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Experimental Comparison between Markets on Dynamic Permit Trading and Investment in Irreversible Abatement with and without Non-Regulated Companies *

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Abstract

This paper examines the investment strategies of regulated companies in irreversible abatement technologies and the environmental achievements of the system in an inter-temporal cap–and–trade market using laboratory experiments. The experimental analysis is performed under varying market structures: firstly, in a market where there are exclusively regulated companies and then in a market with the inclusion of subjects not liable for compliance with environmental regulations. In line with theoretical models on irreversible abatement investment, the paper shows that regulated companies trade permits at a premium. At the same time, steep fixed per unit penalty for excess emissions effectively prompt investments in irreversible abatement technologies. Further, the paper shows that by contributing to the permit demand and supply, the non-regulated companies improve the compliance rate and facilitate the exchange of permits helping the system to achieve a zero-excess permit position.

Keywords: Irreversible Abatement, Stochastic Emissions, Dynamic Trading, Participation Restrictions, Non-regulated Entities.

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, combined with strict and appropriate enforcement, 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 irreversible technology adoption in a dynamic setting with stochastic emissions –exceptions include Ben-David et al. (1999), much less to the study of the impact of the presence of non–regulated companies. In this paper we experimentally investigate the effects of stochastic emissions and

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[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. Australia and New Zealand, among other countries, are discussing plans to develop similar schemes.

strict enforcement mechanisms on the timing of regulated companies' investment in irreversible low-pollution emitting technologies (hereafter irreversible abatement). Firstly, we investigate the affects of a market with solely regulated companies. Secondly, we include non-regulated companies and evaluate the environmental compliance rate (measured as percentage of final net emissions) and the trading efficiency of the permit market (measured as percentage of final net permit holdings and as liquidity level of the permit market).

The control problem of investing in irreversible abatement 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 dynamic 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 abatement costs. More precisely, 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 abatement. Thus, depending on the cost nature of the abatement technology, the permit price can deviate from its well-known theoretical level, i.e. the "true" marginal abatement cost. Despite high irreversible investment costs, the combination of potential high compliance costs and sales opportunities, prompts companies to invest earlier in irreversible abatement. This result has clear policy implications: the 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 severe losses due to strictly enforced stiff per unit penalty for excess emissions.

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 (2011) investigate the effect of asymmetric information on permit price formation, Carmona et al. (2009) analyze different market design alternatives, 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 possible presence of non-regulated companies in the permits market.[3] These are companies not subject to environmental regulations, but active on 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,

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[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.

legislators proposed to limit participation to regulated companies by excluding non–regulated companies from the market. An example of such an attempt is the Carbon Limits and Energy for America's Renewal (CLEAR) bill (S 2877), proposed by Senator Maria Cantwell. The second experiment addresses these concerns.

By introducing two new types of players not subject to environmental regulation, we evaluate their impact on the final net aggregate emissions and on the overall compliance performance. Some of these individuals represent environmental groups who wish to purchase permits to retire them, while others are investors who wish to buy permits to sell later at a profit. We find that in the presence of non-regulated entities the final level of emissions is often below the cap. The overall compliance rate, therefore, is enhanced. We observed that non-regulated subjects contribute to the permit demand, facilitating the selling of unused permits. We also find that the presence of non-regulated entities adds liquidity without increasing permit price volatility. 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. Thus, by favouring the market liquidity, non-regulated subjects improve compliance performance and significantly enhance permit trading. Our findings, therefore, align with some of the concluding remarks of a recent report on carbon markets released by an interagency 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."

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 analysis on irreversible abatement amidst stochastic emissions and abatement costs. Section 4 discusses the second analysis on the impact of the presence of non-regulated subjects on the overall environmental compliance performance. 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 a 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, or any feasible combination thereof. The adoption of the irreversible abatement is undertaken in the presence of stochastic emissions and, consequently, stochastic abatement costs. Regulated companies that do not offset their emissions face a stiff, fixed per unit penalty for excess emissions. The impact of (i) stochastic emissions and strict enforcement on the irreversible investment timing; (ii) the presence of non-regulated companies on the environmental compliance rate; and (iii) the dynamic trading between regulated and non–regulated agents on the market liquidity, 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. Permits are distributed to RCs based on some specific criteria at the beginning of the regulated phase. 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 *ex-ante* emission volume before a one-time irreversible abatement 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. For the sake of interpretation of the investment and dynamic trading strategies, we work under the assumption that the irreversible abatement reduces emissions, but does not influence the output quantity.[5] We assume that the irreversible abatement can only occur once during the regulated period $[0, T]$. Emissions $\{Q^i(t), t = 1, 2, \ldots, T; i \in \mathcal{I}\}$ are stochastic. 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. Emissions, therefore, are

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[4] The European Union Emission Trading Scheme, the largest existing market for permits, 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] We disregard RCs' decision on output production. The analysis of the inter-relationship between permit and output markets has been undertaken by Misolek and Elder (1989), Hahn (1984), 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.

