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Regulated and Non-Regulated Companies, Technology Adoption in Experimental Markets for Emission Permits, and Options Contracts *

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Abstract

This paper examines the investment strategies of regulated companies in abatement technologies, market participants' trading behaviors, and the liquidity level in an inter-temporal cap–and–trade market using laboratory experiments. The experimental analysis is performed under varying market structures: the exclusive presence of regulated companies; the inclusion of subjects not liable for compliance with environmental regulations; the availability of plain vanilla options. In line with theoretical models on irreversible abatement investment, the first experiment shows that regulated companies trade permits at a premium. At the same time the existence of a strict enforcement structure effectively prompts investments in new technologies. The second experiment shows that the presence of non-regulated companies adds liquidity to the market and does not increase price volatility. The last experiment enables us to investigate the impact of the presence of cash-settled options contracts on the trading strategies of regulated companies. Their expected emissions appears to play a significant role in the choice of their options strategy.

Keywords: Abatement Strategy, Irreversible Investments, Participation Restrictions, Market Liquidity, Options Trading.

JEL Classifications: Q50, C02, C91, D40.

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1 Introduction

Behind the global interest in marketable permits for air pollution is the recognition that any meaningful climate change policy has to put a price on emitted carbon dioxide.[1] Pricing emissions is a fundamental lesson from environmental economics and the theory of externalities; the absence of a price charge for scarce environmental resources such as clean air leads to excessive air pollution (Baumol and Oates (1988)). The introduction of surrogate prices in the form of unit taxes or marketable emission permits induces people to economize in the use of these resources.[2] In principle, emission permits embed an economic incentive that should force companies covered by the regulation (hereafter regulated companies) to participate in the market for permits. The basic rationale behind this market is that a high price level for emission permits should attract those regulated companies with lower marginal costs for pollution abatement in order to exploit consequent price differences. Such companies make profits by lowering their level of pollution emissions by more than is necessary to comply with regulations and subsequently sell their extra permits. An effective implementation of market-based instruments, therefore, should modify the operational decisions of regulated companies, ultimately generating investments in process improvements or adoption of low pollution–emitting technologies.

Since Crocker (1966) and Dales (1968), economists have shown (in a deterministic setting) that a system of marketable permits can achieve a given level of emissions reduction in a low-cost fashion. Similarly, after Montgomery (1972), several theoretical models have been proposed to analyze the cost efficiency of a system of marketable permits and investigate its inter-temporal properties. Among others, we refer to Rubin (1996), Cronshaw and Kruse (1996), Schennach (2000), and Maeda (2004). At the same time, extensive literature on the use of laboratory experiments to investigate emission trading programs has emerged and is thoroughly discussed by Muller and Mestelman (1998), Isaac and Holt (1999) and, more recently, by Bohm (2003). Although experimental procedures have been used to evaluate policy instruments, including some aspects of emission trading programs (see Cason (1995), Cason and Plott (1996), Stranlund et al. (2005), Murphy and Stranlund (2006) and Murphy and Stranlund (2007)), these techniques have not yet been widely applied to investigate the relationship between the trading of permits and new technology adoption –exceptions include Ben-David et al. (1999), much less to the study of the impact of the presence of non–regulated companies or derivative contracts. In this paper we first experimentally investigate the effects of uncertain total pollution emissions and strict enforcement mechanisms on the timing of regulated companies' investment in irreversible emission–abating

[1]We refer to Stern (2008) and Stern (2007), respectively, for an overview and a comprehensive discussion on the economics of climate change.

[2]Cap–and–trade programs are currently quite popular. Examples include the Acid Rain Program in the U.S., the European Union Emissions Trading Scheme in Europe, the Regional Greenhouse Gas Initiative signed by ten northeastern states in North America. Canada and New Zealand, among other countries, are discussing plans to develop similar schemes.

technologies (hereafter low pollution–emitting technologies). We then extend our first experimental setting and investigate the impact of the presence of non-regulated companies on the trading efficiency of the permit market (measured with respect to the market liquidity). Finally, introducing option contracts, we study the options trading pattern of regulated companies with respect to their investments and permit trading strategies.

The control problem of investing in irreversible abatement equipment has been the subject of experimental methods (Ben-David et al. (1999)) and theoretical models (Chao and Wilson (1993), Fullerton et al. (1997) and Taschini (2008)). The experimental platform we construct allows us to study the investment and permit trading strategies of regulated companies. In line with the earlier theoretical models, we find that the market price of emission permits does not necessarily reflect the abatement cost. On the contrary, regulated companies trade permits at a –sometime relatively high– premium. From potential sellers' perspective, such a strategy might reflect companies' intent to recoup not only investment costs, but also obtain significant compensation for undertaking an irreversible investment. Thus, depending on the cost nature of the low–emitting technology, the permit price can deviate from its well-known theoretical level, i.e. the "true" marginal abatement cost. Despite high investment costs, the potential significant cost of not complying with the regulations effectively prompts companies to invest earlier in low pollution–emitting technologies. This result has clear policy implications: the abatement investment efforts of those companies facing irreversible investments are driven by the possibility of making large profits (by selling extra permits) and, equally important, avoiding potential severe losses due to the existence of strict enforcement mechanisms.

Stochastic equilibrium models have been recently employed to determine the dynamic price of emission permits while also assessing various policy aspects - Seifert et al. (2008) discuss companies' risk aversion, Chesney and Taschini (2008) investigate the effect of asymmetric information on permit price formation, Carmona et al. (2009) analyze the effect of windfall profits, and Grüll and Kiesel (2009) provide a theoretical sound discussion on the permit price slump in the first phase of the European Union Emission Trading Scheme (EU ETS). Although all these models provide a deeper understanding of the dynamic formation of the price of emission permits in a stochastic framework, they do not explicitly account for the presence of non-regulated companies in the permits market.[3] These are companies not subject to environmental regulations, but active in the permit market. Such a group includes financial institutions, brokers, and eco–friendly non–for–profit organizations. Lately, some stakeholders have raised concerns about the possible harmful impact of speculators in the markets for pollution control. In response, legislators proposed to limit participation to regulated companies by excluding non–regulated companies from

[3]Focusing on pricing contingent claim contracts in an equilibrium framework, the paper of Kijima et al. (2010) is the only article accounting for the participation of non-regulated entities in the permit market.

the market. An example of such an attempt is the Carbon Limits and Energy for America's Renewal (CLEAR) bill (S 2877), introduced by Senator Maria Cantwell. The second experiment addresses these concerns.

By introducing two new types of players not subject to environmental regulation (eco-groups and speculators) we evaluate their impact in terms of market liquidity and permit price volatility. On the one hand we observe that non-regulated companies are natural permits buyers, especially at the beginning of each experimental round. They directly enhance the liquidity of the permit market, thereby favoring investments in low pollution–emitting technologies. Such a result is statistically significant and particularly evident in the last rounds of each experimental session. Despite few observations of trading behaviors of non–regulated subjects that would add to price variability, there is no statistically significant effect on volatility. This result is consistent with Ben-David et al. (1999), who investigated the price variability in a market with more heterogeneous traders and found weak evidence for larger price volatility. Our findings, therefore, align with some of the concluding remarks of a recent report on carbon markets released by an inter-agency working group led by the U.S. Commodity Futures Trading Commission: "Open market participation promotes the development of market liquidity... Therefore, [US] carbon markets should encourage broad participation."

Lately, numerous exchanges have been offering derivative contracts on emission permits. The analysis of the concomitant presence of market-based instruments other than spot or futures contracts on emission permits is rather scant in literature. Understanding how this market works is important for those stakeholders concerned about the need to regulate such instruments. Laboratory experiments are a useful method for exploring possible outcomes given the current, limited experience. This last experiment allows us to investigate the option trade pattern of market participants, particularly that of regulated companies. We argue that the supply and demand schedule of options contracts reflects the regulated company's status with respect to technology adoption, their then (spot) permit portfolio, and their (expected) future total emissions at the moment the option(s) are traded. In particular, we observed that regulated companies with an expected shortage of permits tend to buy call or (possibly) sell put options. Regulated companies with an expected excess of permits tend to buy put or (possibly) sell call options. Orders to buy puts or sell calls are, however, less observed when regulated companies are in permit excess. The options contracts we consider are European cash-settled contracts. The cash-settlement provision prevents any impact on the initial cap (the original environmental target) and the overall number of permits in circulation.

The rest of the paper is structured as follows. Section 2 describes the experimental design and the procedures common to each experiment. Section 3 presents the results of the first experiment (irreversible investment in abatement technology amidst uncertainty about emissions and abatement costs). Section 4 and Section 5 discuss the second (presence of non-regulated subjects) and the third (concomitant presence of options contracts) experiments. The last section concludes.

2 Experimental Protocol

The aim of our experiments is to simulate a cap-and-trade system that replicates a simplified version of the EU ETS market for permits. Our attention focuses on the problematic decision of achieving compliance at minimum cost. To meet this target, regulated companies, depending on their situation, have the option of adopting an irreversible and costly cleaner technology, buying or selling the permits, utilizing permits, or any feasible combination thereof. The adoption of the new technology is undertaken in the presence of uncertain emissions and, consequently, uncertain abatement costs. Regulated companies that do not offset their emissions face severe penalties which are strictly enforced. The impact (i) of trading and investment strategies on the dynamics of the allowance price; (ii) of trading between regulated and non–regulated agents on the market liquidity; and also the trading pattern of option contracts with respect to the status quo of regulated agents, are the subjects of our analysis.

