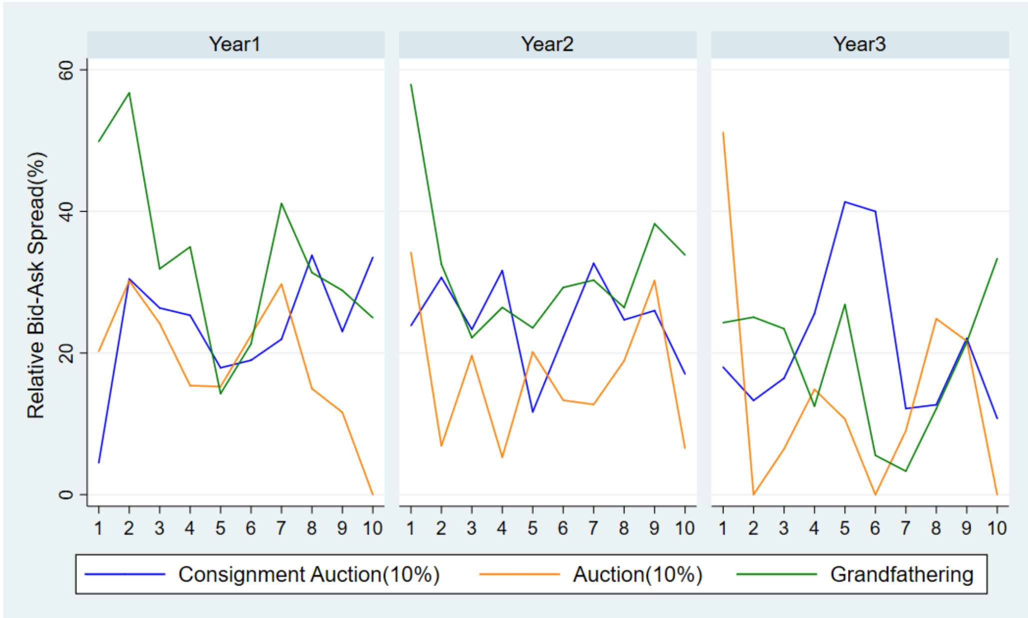

Fig. A3 The relative average bid-ask spread in every 33 seconds by treatment

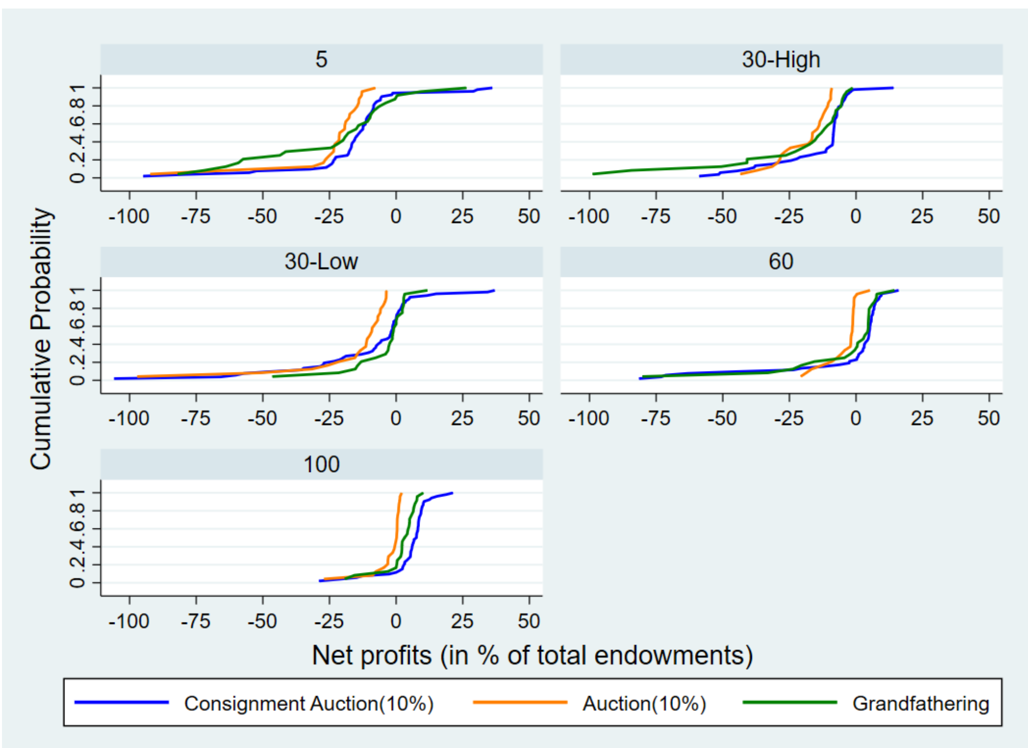

Fig. A4 Cumulative distributions of net profits by categories of firms

Fig. A5 Violin plots of net profits by categories of firms

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Online Sample Instructions for Consignment Auction

Preparation for the experiment

Platform registration: WeChat applet

Each subject needs to register on the experimental platform before participating in the experiment. Figure SI-1 shows the registration page.

Figure SI-1. Registration

Overview

This experiment is a study of how people make economic decisions. Your performance will be ranked and evaluated based on your total earnings of the experimental currency, and you will receive different levels of certificates issued by Tsinghua University as shown in Figure SI-2 according to your ranking. If you follow the instructions and make careful decisions, you will earn more of the experimental money and receive a certificate with a higher ranking. The experimental money you earn will depend both on the decisions you make and the decisions of others. Your experimental earnings (profits) will be added up over the course of the experiment. Please do not communicate with other participants in the experiment. If you have questions regarding these instructions, raise your hand and an instructor will come by to answer your questions.

Figure SI-2. Certificate from Tsinghua University