purely stochastic 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. $\sum_{s=0}^{t} Q^i_{\cdot}(s)$, where $\{\cdot = (old, new)\}$ indicates production under the *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 reference level of emissions corresponds to the total *expected* pollution volume under the old technology, $\mathbb{E}[\sum_{s=0}^{T} Q^i_{old}(s)]$, where $i \in \mathcal{I} = (H \cup L)$, 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. $\mathbb{E}[\sum_{s=0}^{T} Q^h_{old}(s)] > \mathbb{E}[\sum_{s=0}^{T} Q^l_{old}(s)]$, 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 each experimental session, i.e. the end of the compliance period T, the regulator requires RCs to reconcile their permit holdings with their accumulated emissions. In practice, each RC must own a sufficient number of permits to cover her final emissions. Conversely, a fixed per unit penalty, P, for excess emissions is levied. RCs control their compliance strategy adopting an irreversible and costly abatement or trading permits. More precisely, at every period $t = 1, 2, \dots, T$, each RC can (i) decide (if not done before) to undertake an abatement investment that reduces the future expected emission volume instead of keeping the old technology, and (ii) trade permits instead of holding on to the number of allowance possessed. Because the overall regulated period is finite, the adoption of the abatement technology generates a limited in time benefit. In the presence of stochastic emissions, both the emission reduction and the benefit (opportunity cost) to undertake irreversible abatement are stochastic.

For convenience, an identical initial budget is allocated to all RCs. Let I represent the cost for undertaking irreversible abatement and let it be equal for all RCs. Because RCs are characterized with respect to the intensity of their emissions, High-RCs and Low-RCs face different opportunity costs when undertaking irreversible abatement.[6] At every period t, we can quantify the time-dependent opportunity cost to invest in the new technology by evaluating the cost per expected reduced unit of emission:

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

Here $Q^i_{old}(s)$ and $Q^i_{new}(s)$ represent the emission at time s before and after undertaking irreversible

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[6] 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.

abatement, respectively. Figure 2 represents graphically the time-dependent and company-specific opportunity cost of adopting a new technology that halves the high pollution emissions scenario. In particular, Figure 2 represents the cost expected per reduced unit of emission for both Low-RCs (left) and High-RCs (right) when $I = 400$. Intuitively, the later the adoption of the irreversible abatement, the shorter the useful remaining time period and, consequently, the higher the cost per expected unit of reduced emission.[7]

Experimental Procedure Experiments were conducted at the Laboratory of the Department of Banking and Finance of the University of Zurich. After all subjects arrived for the session, they were randomly assigned to a private computer. The subject pool was composed of graduate students, mostly with economic or finance background. Each session began with an instruction period and a questionnaire.[8] 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 non-regulated companies; two with a pair of non-regulated companies; and two with 6 non-regulated companies. The role played by non-regulated companies is discussed later. Each session had four rounds, with each round consisting of 20 periods (60 seconds per period). Every trading period, therefore, is repeated 160 times (20 periods, 4 rounds, 2 sessions). This corresponds to a minimum number of 160 repeated and distinct decisions. 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 90 subjects and a constant number of RC's throughout all experiments. The experiment ran over 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), the probability p, the cost for undertaking the irreversible abatement I, 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 emissions $(\sum_{s=0}^{t} Q^i(s))$ and the current net permit holdings. This last number corresponds to the sum of all permits pur-

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[7] According to the net-present-value approach, $C^i(t)$ is the critical level at time t at which the decision to adopt the irreversible abatement 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 irreversible abatement. 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 investing in the irreversible abatement. In this case we would expect an increase in the future permit market price.

[8] Based on students' answers to the questionnaire, most of them had a good understanding of the dynamics involved in the game. 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.

Global Parameters	
Number of rounds	4
Number of periods T	20
Initial lab. money RCs	1.000
Penalty P	40
Investment cost I	400
$\{q^L_{old,u}, q^L_{old,d}\}$ $\{q^H_{old,u}, q^H_{old,d}\}$	$\{12, 5\}$ $\{30, 10\}$
$\{q^L_{new,u}, q^L_{new,d}\}$ $\{q^H_{new,u}, q^H_{new,d}\}$	$\{6, 5\}$ $\{15, 10\}$
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: Set of parameters used in the experiments.

chased minus those sold up to time t, plus the initial number of permits, minus the current emissions. A negative number implies a current shortage of emission permits. The RC$_i$'s historical aggregate emissions ($\sum_{s=0}^{t} Q^i(s)$), the historical aggregate 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 (2011), the aggregate emission volume is observable with a one-period lag.[9] The computer screen also reports the maximum and minimum *expected* emissions (respectively, aggregate emissions) for RC$_i$ (respectively, including every RC$_j, j = 1, \ldots, \mathcal{I}, j \neq i$).[10] A screen shoot that includes these information is reproduced in the appendix.

This experiment places RC-subjects in a decision context that resembles the situation a regulated company faces in an emissions-constrained economy under a system of emission permits. The irreversible abatement and trading strategies are recorded as follows. At every period t, each RC can decide to undertake (if not done previously) an irreversible abatement 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 I. 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 constraints (players cannot sell more than what they hold). A player could also decide to hold on to the permits possessed by pressing a specific button ("No selling - No buying"). At the end

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[9] 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 (2011) for further discussion about the modeling of partial information and its theoretical implication on dynamic equilibrium pricing.