The basic setup is an emission trading scheme where the number of regulated companies (hereafter RCs) is given and fixed, ($\mathcal{I}$). The policy regulator sets an initial number of permits, i.e. the cap, and then distributes permits to RCs based on some specific criteria. We assume that the cap is set with respect to a given historical emission volume in a reference period, the so-called baseline year. In this experiment, such a reference level is the *expected* emission volume before a change in the production process takes place. As the aim of the regulator is to curb emissions, the initial allocation of permits to RCs corresponds to a pre-specified fraction $\{\gamma, 0 < \gamma < 1\}$ of their reference emission volume. Various allocation criteria exist. Here we consider and implement the criteria according to which permits are allocated for free, so-called grandfathering.[4]

RCs are characterized by their emissions and income profiles. However, for the sake of interpretation of the investment and trading strategies, we adopt a partial equilibrium approach. In particular, we work under the assumption that the adoption of technological innovation reduces emissions, but does not influence the output quantity and price. Therefore, we disregard RCs' decision on output production and assume RCs are price takers in the output market.[5] We

[4]The European Union Emission Trading Scheme currently implements a grandfathering allocation criterion. This grants RCs an initial number of permits equal to a certain percentage of their pollution emitted at a fixed baseline year. In the first phase, 1990 was the baseline year for the majority of the participating European countries. We refer to Aihman and Zetterberg (2005) for a comprehensive discussion about other allocation criteria of emission permits.

[5]The analysis of the inter-relationship between permit and output markets has been undertaken by Misolek and Elder (1989), Hahn (1983), and Malueg (1990) respectively. Wräke et al. (2008) use a laboratory experiment to assess how much of the permits' value is passed on by participants through output electricity prices.

assume the abatement investment can only occur once during the regulated period $[0, T]$, and that it is irreversible.[6] Consistent with the theoretical equilibrium models of Seifert et al. (2008), Chesney and Taschini (2008) and Carmona et al. (2009), pollution emissions $Q^i(t)$ are uncertain, $\{Q^i(t), t = 1, 2, \ldots, T; i \in \mathcal{I}\}$. In order to keep our model tractable, we consider the following simple, binomial dynamics for the emissions at each period t:

$$Q^i(t) = \begin{cases} q_u^i, & \text{with probability } p. \\ q_d^i, & \text{with probability } 1-p, \end{cases} \quad \text{where} \quad q_u^i > q_d^i, \quad \text{for} \quad i \in \mathcal{I}. \tag{1}$$

The factors q_u^i and q_d^i denote the production regime of the i-th RC from time $t-1$ to t. RCs' productions are subject to economic and financial shocks, among other factors. These are assumed to be exogenous, with the demand for an RC's products contingent on phenomena beyond its grasp (a widespread crisis or a product demand collapse, for example). When demand is high, RCs' emissions are high (q_u), whereas a lower demand is represented by lower emissions (q_d). p indicates the probability of the event *high demand* and, for the sake of participants' computational efforts, it is assumed constant and equal to 50%, i.e. $p = 0.5$. The realization of the states of the economy, however, are drawn from $\mathcal{I}$ independent uniform distributions. Pollution emissions, therefore, are purely random in the experiment. Nevertheless, because state probabilities are constant and independent, it is straightforward to compute the expected total volume of emissions. Recalling Equation (1), the total volume of pollution emitted at time t by the i-th RC is simply given by the sum of all emissions up to time t, i.e. $\sum_{s=0}^{t} Q_{\cdot}^i(s)$, where $\{\cdot = (old, new)\}$ indicates *old* or *new* technology. We also consider two different types of regulated companies: high $\{H\}$ and low $\{L\}$ emitters and we label them High-RCs and Low-RCs, respectively. As described before, the emission reference level corresponds to the total *expected* pollution volume with the old technology, $\mathbb{E}[\sum_{s=0}^{T} Q_{old}^i(s)]$, where $i \in \{H, L\}$, and $\mathbb{E}$ represents the expectation operator. By construction, High-RCs are characterized by a higher expected emission volume as opposed to Low-RCs, i.e. $\mathbb{E}[\sum_{s=0}^{T} Q_{old}^h(s)] > \mathbb{E}[\sum_{s=0}^{T} Q_{old}^l(s)]$, where $h \in \{H\}$ and $l \in \{L\}$. Consequently, High-RCs receive a higher initial number of permits than Low-RCs.

At the end of the compliance period, the regulator requires RCs to reconcile their permit holdings with their accumulated emissions. In practice, each RC must own a sufficient number of emission permits to cover the final pollution volume at the end of each experimental session. Conversely, a penalty, P, per missing permit is levied. In our experiments this parameter corresponds to 40 units of experimental money. RCs control their compliance strategy adopting an irreversible and costly cleaner technology, buying or selling the permits, utilizing permits, or any feasible combination thereof. More precisely, at every period $t = 1, 2, \ldots, T$, each RC can (i) decide (if not

[6] We refer to Chao and Wilson (1993), Fullerton et al. (1997) and Taschini (2008) for theoretical models which address the problem of investing in irreversible emission abatement equipments. Using laboratory market experiments, Ben-David et al. (1999) investigates technological heterogeneity and irreversible investment.

done before) to undertake an abatement investment that reduces the future expected emission volume, and (ii) trade permits or (iii) hold on to the number of allowance possessed. Whether undertaken by a High-RC or a Low-RC, the investment in low pollution–emitting technology is an irreversible and costly decision that is assumed to reduce the expected pollution emissions. Because the overall regulated period is finite, T, the adoption of the abatement technology generates a limited in time benefit. Further, pollution emissions, and consequently emission reductions, are uncertain. The opportunity cost (benefit) to adopt low pollution–emitting technologies, therefore, is uncertain as well.

For convenience, an identical initial budget is allocated to all RCs. Let I represent the cost for installing the new technology and let us set I equal to a fixed fraction α of the initial budget. Because initial budgets are identical and RCs are characterized with respect to the intensity of their emissions, High-RCs and Low-RCs face different opportunity costs when adopting the new technology.[7] At every period t, we can quantify the time-dependent opportunity cost to invest in the new technology by evaluating the expected cost per reduced unit of emission:

$$C^i(t) = \frac{I}{\mathbb{E}\left[\sum_{s=t}^{T} Q^i_{old}(s) - \sum_{s=t}^{T} Q^i_{new}(s)\right]}, \quad i \in \{H, L\} \quad \text{and} \quad t = 1, 2, \ldots, T-1. \tag{2}$$

Here $Q^i_{old}(s)$ and $Q^i_{new}(s)$ represent the emission at time s before and after the adoption of the low pollution–emitting technology, respectively. Figure 2 represents graphically the time-dependent and intensity-specific opportunity cost of adopting a new technology that halves the high pollution emissions scenario. In particular, Figure 2 represents the expected cost per reduced unit of emission for both Low-RCs (left) and High-RCs (right) when $\alpha = 40\%$. Intuitively, the later the adoption of the new technology, the shorter the useful remaining time period and, consequently, the higher the expected cost per unit of reduced emission.

According to the net-present-value approach, $C^i(t)$ is the critical level at time t at which the decision to adopt the new technology should be taken by company i. If the permit market price is higher than $C^i(t)$, the i-th company would be better off selling permits and using the proceeds to finance the technology adoption. A larger permit supply, and a corresponding reduction in the permit demand, would then induce lower future permit prices. Conversely, if the permit market price is lower than $C^i(t)$, the i-th company would be better off buying cheaper permits and not adopting the low pollution–emitting technology. In this case we would expect an increase in the future permit market price.[8]

[7] Due to more stringent air quality regulations in recent years, newer plants typically have more sophisticated emissions control technology already installed. So, for a given industrial sector and a given level of output, companies employing old technology (High-RCs in our case) often emit relatively higher amounts of pollution emissions and can typically control them more cheaply.

[8] Such a strategy assumes instantaneous investments and unlimited availability of market counter-parties.

Experimental Procedure Experiments were conducted at the Laboratory of the Department of Banking and Finance of the University of Zurich. The subject pool was composed of graduate students, mostly with economic or finance background. Based on students' answers to a questionnaire distributed at the beginning of each session, most of them had a good understanding of the dynamics involved in the game.[9] After all subjects arrived for the session, they were randomly assigned to a private computer. Each session began with an instruction period. Once everyone finished reading the instructions and answering the controlling questions, the first trading round began. The relatively simple construction of the experimental market did not require subjects to participate in training sessions, and instructions provided to subjects were sufficiently detailed to avoid extra oral explanations.

The experiment consisted of six sessions (two without, two with non-regulated companies, two with non-regulated companies and option contracts). Each session had four rounds, with each round consisting of 20 periods (60 seconds per period). Every trading period, therefore, is repeated 160 times (corresponding to a minimum number of 160 decisions per experiment). The number of subjects in the experiments ranged from 12 (only RCs) to 18 (12 RCs plus non RCs) per session, for a total of 88 subjects and a constant number of RC's throughout all experiments. The first experiment (two sessions) ran over Z-Tree, a toolbox designed for economic experiments at the Institute for Empirical Economics of the University of Zurich. Subsequently, we developed an *ad-hoc* java-based experimental platform. In all sessions the main parameters were fixed and clearly stated in the instruction paper as shown in Table 1. An excerpt of the instruction paper is included in the Appendix. Each computer screen reported all relevant information. In particular, emission intensities (q_u^i, q_d^i) and their probability p, the cost for abating emissions, and firm-specific initial number of allowances were reported on each screen.