You will be participating in two rounds of emissions permit trading. At the beginning of each round, you will be randomly assigned to a group of twenty players. Each group consists of twenty coal-fired power firms of 10 types, defined based on the capacity of power generation and emission intensity. There are two identical firms in a trading market within each type, and each firm is represented by one player. Figure SI-3 demonstrates groups of 20 firms of 10 types. Firm types will be randomly assigned among the twenty players, with the type assignment remaining fixed in one round.

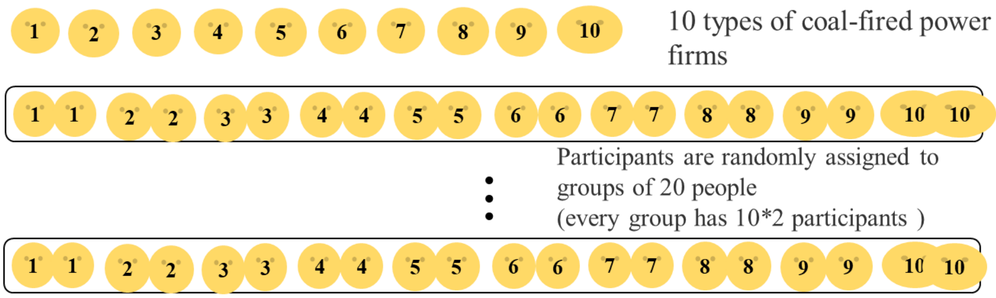

Figure SI-3. Groups of 20 firms of 10 types

An emission permit trading process consists of **three** stages (Figure SI-4).

The first stage is defined as the primary market, where you will receive permits initially for free based on a benchmark emission intensity. A pre-determined portion of your permits will be automatically collected by a third party, pooled together, and then auctioned off back to all group members.

After the primary market, you will enter a spot market, i.e., the second stage, where you can trade permits directly with each other. The transaction rules of the primary and spot markets will be explained later.

The third stage is for permits compliance, during which your permit holdings will be compared with your total emissions. You will need to pay fines (a given permit price for compliance) for permit deficits if your total emissions are greater than your permit holdings after trading.