[10] Analytically, the company i-th *expected* future emissions corresponds to $\mathbb{E}[\sum_{s=t}^{T} Q^i(s)]$, and the *expected* cumulative and aggregate emissions corresponds to $\mathbb{E}[\sum_{j=1,j\neq i}^{\mathcal{I}} \sum_{s=t-1}^{T} Q^j(s)]$.

of each session, which corresponds to period T, the computer screen reports the final budget, net penalty costs for RCs (when applicable), and the net final 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 clear – meet compliance while maximizing profits. In the experiment, RCs' profit corresponds to Swiss Francs (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 later, 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. 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 limit order books and also operationalized in several experimental economics papers.[12] In the presence of a non-unique maximum quantity,

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[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.

we consider the so–called *first mover advantage* criteria that identifies a unique solution in a quite simple manner. Let us define Λ as the set of prices that 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 random emission are drawn from a uniform distribution and the next period begins.

3 Experiment one: adoption of irreversible abatement technology and compliance rate

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 holds across all six sessions and is graphically observable in Figure 4. The upper diagram of Figure 4 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 an irreversible abatement increases dramatically across the four rounds. Conversely, the lower diagram of Figure 4 reports the percentage of Low-RCs and High-RCs that never adopt the irreversible abatement across the four rounds. This number decreases quite significantly across the four rounds. As Figure 4 suggests, a learning effect is present in the first round. Results from the first rounds, therefore, convey relevant policy implications: The impossibility to borrow permits from future -next round- permit allocation, let RCs realise sooner their limited ability to meet compliance exclusively relying on permits. Here the lack of borrowing provisions is implemented with a marked separation between consequent rounds. Such a policy feature, together with the presence of a high and fixed per unit penalty for excess emissions and a strict cap, reinforce the incentive to undertake irreversible abatement. Table 2 investigates the adoption of low–emitting technology round-by-round. Consistent with Figure 4, Table 2 shows that the majority of RCs undertake irreversible abatement 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 change of the slope in Figure 4 of the percentage of RCs that never adopt the irreversible abatement, this effect is stronger for High-RCs. The lower diagram of Figure 4, in fact, shows a systematic decrease in the percentage of High-RCs that never undertake irreversible abatement. On the contrary, this Figure shows that a significant number of Low-RCs prefer to discard this option. The rationale behind such a result can be explained by the existence of different opportunity costs. In particular, High-RCs face higher incentives to invest in irreversible abatement. This might cause some RCs to free ride on others' investments. To better understand this, let us distinguish among the possible compliance status of RCs. In principle, a low permit price makes the investment in irreversible abatement a non-viable strategy. RCs n permit need would find the purchase of permits a cheap compliance alternative. Conversely, a high permit price generates potential profits from the sale of unused permits and, at the same time, makes offset of uncovered emissions expensive.[13]

A constant maximum price for emissions in excess of their permit holdings may weaken the final environmental result. Because the payment of the penalty is in fact an alternative to compliance, the penalty is effectively a price ceiling and it acts like a *safety valve*. However, Figure 5 shows that the presence of a (high) certain *safety valve* does not hamper the intended environmental target. Figure 5 shows that the total realised emissions is lower than allowed emissions, ie. the cap, in most of the cases. So, the environmental compliance rate systematically improves across the four rounds. Thus, a stiff penalty, together with a stringent cap, makes irreversible abatements viable compliance alternatives.

A second relevant result is intimately related to the previous discussion. Under irreversible abatement with limited-in-time benefits, the permit price does not necessarily reflect the proxy for the marginal abatement cost we introduced in Equation (2). Because the investment cost is fixed, the marginal abatement cost can be easily approximated by the cost per expected reduced unit of emissions, $C(t)$. Assuming this approximation holds, the difference between the marginal abatement cost and the observed permit price can be easily computed. For the sake of the presentation, let us focus on the *immediate investment* situation in all rounds except the first one –recall Table 2. When a Low-RC immediately adopts (respectively, does not adopt) the irreversible abatement, she is expected to offer to sell (respectively, to buy) permits at a price in the range of 7-8 units of experimental money. Similarly, an High-RCs is expected to offer to sell or buy permits for 2-3 units of experimental money. As Figure 6 shows, the realized permit price is by no means concentrated around the ranges highlighted before. Consistent with the findings of Chao and Wilson (1993), Fullerton et al. (1997) and Taschini (2008), RCs typically offer to sell or accept to buy permits at a premium. Observed prices, therefore, are often higher than their cost per expected reduced unit of emissions. The premium that sellers charge reflects their intent to recover investment costs including a significant compensation for undertaking an irreversible abatement. In a similar way, the savings realized by postponing the irreversible abatement investment justifies the premium buyers accept to pay.

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[13] In practice, each RC tries to answer the question: will the capital-spending in irreversible abatement be lower than the potential revenues from permits sales (or lower than the cost of avoided penalties)? Or would waiting to invest in irreversible abatement and perhaps offset emissions by purchasing cheap permits be a cheaper strategy?

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

By definition, emission permits are fully transferable. In particular, permits can be traded by companies not subject to environmental regulations. An experimental investigation of the potential impact of such market players is lacking. This section investigates how the presence of non-regulated companies affects aggregate net-emissions, the overall compliance performance and, implicitly, the liquidity level of the permit market. Finally, 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 briefly 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 systematic permit scarcity. The lack of permits should be reflected in higher permit prices and, ultimately, in stronger incentives to adopt irreversible abatement. 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.