At each period t every computer screen also reports the current volume of emitted pollution $(\sum_{s=0}^{t} Q^i(s))$ and the corresponding remaining number of unused emission permits. This last number corresponds to the sum of all permits purchased or sold up to time t, plus the initial number of permits, minus the present emission volume. A negative number implies a current shortage of emission permits. The RC_i's historical pollution emissions $(\sum_{s=0}^{t} Q^i(s))$, the historical pollution emissions of the remaining RCs $(\sum_{j=1,j\neq i}^{\mathcal{I}} \sum_{s=0}^{t-1} Q^j(s))$, and the time series of the permit price $(S(s), s = 0, \ldots, t)$ are reported graphically. Similar to the model of Chesney and Taschini (2008), the aggregate emission volume is observable with a one-period lag.[10] The computer screen also reports the current emission volume, as well as the maximum and minimum *expected* emissions (respectively, aggregate emissions) volumes for RC_i (respectively, including

[9] Although most of the students had a clear interest in the compliance managerial tasks, students' motivation was not a concern given the fundamental trading decisions under investigation in the experiments.

[10] A one time lag imposed on the observation of others emissions accommodates the realistic existence of non-perfect information. We refer to the model of Chesney and Taschini (2008) for further discussion about the modeling of partial information and its theoretical implication on dynamic equilibrium pricing.

Global Parameters	
Number of rounds	4
Number of periods T	20
Number of High-RCs and Low-RCs	10-14
Initial lab. money RCs	1.000
Penalty P	40
Investment cost I	400
$\{q_u^L, q_d^L\}$	$\{12, 5\}$
$\{q_u^H, q_d^H\}$	$\{30, 10\}$
States probability, p	50%
Percentage of free allocated permits	70%
Number of free allocated permits	$\{119, 280\}$
Extra Parameters	
Initial money eco-groups	2.000
Initial money speculators	4.000

Table 1: The first set of global parameters characterizes all three experiments. The extra parameters are information relevant for the last two experiments.

every $\mathrm{RC}_j, j = 1, \ldots, \mathcal{I}, j \neq i$). A screen shoot that includes these information is reproduced in the appendix. A number of relevant information is, therefore, provided to market participants and ultimately reflected in the observed permit price dynamics.

This experiment places RC-subjects in a decision context that resembles the situation a regulated company faces in a typical emissions-constrained economy. Every company produces and, as a by-product, pollutes. However, at a pre-specified date each regulated company has to surrender a sufficient number of permits. As mentioned before, we assume that the adoption of a low pollution–emitting technology reduces emissions but does not influence the output quantity. This allows us to disregard the subjects' decision on output production. Thus, the adoption of low–emitting technology, the trading of emission permits, and the utilizing of permits are the only alternatives at RCs' disposal to control emissions and achieve compliance. Such decision strategies are modeled here in a discrete dynamic framework. At every period t the computer screen shows two distinct columns where each player can enter her/his bid or ask offers and the corresponding quantity of permits she/he is willing to buy or sell. Offers must respect budget and permit portfolio constraints. A player could also decide to hold on to the permits possessed by pressing a specific button ("No selling - No buying"). At every period, each RC can also decide to undertake (if not done previously) an irreversible abatement investment by clicking the button "Change technology". As a result, the corresponding higher emission level is halved and her/his budget is reduced by an amount equal to $\alpha \cdot I$. At the end of each session, which corresponds to period T, the computer screen reports the final budget, net potential penalty costs for RCs, and the final net number of permits. All subjects are financially rewarded based on their performances.

Recalling that emission permits have no redemption value after T, each subject's final payoff simply depends on her/his final budget.

Each i-th regulated company starts with an initial budget of 1,000 units of experimental money and $\gamma \cdot \mathbb{E}[\sum_{s=0}^{T} Q^i_{old}(s)]$ allowances. RCs' objective is clearly: maximize profits while meeting compliance. In the experiment, RCs' profit corresponds to CHF 0.6 for every 100 units of remaining experimental money (net potential penalty costs at maturity).[11] Eco-groups and speculators, two types of players not subject to environmental regulations (non-RC) and introduced in the second experiment, receive an initial budget that is double and quadruple, respectively, the RCs' initial budget. As they are excluded from regulations, however, they do not receive initial emission permits. Recalling that non-regulated companies have no compliance obligations, their performance depends exclusively on their trading strategies. Speculators, labelled FIs, are rewarded based on their final amount of experimental money in excess of their initial budget. Performances of eco-groups, labelled NGOs, are measured in terms of final permits holdings. In particular, every FI obtained CHF 1.20 for every 100 units of experimental money beyond the initial 4.000; and every NGO obtained CHF 1 for every 10 permits. Because emission permits have no redemption value, it is in the FIs' best interest to disinvest their permit portfolio before period T, whereas NGOs simply needs to collect as many permits as possible (more on this later).

The average earnings per RC were CHF 35, whereas the average earnings per FI and NGO were CHF 25 and CHF 32, respectively. These amounts include a CHF 15 show-up fee to encourage prompt arrival. Once subjects are paid, they are excused from the laboratory. All sessions lasted approximately 2 hours.

Market Price Mechanism The following steps comprise a single period of a session for all three experiments under investigation. Every player can enter her/his so-called "revealed" demand (or supply) schedule for permits in the form of a combination of a bid (or ask) price and the corresponding permits quantity. The market price mechanism which administers all transactions and then informs each subject whether her/his purchase or sale, is quite standard. In each period bids are ranked from high to low, and offers from low to high. This generates a "revealed" demand and "revealed" supply schedule similar to that shown in Figure 3. The total number of transactions of emission permits is determined by the intersection of the demand and supply schedules at each period. As we are in a discrete setup, this market price is in fact the one that maximizes the overall traded quantity of permits. This mechanism is commonly proposed in designing order books and also operationalized in several experimental economics papers.[12] In the presence of a non-unique maximum quantity, we consider the so–called *first mover advantage* criteria that identifies one unique solution in a quite simple manner. Let us define Λ as the set of prices that

[11]Negative values correspond to a zero payoff.

[12]This scheme is presented in more detail in Schindler (2007). Cason and Plott (1996) and Cronshaw and Kruse (1999) employ a similar procedure to determine the price of SO_2 permits in the U.S. market.

maximizes the quantity traded. If the first price in chronological order in Λ is a bid-price, then the market price corresponds to the $\min\{\Lambda\}$. Conversely, if the first price in chronological order in Λ is an ask-price, then the market price corresponds to the $\max\{\Lambda\}$. After all transactions are completed, permit stocks and monetary balances are updated, $\mathcal{I}$ new emission realizations are drawn from a uniform distribution and the next period begins.

3 Experiment one: adoption of irreversible abatement technology and permit price

The percentage of Low-RCs and High-RCs that do not adopt the new technology in any period is the highest in the first round. This is observable across all six sessions. Penalty payments, in fact, severely decrease in magnitude and frequency in the subsequent rounds. As Figure 4 suggests, a possible learning effect vanishes immediately after the first round. Results from the first rounds, however, should not be disregarded. They convey relevant policy implications. The impossibility to borrow permits from future -next round- allowances allocation let RCs be faced with their inability to meet compliance in a advisable fashion. The lack of borrowing provisions, implemented in the experiment with a marked separation between consequent rounds, therefore, reinforces the incentive to undertake irreversible investments. Such a policy feature, together with the presence of a strict enforcement structure, represented by an unavoidable compliance verification process and high penalties for non-compliance, effectively spur investments in new technologies. This is graphically observable also in Figure 5. The upper diagram of Figure 5 represents the percentage of Low-RCs and High-RCs that adopt the new technology immediately, i.e. at period 1. The number of regulated companies that undergo a low–emitting technology adoption increases dramatically across the four rounds. The lower diagram of Figure 5 reports the percentage of Low-RCs and High-RCs that never adopt low–emitting technology across the four rounds. This number decreases quite significantly across the four rounds. Table 2 investigates the adoption of low–emitting technology round-by-round. Consistent with Figure 5, Table 2 shows that the majority of RCs in fact adopt the new technology quite early, i.e. during the first periods.

Median (period)	round 1	round 2	round 3	round 4
High-RC	3	1	1	1
Low-RC	9	1	1	1

Table 2: Median of the period of technology adoption across all sessions.

As reflected by the variation in the slope of the percentage of RCs that never adopt the new technology, this effect is stronger for High-RCs. The lower diagram of Figure 5, in fact, shows a constant decrease in the percentage of High-RCs that never adopt the low–emitting technology.

On the contrary, a significant number of Low-RCs prefer to hold on to the abatement investment. The rationale behind such a result is the fact that High-RCs and Low-RCs are faced with different incentives in investing in the new technology. To better understand this, let us differentiate among the compliance status of RCs. In general, a low permit price makes the investment in the new technology a non-viable strategy. RCs in permits shortage would find compliance by means of allowance purchase a cheaper alternative. Conversely, a high permit price increases potential profits from the sale of extra permits and raises potential compliance costs due to uncovered emissions. In practice, each RC tries to answer the question: will the irreversible pollution-reducing capital-spending cost less than the potential revenues from allowance sales plus avoided penalties? Or would waiting to invest in the new technology and perhaps offset emissions by purchasing cheap allowances be a better strategy? This might provide incentives for some RC to free ride on the other firms' investments. Because Low-RCs face low opportunity costs, as opposed to High-RCs, such an incentive might be stronger for them.[13] It is important to notice that in all experiments, regardless of the different opportunity costs, the potential compliance costs and the enforcement structure are sufficiently stringent to render an irreversible investment in low pollution–emitting technology a viable alternative for Low-RCs. Such a strategy is evident starting from the second rounds, as reported in Figure 5.