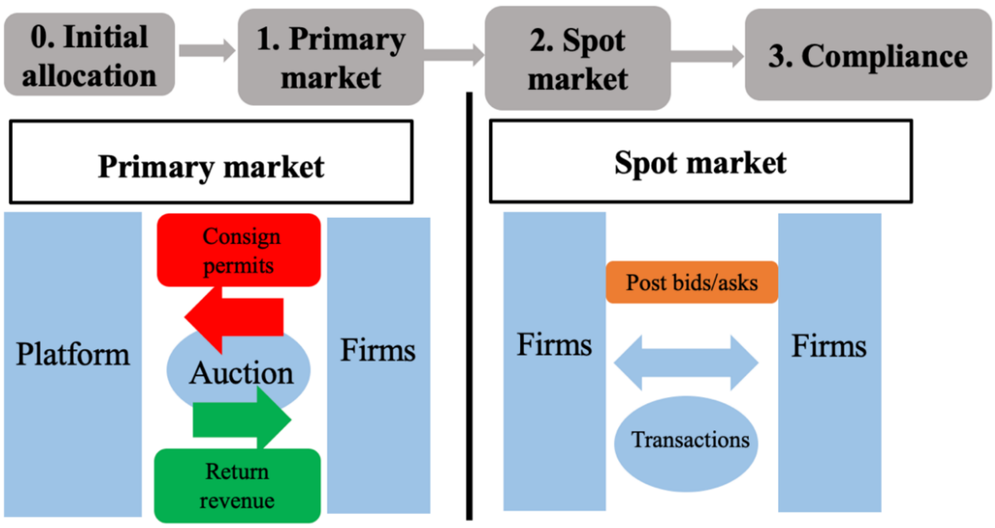

Figure SI-4. Three stages of an emission permit trading process

Each round consists of three years (periods) of emissions permit trading. In each year, you will stay in the same group to go through a complete permit trading process. Group members are reshuffled among all players over rounds. Before the first year in the first round, there is a year 0 used as a practice period. Figure SI-5 shows the arrangement of two rounds in a session.

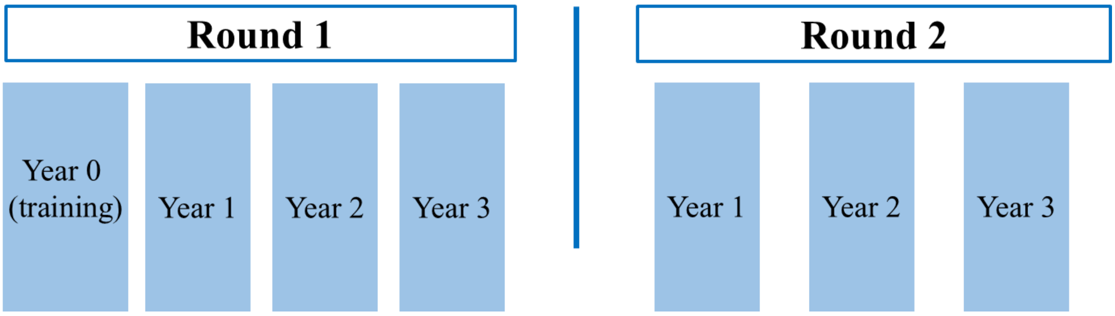

Figure SI-5. Two rounds in a session

Firms' Information

At the beginning of each round, you will learn the following information (parameters) of the types of firms you represent as shown in Figure SI-6 and Table SI-1.

Endowment: Your endowment is given by the product of your capacity of power generation (MW), the hours of power generation (5000 hours), and the output (electricity) unit profit (0.1 yuan/kWh). In the experiment, the hours of power generation and the electricity unit profit are fixed and the same for all firms. Therefore, your endowment is determined by your capacity of power generation. There are four types of generation capacity (50, 300, 600, and 1,000 MW)**.**

Emission Intensities and Emissions: Among four types of generation capacity (50, 300, 600, and 1,000 MW), the 300 MW firms have four types of emission intensities (ton/MWh), and the other three have two levels each.

$$\text{Your emission} = \text{your capacity} \times \text{power} - \text{generation } \mathbf{hours} \times \text{emission intensity.}$$

Emissions Permits: Electricity production generates emissions of pollutants. You need to hold emissions permits to produce and will be fined otherwise. Your initial endowment of emissions permits is equal to the product of your output and a pre-determined benchmark emissions intensity. Benchmark emissions intensities in years 1 to 3 are 1.015, 0.985, and 0.955 ton/MWh, respectively.