As first result, it is interesting to observe that the presence of non-RCs does matter. Aggregating final net emissions (emissions below the cap) across rounds, the upper diagram of Figure 7 shows the impact of non-RCs on excess emissions. In the absence of non-RCs, left hand side of the diagram, the level of net emissions becomes positive only in the last round. Likely, this is the round when the potential costs due to a fixed, stiff per unit penalty are apparent. In the presence of non-RCs, right hand side of the upper diagram, the net emission rate has a positive and increasing trend starting from the second round. This can be explained considering the role played by non-RCs in the market. Both NGOs and FIs do not receive emission permits. Non-RCs, therefore, need to purchase permits before being able to actively participate in the permit market. As a result, non-RCs are natural permit buyers and contribute to the permit demand, facilitating the selling of unused permits. The importance of having a sufficient number of potential permit buyers is particularly relevant in the presence of several permit sellers. Typically, this is the case in the last two rounds of each session. In these rounds, as observable in Figure 4, a large fraction of the RCs undertake the investment in irreversible abatement. 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 a sufficient demand would depress the permit prices. Non-RCs make up for such a demand and significantly contribute to permit market liquidity, as the analysis that follows discussed in more detailed. Quite remarkably, non-RCs significantly enhance the overall compliance rate. The lower diagram of Figure 7 shows the per-round, final net amount of permits in the absence of non-RCs (left hand side) and in the presence of non-RCs (right hand side). Noticeably, non-RCs facilitate permits exchange leading to a final zero-net permit supply. So, in this experiment, the presence of non-RC leads to an optimal redistributions of permits.[14]

The contribution of non-regulated companies is now analyzed in terms of their 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. We have a total of six sessions, therefore each condition has been tested twice. Each pair of sessions contains a constant number of regulated companies that guarantees 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.[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.

Table 3 reports some summary statistics (standard deviation, standard error, minimum and maximum observed value) relative to the mean of the 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-RCs to the overall liquidity of the permit market, the lower panel of Table 3 disregards all transactions among non-regulated firms and between

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[14] One could argue that the increased compliance rate is a consequence of higher permit prices. We studied this possibility. Unfortunately, an analysis of the time series of emissions along with permit prices does not reveal the presence of an obvious relationship.

[15] 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. 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. 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.

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). The ANOVA test for the upper panel is $F(2, 477) = 18.42$, $p < 0.01$, for the lower panel is $F(2, 477) = 2.64$, $p = 0.07$.

non-regulated 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.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). The ANOVA test for the upper panel is $F(2, 477) = 8.90$, $p < 0.01$, for the lower panel is $F(2, 477) = 4.23$, $p = 0.02$.

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 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-RCs and between non-regulated and regulated companies, such results leads to the following considerations. The contribution of non-RCs 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-RCs– 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 straightforward 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 favouring investments in irreversible abatement. If the market liquidity varies in the presence of non-RCs, 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 behaviours, however, there is no statistically significant effect of the presence of non-regulated traders on the price variability of allowances.

5 Conclusions

This paper undertakes an experimental investigation of a dynamic emission trading where regulated companies can decide when to make a one-time irreversible investment in an abatement technology. Regulated companies receive an exogenous endowment of emission permits, their emissions are stochastic and face a fixed per unit penalty for emissions in excess of their permit holdings. The analysis is done under alternative market structures: (i) in the exclusive presence of regulated companies; (ii) with the inclusion of non-regulated companies.

The first basic set up is used to investigate the effects of stochastic emissions and stochastic abatement costs on the timing of investment in irreversible abatement and the pricing of permits. In line with theoretical models, we observe that the price of permits does not necessarily reflect the marginal abatement cost (approximated by the cost per expected reduced emission). Although abatement investments are irreversible and limited-in-time, the strict enforcement structure in place prompts early investment in abatement. This result has clear policy implications: strict environmental targets, stiff penalties and certain enforcement are relevant institutional factors when major regulated industries face irreversible investments. However, in such a market the permit price might deviate from its well–known theoretical level, i.e. the true marginal abatement cost.

Using this basic set up, we then add non-regulated subjects to the permit market. Some of these individuals represent environmental groups who wish to purchase permits to retire them, while others are investors who wish to buy permits to sell later at a profit. Non-regulated companies act like buyers, contributing to the permit demand and facilitating the selling of unused permits. Quite remarkably, we find that non-RCs improve compliance performance and, by favouring the market liquidity, they significantly enhance permit trading. We also find that the presence of non-regulated entities adds liquidity without increasing permit price volatility. This last result aligns with Ben-David et al. (1999) findings.

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 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) equals the true marginal abatement expected costs? To what extent price containment mechanisms 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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6 Appendix

6a Excerpt of the instruction paper

You are participating in an academic experiment. Please read carefully the following instructions that explain you how to play. In case of ambiguities please ask the instructors.

The session consists of 4 rounds with 20 periods each. The sessions restarts at each round. You earn money by collecting Gulden. 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 will receive 15 Swiss Francs for participating.