The first experiment also conveys a second relevant result which is intimately related to the previous discussion. Under irreversible and limited-in-time abatement technology adoption, the permit price does not necessarily reflect the proxy for the marginal abatement cost we introduced in Equation (2). Given the fixed investment cost structure, the marginal abatement cost can be approximated by the *expected* cost per reduced unit of emissions, $C(t)$. Assuming this holds, the difference between the marginal abatement cost and the observed permit price can be easily computed. A Low-RC (High-RC) that, for instance, adopts the low–emitting technology at period one, or keeps the old technology, should be expected to offer or to buy permits at a price in the range of 7-8 (2-3) units of experimental money. This is not the case, as shown graphically by Figure 6 and Figure 7. These figures, similar to those observable in the previous sessions, represent the marginal cost approximation for Low-RCs and High-RCs compared to the allowance price observed during the four rounds of the 5^{th} and 6^{th} sessions, respectively. Consistent with the findings of Chao and Wilson (1993), Fullerton et al. (1997) and Taschini (2008), RCs typically offer to sell or to accept to buy permits at a premium. Observed prices, therefore, are often higher than their *expected* cost per reduced unit of emissions. The premium that sellers charge reflects their intent to recover technology costs including a significant compensation for undertaking an irreversible abatement investment. In a similar way, the savings realized by postponing the irreversible abatement investment justifies the premium buyers accept to pay.

[13]This classic free-rider strategy is more risky in the presence of a larger number of competing buyers (including non-regulated companies) in the market for permits.

4 Experiment two: non-regulated companies, (il)liquidity and trading efficiency of the permit market

By definition, emission permits are fully transferable. In particular, permits could be traded by companies not subject to environmental regulations. An experimental investigation of the potential impact of such market players on the permit market liquidity is lacking. This section investigates how the presence of non-regulated companies influences the liquidity level and the trading efficiency of the permit market. Moreover, because companies not subject to environmental regulations have priorities and objectives different from those of regulated companies, the impact of the presence of non-RCs on the overall price variability is discussed as well.

This section expands the experimental platform described in the previous section. In particular, we introduce two new stylized types of market participants: eco-groups and pure speculators. Eco-groups (hereafter NGOs) represent those institutions that desire to retire permits, thereby denying their use to legitimize emissions and, consequently, create permit scarcity. The lack of permits should be reflected in higher permit prices and, ultimately, in stronger incentives to adopt low pollution–emitting technologies. NGOs' optimal strategy is, therefore, to withdraw from the market as many permits as possible given their budget constraints. Pure speculators (hereafter FIs), instead, represent true profit seekers who consider the permit market as a new opportunity to realize profits. FIs' optimal strategy is clearly to buy permits first and then sell them in the market at a profit. Non-regulated companies, in fact, do not receive emission permits. Both NGOs and FIs, therefore, need to purchase permits before being able to actively participate in the permit market. As a result, NGOs and FIs are natural permit buyers, especially at the beginning of each round, and significantly contribute to permit market liquidity. The relevance of having a sufficient number of potential permit buyers is particularly important in the third and fourth rounds. In these rounds, as observable in Figure 5, the majority of the RCs undertake the investment in the low pollution–emitting technology. In principle, the higher the number of RCs that undertake the investment, the larger the potential quantity of permits that can be offered for sale. Clearly, an excessive supply of permits that is not offset by sufficient demand depresses allowance prices. In this case extra buyers participating in the market might be helpful. Indeed, we observe that the presence of NGOs and FIs sustains the permit price at the beginning of these rounds and maintains market liquidity afterwards.

The contribution of non-regulated companies is analyzed in terms of impact on the liquidity level of the permit market. We propose two measures that attempt to quantify the liquidity level under three different conditions: "RCs" corresponds to a permit market without non-regulated companies; "RCs/1 NGO/1 FI" corresponds to a permit market with 1 eco-group and 1 speculator; and "RCs/3 NGO/3 FI" corresponds to a permit market with 3 eco-groups and 3 speculators.

Considering a total of six sessions, each condition has been tested twice. Each pair contains a constant number of 24 regulated companies and, therefore, a constant number of distributed allowances granting a coherent comparison of the liquidity level (total available allowances) among the three pairs of sessions. An ANOVA analysis comparing the variation within treatments with the variation across treatments is used to assess the impact on the liquidity level.[14] Non significance of the test associated with the one-way analysis of variance implies that the presence of non-regulated companies has no effect on the liquidity level of the permit market. Conversely, significance implies that the liquidity level is statistically different in the presence of non-RC market participants.[15]

The first measure $\mathcal{T}(t)$, labeled as *effective trades*, counts the number of buyers' and sellers' offers that are successfully matched. The measure $\mathcal{T}(t)$ quantifies at each period $t \in [0, \ldots, T]$ of every round the number of trades that successfully take place and, therefore, measures the activity level of the permit trading market.

All Companies	N	Mean	Std. dev.	Std error	Min	Max
RCs	160	1.87	1.85	0.14	0	8
RCs/1 NGO/1 FI	160	2.41	1.77	0.14	0	7
RCs/3 NGO/3 FI	160	3.16	2.07	0.16	0	9
Only RCs	N	Mean	Std. dev.	Std error	Min	Max
RCs	160	1.87	1.85	0.14	0	8
RCs/1 NGO/1 FI	160	1.97	1.57	0.14	0	7
RCs/3 NGO/3 FI	160	2.29	1.74	0.13	0	7

Table 3: Summary statistics of the *effective trades* measure $\mathcal{T}$ (i.e., the numbers of buyers' and sellers' offers that are successfully matched. The upper panel considers trades among all companies. The lower panel disregards trades among non-regulated companies and between regulated and non-regulated companies. "RCs" corresponds to the sessions without non-regulated companies (first pair of sessions); "RCs/1 NGO/1 FI" corresponds to the sessions with 1 eco-group and 1 speculator (second pair of sessions); and "RCs/3 NGO/3 FI" corresponds to the sessions with 3 eco-groups and 3 speculators (third pair of sessions).

Table 3 reports some summary statistics (standard deviation, standard error, minimum and maximum observed) relative to the mean of measure $\mathcal{T}(t)$ pooling together all rounds under the three different conditions. In particular, the upper panel of Table 3 considers the numbers of buyers' and sellers' offers that are successfully matched among all companies. To better understand the contribution of non-regulated companies to the overall liquidity of the permit market, the lower panel of Table 3 disregards all transactions among non-regulated firms and between non-regulated

[14] A one-way analysis of the variance, ANOVA, assesses whether the mean of each proposed measure differs significantly among the three conditions. In our case the null hypothesis to be tested is whether the markets under the three conditions have the same means of a specific measure. The alternative hypothesis is that at least under one condition the mean of that measure is significantly different.

[15] In this last case we know that under other conditions the market performs differently. We do not know, however, which conditions vary. By assuming equal variances among the tested groups, the post-hoc Tukey test offers an answer to this question. When the homogeneity assumption is violated we need to run the post-hoc Games-Howell test.

and regulated companies. An ANOVA analysis rejects the null hypothesis of the means being equal across both *All Companies* and *Only RCs* treatments at the 1% and 10% level, respectively.[16] In addition, post-hoc Tukey test reveals significantly contrasting performances among the various markets. The level of *effective trades* is statistically different and, therefore, the presence of non-RCs adds liquidity to the market.

The second measure $\#\mathcal{T}(t)$, labeled as *volume of traded permits*, counts the number of permits that are successfully exchanged at each period $t \in [0, \ldots, T]$. The total number of allowances traded measures the activity level of the permit market, regardless of the number of buy and sell orders left unsatisfied. Ben-David et al. (1999) investigated a the same variable, exchanged volume, in order to test the activity level of the experimental market.

All Companies	N	Mean	Std. dev.	Std Error	Min	Max
RCs	160	9.76	14.3	1.13	0	75
RCs/1 NGO/1 FI	160	14.02	18.3	1.45	0	127
RCs/3 NGO/3 FI	160	18.07	20.1	1.59	0	100
Only RCs	N	Mean	Std. dev.	Std Error	Min	Max
RCs	160	9.76	14.3	1.13	0	75
RCs/1 NGO/1 FI	160	7.06	11.1	0.88	0	82
RCs/3 NGO/3 FI	160	5.99	8.21	0.65	0	30

Table 4: Summary statistics of the *volume of traded permits* measure $\#\mathcal{T}$ (i.e., the number of permits that are successfully exchanged at each period $t \in [0, \ldots, T]$. The upper panel considers trades among all companies. The lower panel disregards trades among non-regulated companies and between regulated and non-regulated companies. "RCs" corresponds to the sessions without non-regulated companies (first pair of sessions); "RCs/1 NGO/1 FI" corresponds to the sessions with 1 eco-group and 1 speculator (second pair of sessions); and "RCs/3 NGO/3 FI" corresponds to the sessions with 3 eco-groups and 3 speculators (third pair of sessions).

Table 4 reports some summary statistics relative to the mean of the measure $\#\mathcal{T}$ pooling together all rounds together. As before, the upper panel of Table 4 considers the number of permits that are successfully exchanged at each period $t \in [0, \ldots, T]$. The lower panel of Table 4 disregards all transactions among non-regulated firms and between non-regulated and regulated companies. In contrast to Ben-David et al. (1999), an ANOVA analysis rejects the null hypothesis of the means of the *volume of traded permits* being equal across both *All Companies* and *Only RCs* treatments at the 1% level. In their experimental markets, Ben-David et al. (1999) observe that the presence of (more) heterogeneous agents does not result in higher volumes of trades. In our experimental market, tests indicates that the total volume of trades in the market with 3 NGOs and 3 FIs is a great deal larger than the other two markets.