At the beginning of the primary market, 10% of your initial permit endowment will be automatically consigned to a third party for auction and will receive the sales revenue from these "consignment" sales at the end of the primary market. Therefore, your permit surplus is the difference between 90% of your initial permit endowment and your total emissions. A negative number of permit surplus indicates permit deficits.

Figure SI-6. Information display for firms

Table SI-1. Main parameters for firms

Firm type	Same in each year				Initial permits allocated		
	Capacity	Endowment	Emission	Emission intensity	Year 1	Year 2	Year 3
	MW	k-yuan	ton	ton/MWh	ton	ton	ton
1	50	25,000	300,000	1.2	253,750	258,990	251,220
2	50	25,000	275,000	1.1	253,750	258,990	251,220
3	300	150,000	1,650,000	1.1	1,522,500	1,553,940	1,507,322
4	300	150,000	1,575,000	1.05	1,522,500	1,553,940	1,507,322
5	300	150,000	1,500,000	1	1,522,500	1,553,940	1,507,322
6	300	150,000	1,425,000	0.95	1,522,500	1,553,940	1,507,322
7	600	300,000	2,730,000	0.91	3,045,000	2,877,990	2,791,650
8	600	300,000	2,700,000	0.9	3,045,000	2,877,990	2,791,650
9	1,000	500,000	4,400,000	0.88	5,075,000	4,796,650	4,652,751
10	1,000	500,000	4,350,000	0.87	5,075,000	4,796,650	4,652,751

Transaction rules for permit trading

The first stage: Consignment auction in the primary market (Figure SI-7)
You need to buy permits through an auction before you can trade in the spot market (the second stage). The auction used here is the uniform price sealed bid auction, in which everyone places a bid by specifying a price (bidding price) and a quantity (bidding quantity) for permits to buy. The lower and upper bounds of the price collar for the bidding price are 50 yuan/ton and 150 yuan/ton, respectively, and the prices posted need to be multiples of 10. You can submit your bid once a year, and you cannot withdraw your bid once it is submitted.

The number of permits to be auctioned (i.e., the supply) is 10% of your group's total initial permit endowment. When the total demand (the sum of bidding quantities) exceeds the supply, bids are ranked by price in descending order with the associated quantity accumulated up to the supply of permits to be auctioned, at which the price is the auction clearing price. Permits are then awarded to all the winning bidders at this price. Firms with a higher bidding price have a higher priority to earn the permits until the supply is exhausted. When the total demand is less than the supply, the lowest bidding price is the auction clearing price. The revenue generated by auctioning off these permits is equal to the uniform auction-clearing price multiplied by the quantity of permits awarded.

Under the consignment auction, the permits collected for auction are consigned and still owned by the firms in the sense that the revenue generated from the auction belongs to the firms. That is, the auction revenue will be fully returned to the group members, each with a share which equals the ratio of your individually consigned permits to the total of consigned permits. If the demand is less than the supply, the unsold consigned permits will be returned to you in proportion to your consigned share of the total supply.

Thus, your net profit in the primary market = market-clearing price × (your consigned permits − permits you purchased − returned permits if any)

Figure SI-7. Consignment auction in the primary market

Below are two numerical examples to demonstrate the calculations used in consignment auction.