In each period you receive information about your and yours colleagues' present and past emissions, and about the permit market price. Your objective is to offset your emissions with permits and maximize your profits. Based on the information reported on your scree you can decide to (i) change technology and reduced emissions, (ii) buy or sell permits, and (iii) hold on to your permits. In each period you have 60 seconds for deciding. After 60 seconds the next period starts. The following figures summarize the information reported on the scree of your videon:

1. Here we report your current budget and the costs for technology change. It also reports the probabilities of the pollution emission states (sharp increase or mild increase).

2. Here we report the current amount of permits you possess, the amount of permits used and the amount of permits unused. If the last number is below 0, you are short of permits and at period $T = 20$ you have to pay a fixed per unit penalty of 40 Gulden for excess emissions.
3. Here we report the aggregated probability of a sharp increase and a mild increase, respectively, in the emissions of all other players.
4. This cell tells whether you successfully bought or sold permits in the last period.
5. Minimum (Maximum) shows your minimum (maximum) expected amount of emissions, i.e. final emissions in case of permanent mild (sharp) pollution emissions.
6. This field reports (5) for all other players with one time lag – in other words with respect to the previous period.
7. This graph shows the evolution of emission prices up to the previous period.
8. This graph shows the evolution of your company's cumulated pollution.
9. This graph shows the evolution of the cumulated pollution of 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 buy or sell in a period. After having placed an offer you might need to wait for other players to place their orders.
12. Here we report the 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 you are not interested in entering orders).
14. Pressing this button you change technology. Technology can be changed only once and it costs you 400 Gulden. The new technology reduces the sharp emissions state by half. In this example, by changing technology your higher pollution state reduceds from 30 to15.
15. Here you see the rank of all players with respect to their net emissions. This ranking does not report players' performance in the game.
16. This is your position in the ranking of box (15).
17. Room for extra info - when available.

This instruction paper was distributed to all players playing the role of regulated companies. The instruction paper distributed to players playing the role of non-regulated companies includes also information about NGOs' and FIs' final payoffs. Obviously, the NGOs' and FIs' screen did not report information about personal accumulated pollution or cost of the technology change. Yet, these players obtain information about accumulated pollution and price level.


You have the ID: 3

Information

Balance	1043
Cost technology change	400
With probability 50% pollution raises	30
With probability 50% pollution raises	10
Amount of permits	278
- Own pollution	250
Permits left	28
Market Rank	2

Pollution

The other player's total average of a small/large increas of the pollution is

50% to 50%

My accumulated pollution

Minimum	Maximum	Current pollution
90	270	250

Accumulated pollution of the other players

Minimum	Maximum	Current pollution
150	420	285

Info

Round	11
Time	13

Trading Info

You have 1 permission bought

Past trading prices

8
10
10
14
6

Change

The technology change halves the higher increase of the pollution. This costs you 400 Gulden.

You have the ID: 3

Information: Balance 1043; Cost technology change 400; With probability 50% pollution raises 30; With probability 50% pollution raises 10; Amount of permits 278; - Own pollution 250; Permits left 28; Market Rank 2

Pollution: The other player's total average of a small/large increas of the pollution is 50% to 50%

My accumulated pollution: Minimum 90, Maximum 270, Current pollution 250

Accumulated pollution of the other players: Minimum 150, Maximum 420, Current pollution 285

Round 11, Time 13

Trading Info: You have 1 permission bought

Past trading prices: 8, 10, 10, 14, 6

Change: The technology change halves the higher increase of the pollution. This costs you 400 Gulden.

Figure 1: An example of a screen-shot. Close-up of the evolution of the permit price (upper part) close-up of the evolution of the cumulated emissions (lower part).

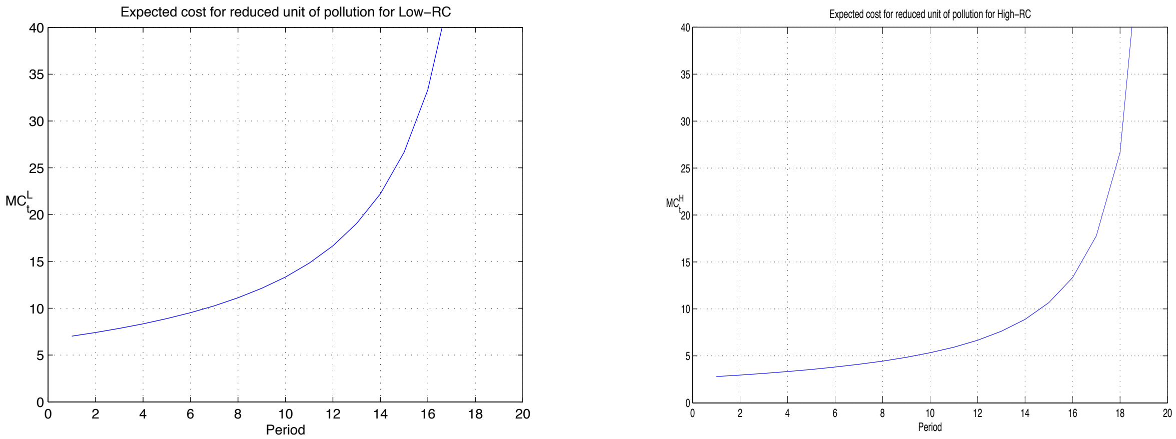

Figure 2: Cost per expected reduced unit of emission as a function of the remaining time for Low-RC (left column) High-RCs (right column). The parameters we use are $I = 400, P = 40, \{q_u^H, q_d^H\} = \{30, 10\}, \{q_u^L, q_d^L\} = \{12, 5\}$, and $p = 50\%$. As in the experiment, $t = [1, 2, \ldots,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

Figure 3: 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 offered quantity.