In principle, the larger the number of active (non-RCs) traders, the larger the level of observed activity on the market. A closer look to our results, however, reveals a few more interesting

[16]Results of the one-way ANOVA test and summary statistics corresponding to the single rounds are not reported here for the sake of brevity and are available upon request from the authors.

results. The bottom panel of Table 3 reports a lower, yet increasing $\mathcal{T}$, the number of trades that successfully take place at each period. The bottom panel of Table 4, instead, reports a significantly decreasing $\#\mathcal{T}$, the number of permits successfully exchanged at each period. Recalling that the two measures are re-computed disregarding all transactions among non-regulated firms and between non-regulated and regulated companies, such results leads to the following considerations. The contribution of non-regulated companies to the increase in *effective trades* is significant, but not exclusively ascribable to them. Such a contribution can be quantified by computing the difference between $\mathcal{T}$ under the various conditions with and without non-regulated companies and by taking their ratio. Considering 1 NGO and 1 FI, for instance, the percentage of the increase in $\mathcal{T}$ -due to the mere presence of non-regulated companies- which goes to RC, is almost 20 percent. This number is obtained by computing the ratio $(1.97 - 1.87)/(2,41 - 1.87)$. With 3 NGOs and 3 FIs such a number decreases slightly to 30 percent. Because $\#\mathcal{T}$ represents the quantity of permits successfully exchanged (per trade) among regulated firms, its decreasing trend can be interpreted in a straeighforward way. A significant part of the permits successfully exchanged (per trade) comes from trades among non-regulated companies or between regulated and non-regulated companies.

The presence of non-regulated companies, therefore, directly enhance the liquidity of the permit market, thereby favoring investments in low pollution–emitting technologies. If the market liquidity varies when non-RCs are participating, can we observe an impact on the price variability? We run, therefore, an exercise similar to the analysis undertaken by Ben-David et al. (1999). The experimental evidence, they report, is inconclusive. Our analysis is consistent with Ben-David et al. (1999) findings. In our experiments, in fact, there are only few observations of a high price variability. These observations, as predicted by Seifert et al. (2008) - Section 4, are concentrated toward the end of the experimental rounds, i.e. T. On the one hand, because unused permits have no redemption value after period T, such a higher price variability could be ascribable to desperate attempts to liquidate permit holdings when the overall market is in permit excess. On the other hand, because a penalty is levied for non-offset emissions, price variability could be ascribable to attempts to corner the market when the overall market is in permit shortage. Despite these few observations of trading behaviors, however, there is no statistically significant effect of the presence of non-regulated traders on the price variability of allowances.

5 Experiment three: vanilla options and permit price

The fast-growing market for plain vanilla contracts (European options) is another aspect that has not been theoretically and experimentally investigated thus far. Options should be used by RCs to optimally manage the costs associated with compliance requirements. For instance, RCs that adopt the low pollution–emitting technology with the intention of selling unwanted permits in the market might be discouraged in doing so by the possibility of not being able to sell permits at an appropriate price eventually failing to recoup the investment costs. Put options offer insurance against future permit prices that are too low. Focusing on how regulated companies make use of such contracts, we investigate RCs' options trading pattern with respect to their level of technology adoption and their permit trading strategies. Typically, RCs with an expected permit shortage (excess) buy call (put) or possibly sell put (call) options. However, the case of orders to buy calls and sell puts when regulated companies are in permits excess is less observed.

This experiment structure is built on the previous ones and consists of three sessions. Unlike the previous experiment, here both regulated and non-regulated companies could trade options. Due to regulatory stipulations, the cap is fixed and permits cannot be created. Thus, we considered only option contracts with cash–settlement provisions. Furthermore, as compliance has to be met only at the end of the regulated period, we make use of European-style options. However, we set the maturity of the options to not overlap with the end period T in order to test for trading volume impacts. In particular, a new screen with two distinct columns (one for European call and one for European put options) appears on the monitor of each computer at time $T/2$. All options have a maturity equal to $T-3$ and a strike price equal to the permit price $S_{T/2}$. These at-the-money options are automatically priced according to the well-known Black and Scholes option formula, in which volatility corresponds to the square root of the sample variance.[17] Therefore, players are only able to determine the quantity of call or put options using a fixed price menu. Options contracts are regulated by cash settlement at time $T-3$.

Both regulated and non-regulated players actively participate in the options market. We investigate the supply and demand structure of options with respect to different measures concentrating however on regulated companies. In particular, we consider whether the option trading strategy of each i-th RC is determined by one of the following four measures:

i. the net permit position at time $T/2$

$$N^i + \sum_{t=1}^{T/2} \#\mathcal{T}^i(t) - \sum_{t=1}^{T/2} Q^i_{\cdot}(t),$$

ii. the net permit position at time $T/2$ minus the maximum final emission

$$N^i + \sum_{t=1}^{T/2} \#\mathcal{T}^i(t) - \sum_{t=1}^{T/2} Q^i_{\cdot}(t) - (T - T/2) \cdot q^i_u;$$

[17] The volatility parameter used to compute the option price corresponds to the historical volatility. For a sample volatility smaller than 0.2 or larger than 0.6, the default volatility value is 0.5. It's worth noting that by using the Black and Scholes option formula, call (put) options are overvalued (undervalued) when the permit price $S_{T/2}$ is close to the penalty level $P = 40$. Profit seekers could exploit such an arbitrage opportunity by selling call (buying put) options.

iii. the net permit position at time $T/2$ minus the minimum final emissions

$$N^i + \sum_{t=1}^{T/2} \#\mathcal{T}^i(t) - \sum_{t=1}^{T/2} Q^i_{\cdot}(t) - (T - T/2) \cdot q^i_d;$$

iv. the net permit position at time $T/2$ minus the expected final emissions

$$N^i + \sum_{t=1}^{T/2} \#\mathcal{T}^i(t) - \sum_{t=1}^{T/2} Q^i_{\cdot}(t) - \mathbb{E}\left[\sum_{t=T/2}^{T} Q^i_{\cdot}(t)\right].$$

N_i represents the initial number of permits allocated by the policy regulator to the i-th RC; $\#\mathcal{T}^i(t)$ represents the number of permits bought ($\#\mathcal{T}^i(t) > 0$) or sold ($\#\mathcal{T}^i(t) < 0$) by the i-th RC at each period t; finally, $Q^i_{\cdot}(t)$ corresponds to the emission of the i-th RC at each period t, under the old ($\cdot = old$) or the new technology ($\cdot = new$).

Considering Figure 8, we observe that RCs' option trading strategies are based on measures iv. This result may be a not that surprising. It is the first experimental attempt, however, ascertaining that option contracts are mostly used for hedging purposes. In particular, options trading strategies are a function of RCs' current permit portfolio, their abatement investment status, and their *expected* future emissions. Figure 8 shows that RCs with a negative expected final permit portfolio (left x-axis) typically tend to buy call or sell put options (upper-left quadrant). Players with a positive expected final permit portfolio (right x-axis) tend to buy put or sell call options (lower-right quadrant). The other strategies outside these quadrants can be properly explained by the presence of very high strike prices. In theory, a very high strike price would prompt offers to buy puts or sell calls even during permit shortage (in expectation) - see also the discussion in footnote 17. Conversely, a very low strike price would prompt offers to buy calls or sell puts even in permit excess (in expectation).[18]

6 Conclusions

This paper undertakes an experimental investigation of the investment strategies of regulated companies in abatement technologies, the market participants trading behaviors, and the liquidity level of the permit market within an inter-temporal cap–and–trade scheme. The analysis is done under alternative market structures: (i) in the exclusive presence of regulated companies; (ii) with the inclusion of non-regulated companies; (iii) under the availability of spot and options contracts.

[18]Such dynamics might also be employed to interpret the behavior of non-regulated companies. FIs and NGOs were expected to buy puts (or sell calls) and buy calls, respectively. On the contrary, when the strike price is very high or low, they play the role of the option contract counterparty by often entering buy orders for call options.

The first experiment investigates the effects of uncertain emissions and uncertain abatement costs on the timing of regulated companies to invest in an irreversible low pollution–emitting technology. In line with theoretical models, we observe that the price of permits does not necessarily reflect the marginal abatement cost (approximated by the expected cost per reduced emission). Although abatement investments are irreversible and limited in time, the strict enforcement structure in place prompts early adoption of low pollution–emitting technologies. This result has also clear policy implications: companies characterized by irreversible investments need to face ambitious environmental targets, severe penalties, and strict enforcement mechanisms in order to be active. However, in such a market the permit price might deviate from its well–known theoretical level, i.e. the true marginal abatement cost.

The second experiment investigates the impact of the presence of non-regulated companies on overall permit market liquidity. Two different measures of trading activity are presented and tested: effective trades and quantity of permits successfully traded. In contrast to Ben-David et al. (1999), we found that the presence of non–regulated companies significantly enhance the liquidity of the permit market. Despite few observations, the presence of non-regulated traders, however, has no statistically significant effect on the price variability of allowances. This result aligns with Ben-David et al. (1999) findings.

Given the fast-growing market for plain vanilla contracts (European options) on emission permits, the last experiment investigates the options trading pattern of regulated companies with respect to their investments and permit trading strategies. We observe that option contracts are mostly employed for hedging purposes. An analysis of the impact of the presence of option contracts on the permit price dynamics is left for future research.