Example 1. Consignment auction with 3 players (permit demand >= permit supply)

Firm	Permit Endowment	Permit consigned	Permit supply	Bidding price	Bidding quantity	Cumulative quantity demanded	Clearing price	Permits purchased
A	100	10	60 (=10+20 +30)	100	20	20	70	20
B	200	20		80	30	50		30
C	300	30		70	20	70		10

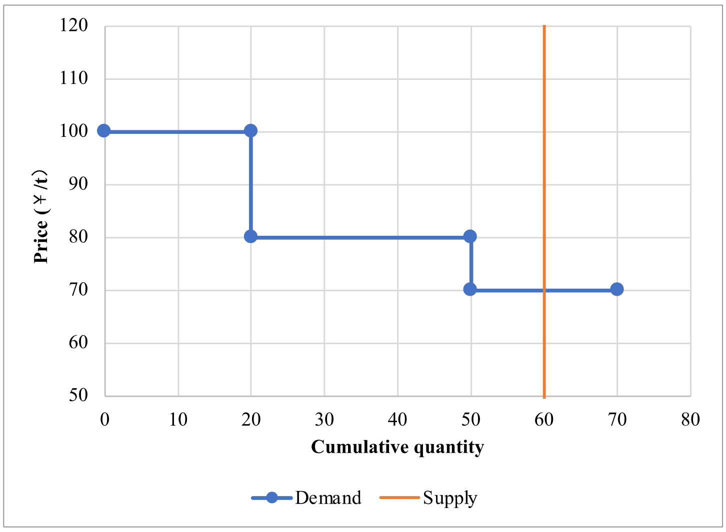

Figure SI-8. The market-clearing price for example 1

$$\text{Net profit of A} = -70 \times 20 + 70 \times 10 = -700$$
$$\text{Net profit of B} = -70 \times 30 + 70 \times 20 = -700$$
$$\text{Net profit of C} = -70 \times 10 + 70 \times 30 = 1400$$

Example 2. Consignment auction with 3 players (permit demand < permit supply)

Firm	Permit Endowment	Permit consigned	Permit supply	Bidding price	Bidding quantity	Cumulative quantity demanded	Clearing price	Permits purchased
A	100	10	60	80	10	10	50	10
B	200	20		70	10	20		10
C	300	30		50	10	30		10

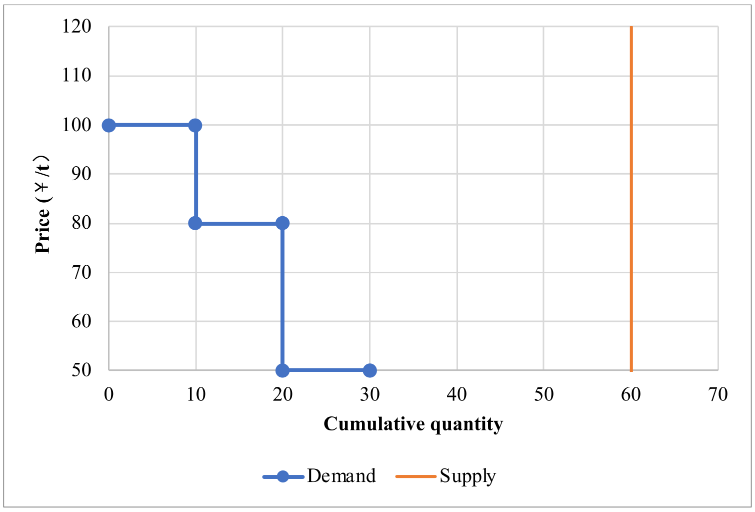

Figure SI-9. The market-clearing price for example 2

$$\text{Returned permits of A} = (60 - 30) \times 10/60 = 5$$
$$\text{Returned permits of B} = (60 - 30) \times 20/60 = 10$$
$$\text{Returned permits of C} = (60 - 30) \times 30/60 = 15$$

$$\text{Net profit of A} = -50 \times 10 + 50 \times (10 - 5) = -150$$
$$\text{Net profit of B} = -50 \times 10 + 50 \times (20 - 10) = 0$$
$$\text{Net profit of C} = -50 \times 10 + 50 \times (30 - 15) = 150$$

The second stage: Continuous double auction in the spot market (Figure SI-10)
After the primary market, you will enter the spot market where you can buy or sell permits with other group members. The continuous double auction is used for spot markets, where all firms can place buy orders (bids) or sell orders (asks) by specifying a price and a quantity for permits to trade at any time when the spot market is running (i.e., multiple posts are allowed, but posted offers cannot be withdrawn). Firms can trade with each other by either submitting their own orders or taking orders posted by others. There are two sessions of spot markets (with a short time break in between) in each year, with each session lasting a fixed length of time.