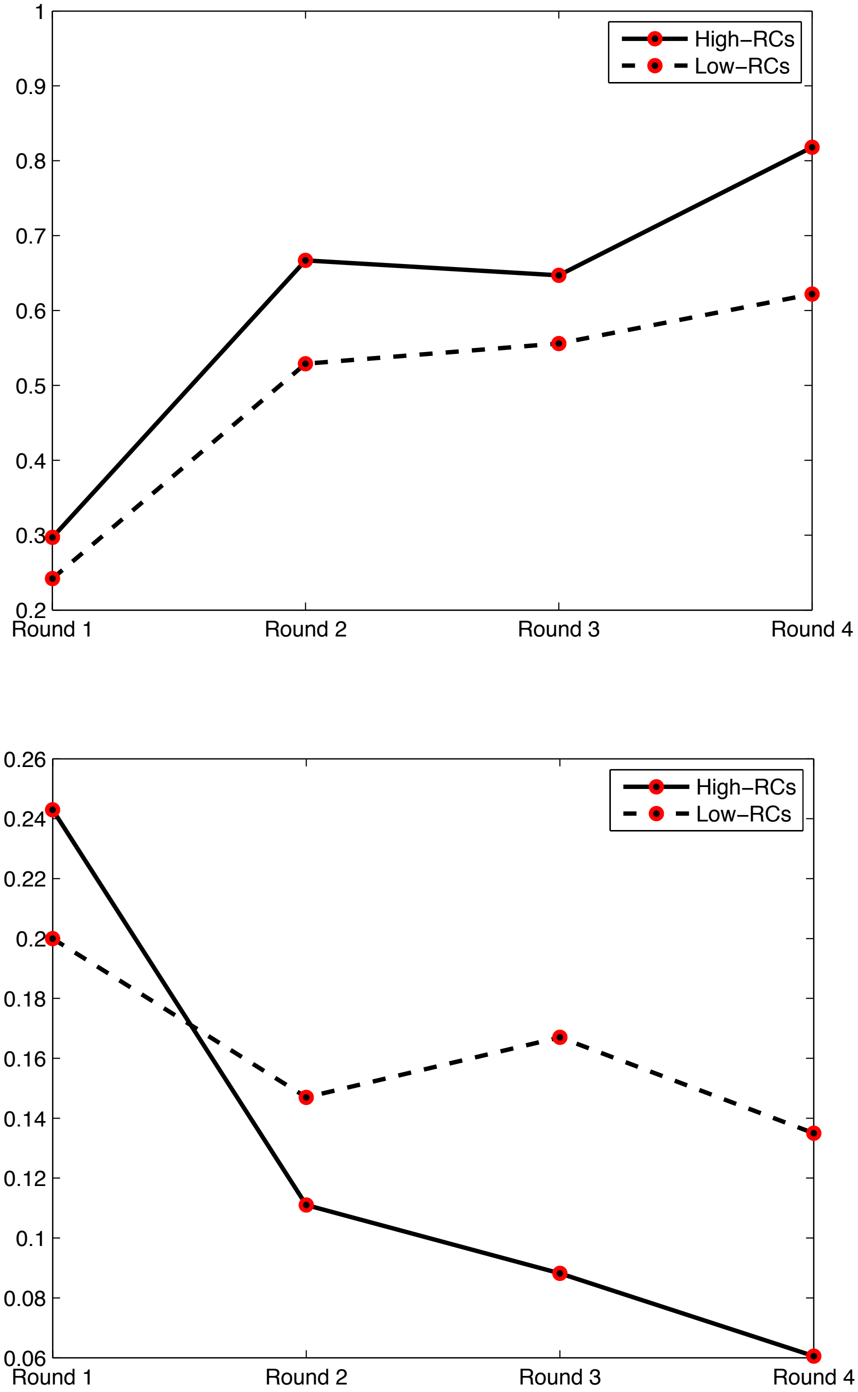

Figure 4: Percentage of High-RCs (solid line) and Low-RCs (dotted line) that adopt irreversible abatement immediately at period 1 (upper diagram). Percentage of High-RCs (solid line) and Low-RCs (dotted line) that do not adopt irreversible abatement (lower diagram). Values are computed aggregating data of the four rounds across all six sessions.