In this paper, we show that in the presence of irreversible abatement investments and non–regulated companies, the overall cost of compliance might increase. At the same time, the possibility of realizing a premium propels irreversible and limited-in-time investments. In the presence of non-regulated companies, these market traders initially sustain the permit price and maintain market liquidity afterwards. In such a framework, the follow-up questions are: Will the premium associated to irreversible investments be always reflected in the permit price? Or, will there be a point at which the cost premium (permit price) peaks then decreases and, eventually, stabilizes throughout the rest of the trading period? To what extent price containment mechanisms, such as floor prices or ceiling prices described in Grüll and Taschini (2011), are desirable and effective instruments to control the allowance price and, ultimately, induce technology investments? These questions remain for future research.

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7 Appendix

7a Excerpt of the instruction paper

You are participating in an academic experiment. Please carefully read the following instructions telling everything you need to know for playing. In case of ambiguities please ask the instructor.

You can earn money by collecting Gulden. The experiment consists of 4 rounds with 20 periods each. The experiment restarts at each round. Your earnings depend on your decisions and on those of the other players. All Gulden you collect during the experiment are converted into Swiss Francs - 100 Gulden = 60 Rappen. In addition, you get 15 Swiss Francs for participating.

In each period you get information about market prices of permits and total pollution emitted in the past by all polluters. Based on this you need to decide whether to change technology, whether to buy or sell permits or to hold on to your permits. You have 60 seconds for deciding. After 60 seconds the next period starts.
Have a look at the picture below showing the screen you are going to face.

1. Here you see the current account and the costs for technology change. It also shows the probabilities for the changes of your pollution process (sharp increase or mild increase)

2. Shows the current amount of permits you possess, the amount of used permits and the remaining unused permits. If the last number is below 0, you have to pay a penalty of 40 Gulden at time $T = 20$ for each unit of negative permit.

3. This shows respectively the aggregated probability of a sharp movement in the pollution process of all other players and the aggregated probability of a mild movement in the pollution process of all other players.

4. This field tells whether you bought or sold permits in the last period.

5. Your total pollution for the current period is calculated here (Actual pollution). Minimum shows the minimum expected amount of pollution (you get this amount if in the remaining periods you always face a mild movement in the pollution process). Maximum shows the maximum expected amount of pollution (you get this amount if in the remaining periods you always face a sharp movement in the pollution process).

6. This field corresponds to field 5) but with respect to all other players with one time lag in other words with respect to the previous period.

7. Shows the evolution of prices of emission trading up to the previous period.

8. Shows the evolution of your company's cumulated pollution.

9. Shows the evolution of the cumulated pollution by the other companies up to the previous period.

10. Here you can insert an order to sell permits. You can specify quantity and price. You cannot sell more permits than you currently possess.

11. Here you can insert an order to buy permits. You can specify quantity and price. The total offer (in monetary value) cannot exceed your "bank" account.

    Remark: You can either buy or sell once in a period. After having placed an offer you might need to wait for other players to place their orders.

12. Time series of the permit price.

13. If you don't want to buy or sell permits you can press this bottom (please press as soon as you decide to not entering orders).

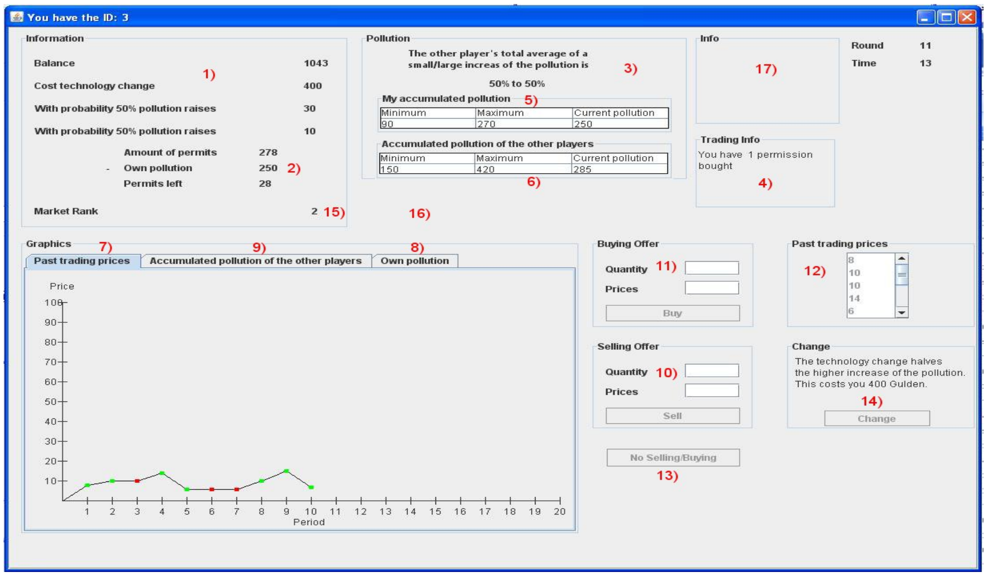
14. Here you can change technology. Technology can be changed only once and it costs 400 Gulden. The new technology reduces the sharp pollution increase by half. In this example, the oncoming possible increases would be 15 instead of 30.

15. Here you can see the total unused certificates of the other participants ranked by player. Again, the number shows the result of the previous period. This ranking does not report players' performance.

16. This is your position in the ranking of box 15).

17. Room for extra info - if required.

7b Screen shoots



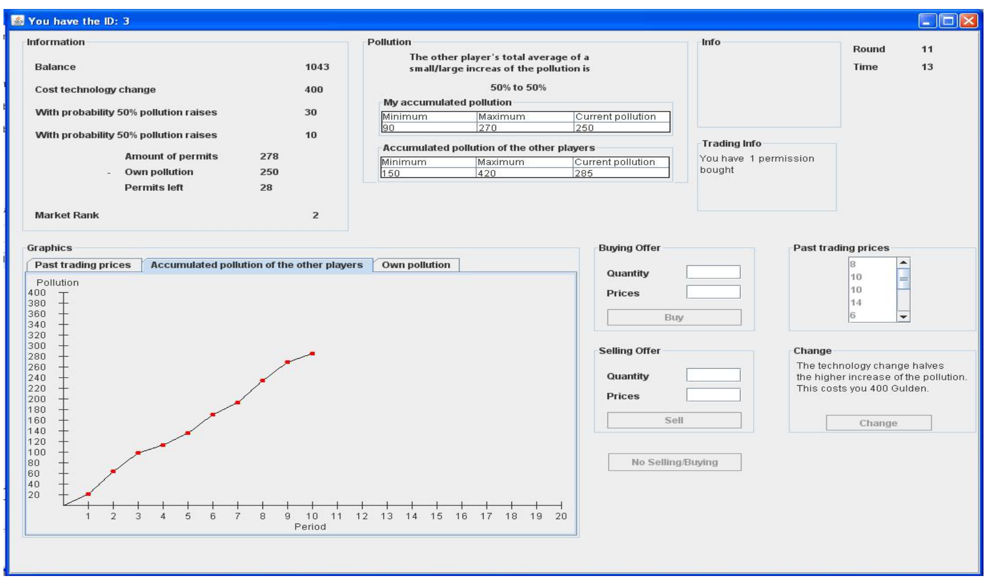


Figure 1: Example of a screen-shot where first the evolution of the permit price is in evidence (upper part) and then the evolution of the total pollution emissions (lower part).

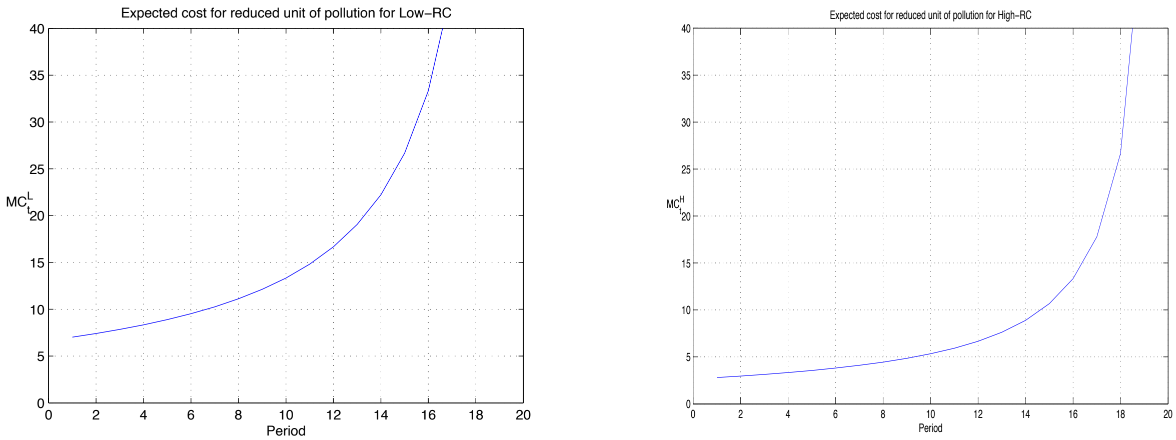


Figure 2: Expected cost per reduced unit of emission as a function of the remaining time for Low-RC (left column) High-RCs (right column). The parameters we use are $I = 400, P = 40, \{q_u^H, q_d^H\} = \{30, 10\}, \{q_u^L, q_d^L\} = \{12, 5\}$, and $p = 50\%$. As in the experiment, $t = [1, 2, \ldots, 20]$.