Note that your trading activity is only limited by your available permits and experimental earnings in your account. The permits you post to sell or the earnings you need for the payments of your posted orders will be preserved once you submit your asks or bids, until associated transactions are actually implemented, or until the end of a session of the spot market.

Your net profit in the spot market =
Total earnings for the permits you sell − total payments for the permits you buy

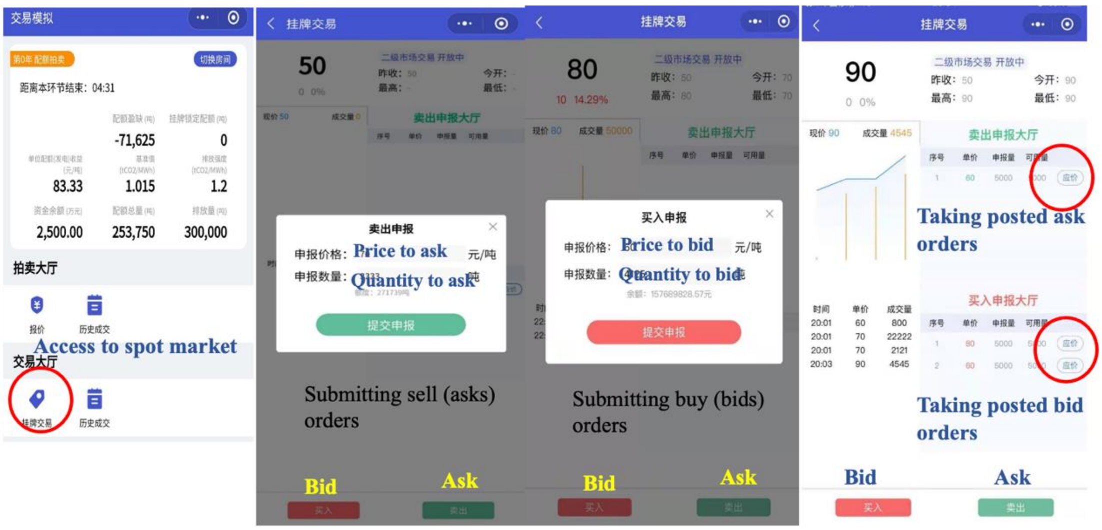

Figure SI-10. Screen shots for the spot market

The third stage: Compliance
When the time for spot markets runs out, the quantity of permits that is equal to your emissions will be deducted automatically from your permit accounts for compliance. If your

permit holdings are not sufficient to cover the emissions at this stage, you will incur a non-compliance penalty of 100 experimental yuan for each unit of uncovered emissions. If your permits holdings are greater than your emissions, the extra permits will be transferred to the next year. After the compliance in the third year, any remaining permits will be bought automatically at a price of 50 experimental yuan per unit.

To summarize,

Your earnings in year 1 or year 2

$$= \text{Endowment} + \text{Net profit in the primary market} + \text{Net profit in the spot market} - \text{fines for noncompliance if any}$$

Your earnings in year 3:

$$= \text{Endowment} + \text{Net profit in the primary market} + \text{Net profit in the spot market} - \text{fines for noncompliance if any} + \text{revenues from permit surplus after compliance if any}$$

Timetable for one round

Year 0 (only for round 1)	The primary market	300s
	Time break	30s
	The first spot market	180s
	Time break	30s
	The second spot market	180s
	Time break	90s
Year 1	The primary market	120s
	Time break	30s
	The first spot market	165s
	Time break	15s
	The second spot market	165s
	Time break	45s
Year 2	The primary market	120s
	Time break	30s
	The first spot market	165s
	Time break	15s
	The second spot market	165s
	Time break	45s
Year 3	The primary market	120s
	Time break	30s
	The first spot market	165s
	Time break	15s
	The second spot market	165s