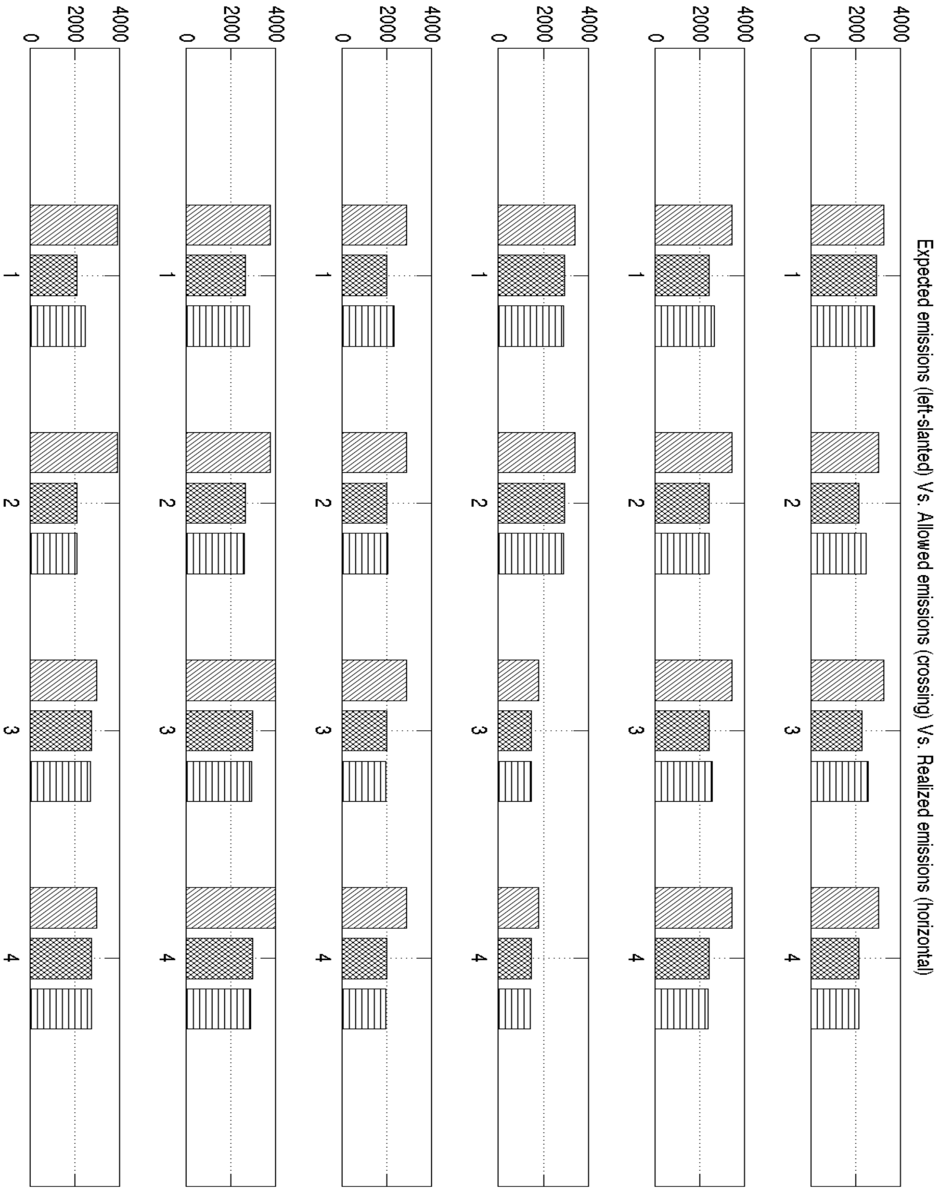

Figure 5: Expected aggregate emissions, $\mathbb{E}[\sum_{i\in\mathcal{I}}\sum_{s=0}^{T}Q^i_{old}(s)]$ - (left-slanted lines), total cap, $\sum_{i\in\mathcal{I}} N_i$ - (crossing lines), and realized aggregate emissions, $\sum_{i\in\mathcal{I}}\sum_{s=0}^{T}Q^i_{\cdot}(s)$ - (horizontal lines), in each session. The first two diagrams correspond to a permit market without non-regulated companies; the second two diagrams correspond to a permit market with 1 eco-group and 1 speculator; the last two correspond to a permit market with 3 eco-groups and 3 speculators.