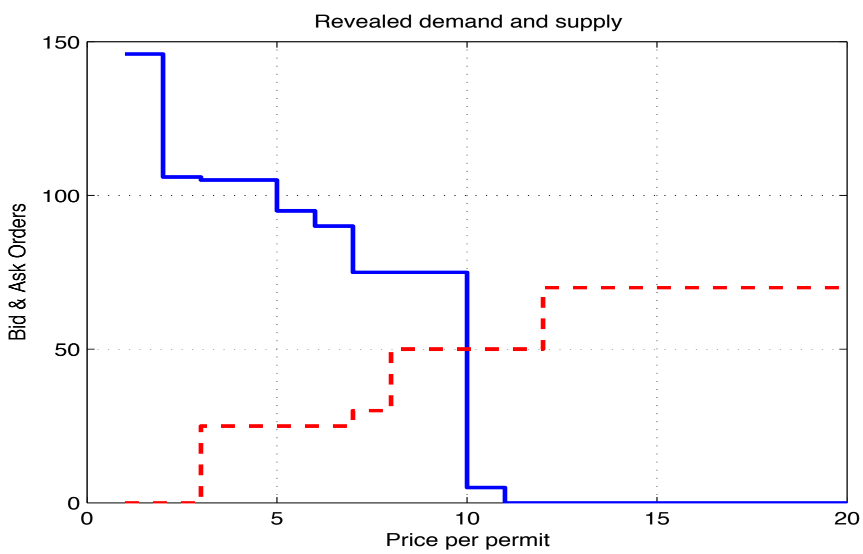


Figure 3: Hypothetical representation of a one-period bid and ask ordering. The intersection of the revealed demand (solid) and the revealed supply (dashed) identifies the quantity of permits that maximizes the traded quantity.

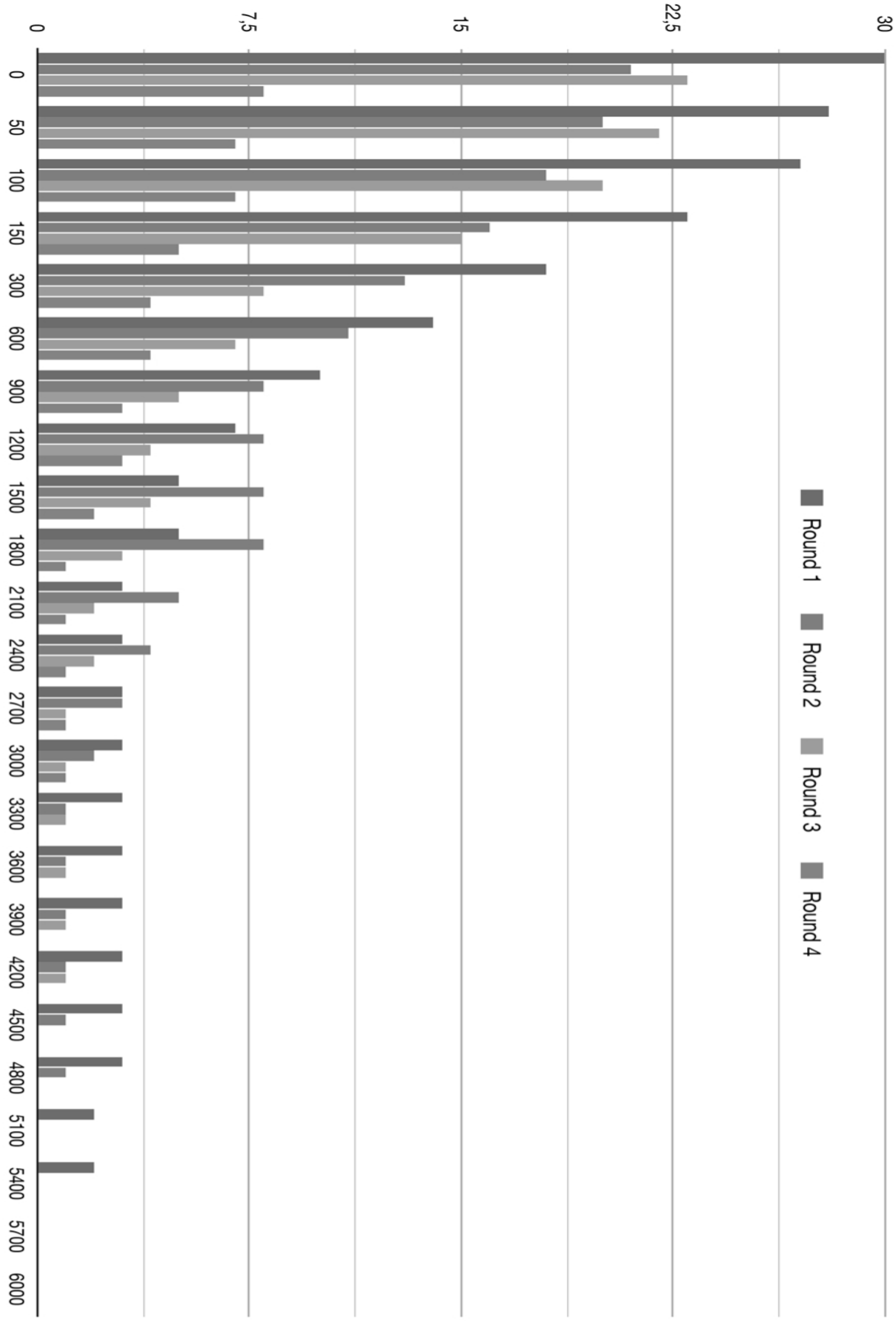
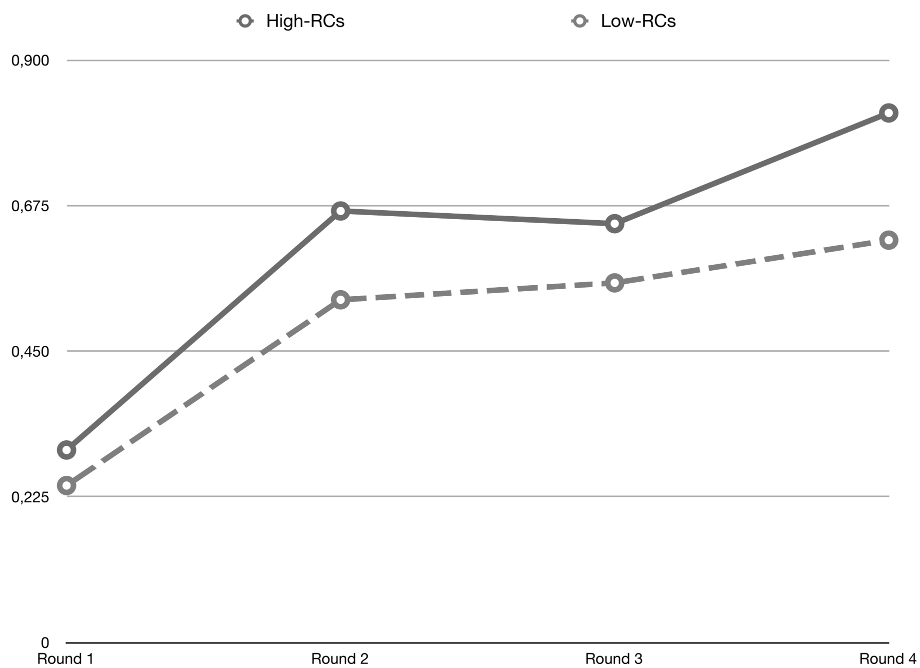


Figure 4: Histogram of the penalty payments in each of the four rounds averaged across the six sessions. The vertical axis represent the number of penalties incurred between the amount represented on the horizontal axis and the maximum possible paid.



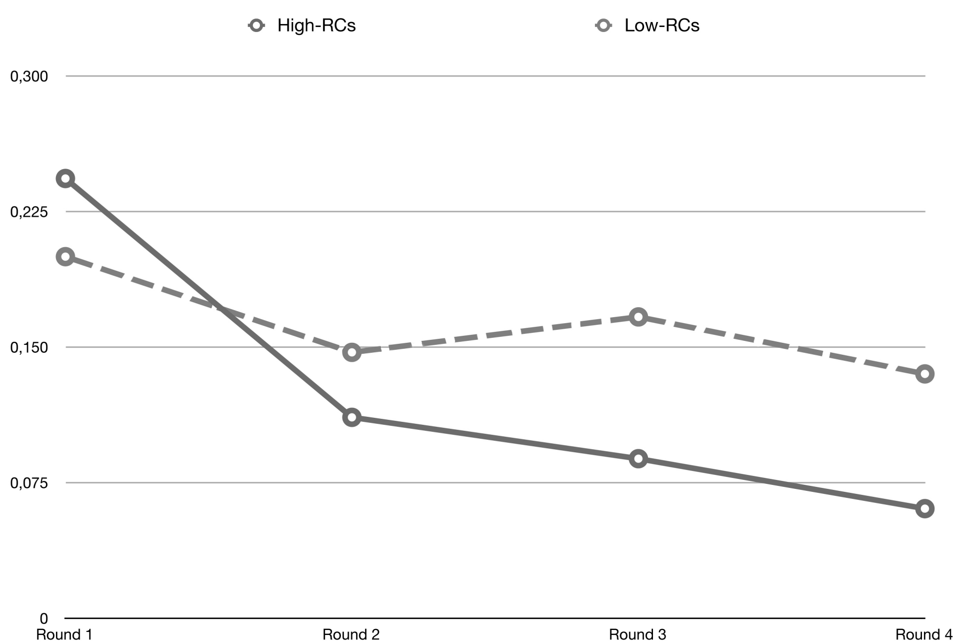


Figure 5: Percentage of Low-RCs (dotted line) and High-RCs (solid line) that adopt the new technology immediately at period 1 (upper diagram). Percentage of Low-RCs (dotted line) and High-RCs (solid line) that do not adopt the new technology (lower diagram). Values are computed considering the four rounds across all six sessions.

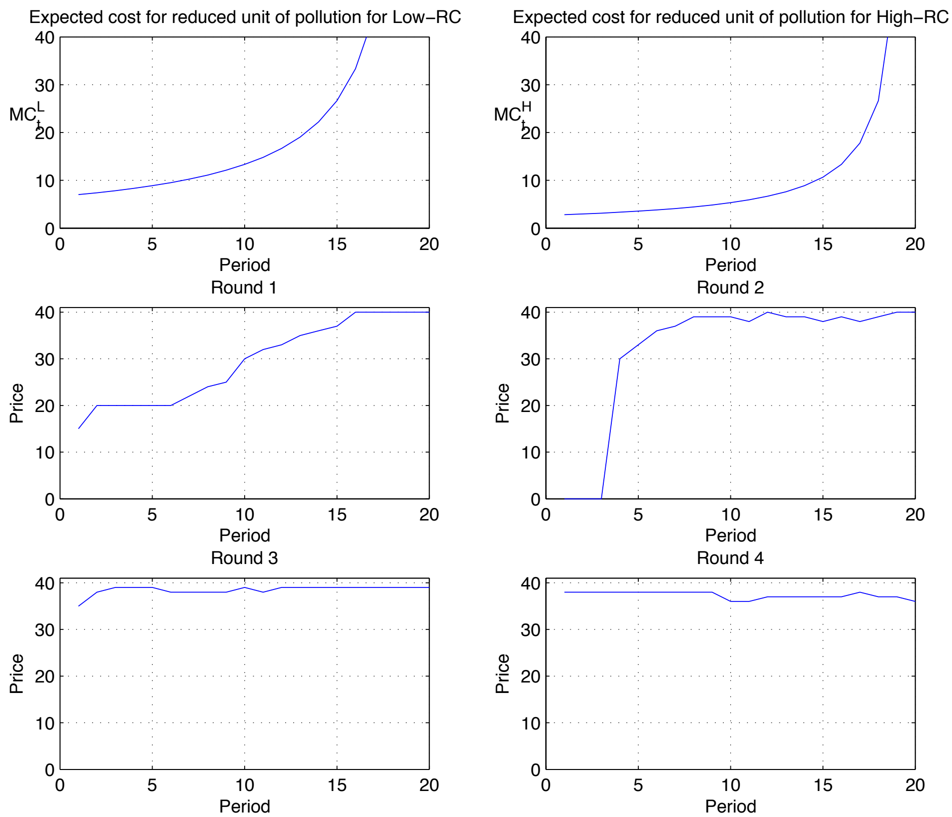


Figure 6: Marginal cost approximation (theoretical expected cost per reduced unit of emissions) for Low-RC and High-RC (upper row) compared to the allowance prices observed during the four rounds of the 5th session.

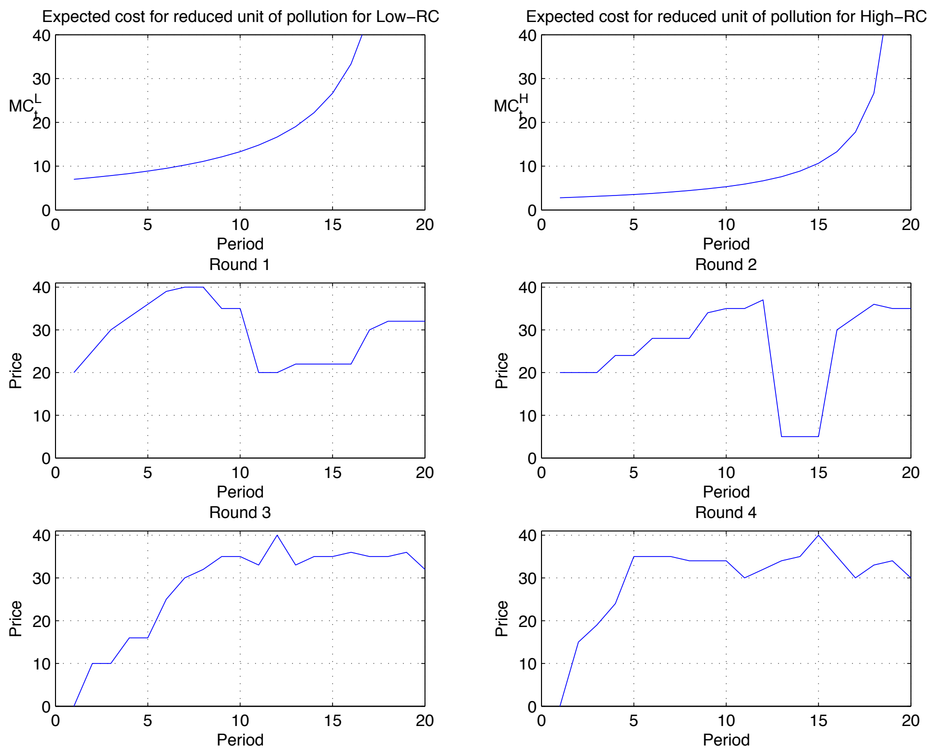


Figure 7: Marginal cost approximation (theoretical expected cost per reduced unit of emissions) for Low-RC and High-RC (upper row) compared to the allowance prices observed during the four rounds of the 6th session.

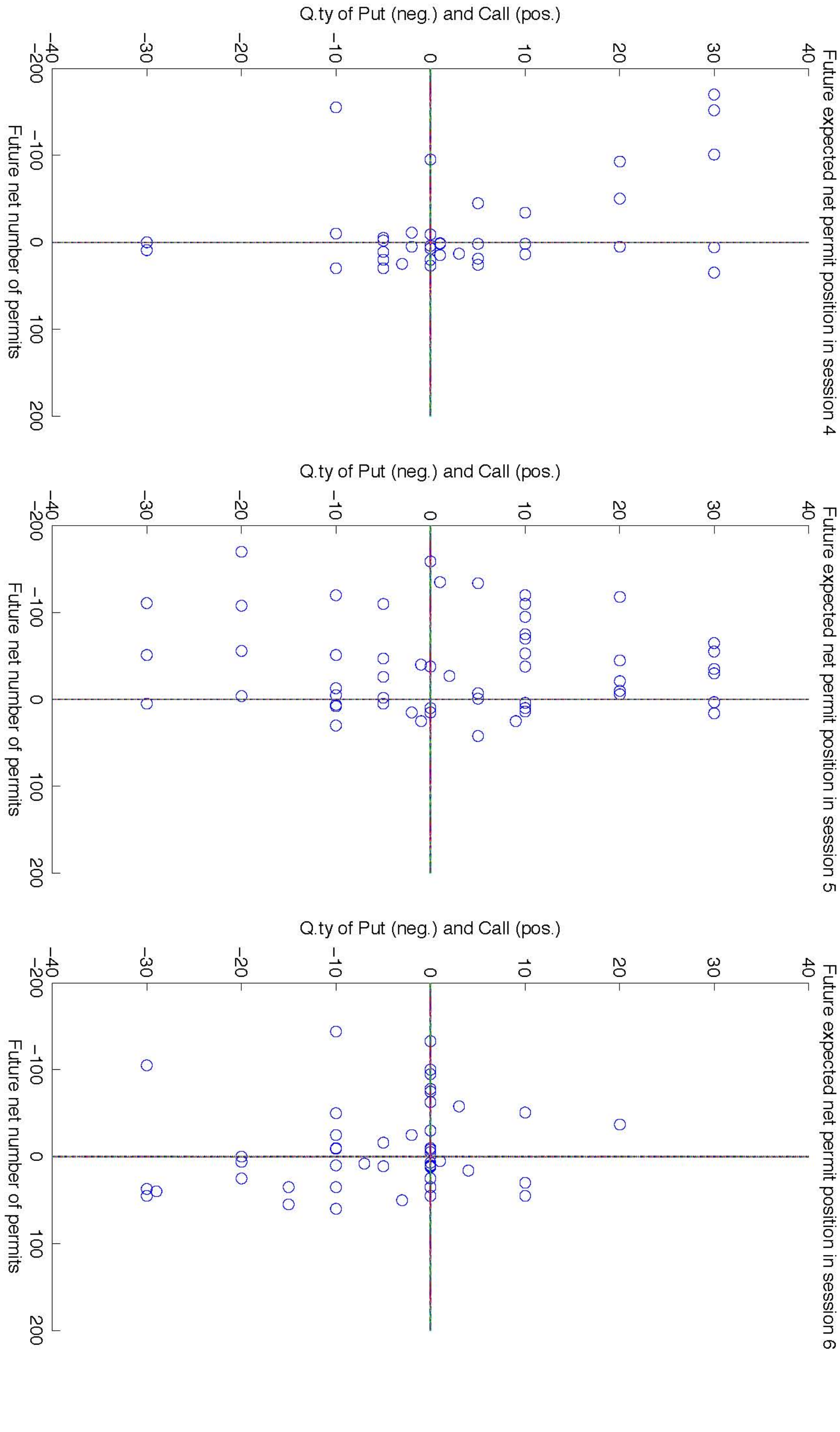


Figure 8: Scatter plot of the options trading strategies with respect to the future expected net permit position. Diagrams correspond to sessions 4, 5 and 6, respectively.