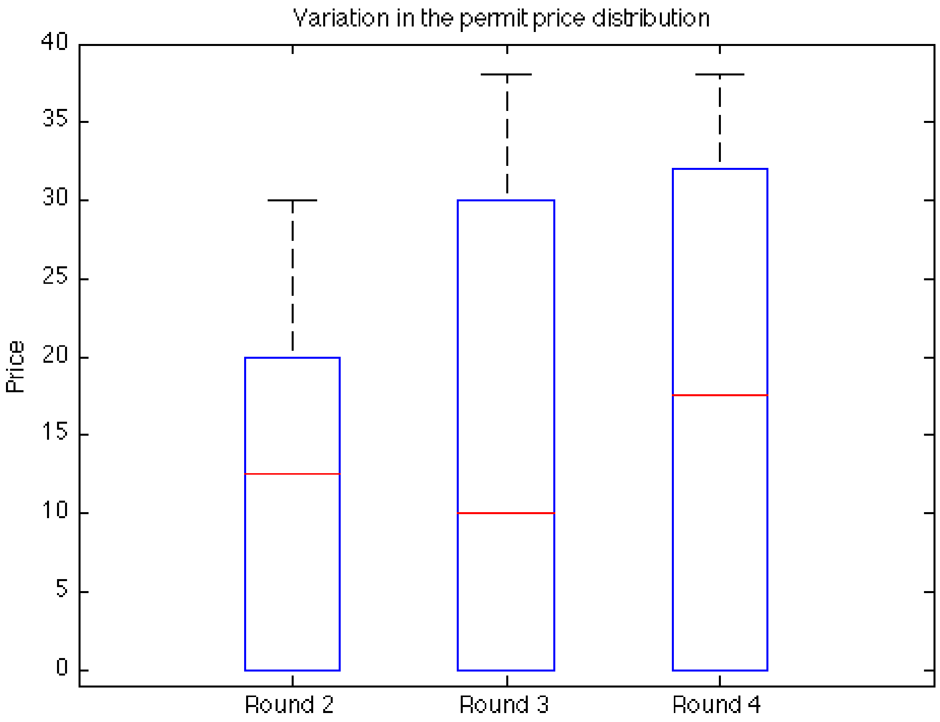

Figure 6: Box plot of the permit price distribution in the second, third and fourth round across all sessions.

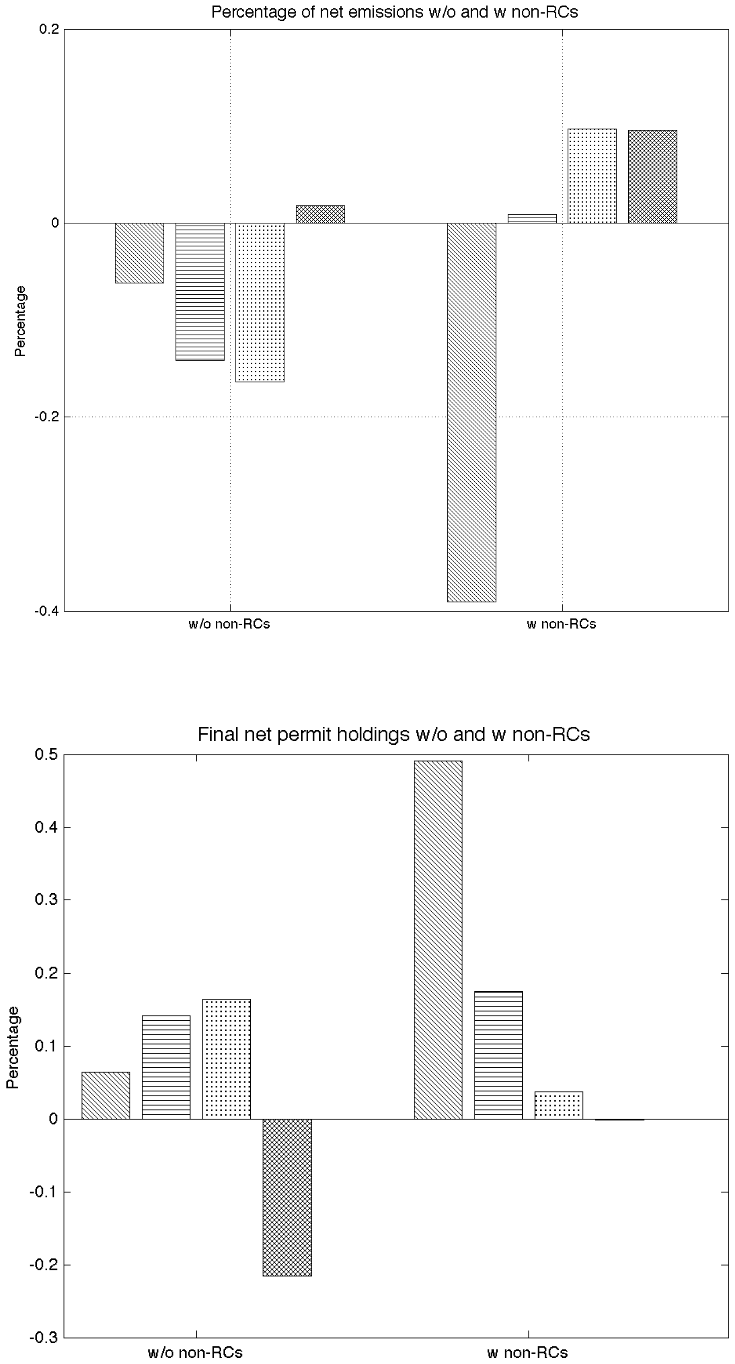

Figure 7: The first diagram reports the final net positions of the aggregate emissions in percentage terms, $\sum_{i\in\mathcal{I}}\Big(\sum_{s=0}^{T} Q^i_{\cdot}(s) - N_i\Big)/\sum_{i\in\mathcal{I}} N_i$, in the absence (left) and presence (right) of non-RCs. The lower diagram reports the final net positions of the permit holdings in percentage terms, $\sum_{i\in\mathcal{I}}\Big(\sum_{s=0}^{T} Q^i_{\cdot}(s) - N_i - \sum_{s=0}^{T} x^i(s)\Big)/\sum_{i\in\mathcal{I}} N_i$, in the absence (left) and presence (right) of non-RCs. Values correspond to the first round (left-slanted lines), the second round (horizontal lines), the third round (dots), and the fourth round (criss-crossing lines).