Investment Incentives under Emission Trading: An Experimental Study

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This version: April 20, 2011

Abstract

This paper presents the results of an experimental investigation on incentives to adopt advanced abatement technology under emissions trading. Our experimental design mimics an industry with small asymmetric polluting firms regulated by different schemes of tradable permits. We consider three allocation/auction policies: auctioning off (costly) permits through an ascending clock auction, grandfathering permits with re-allocation through a single-unit double auction, and finally grandfathering with re-allocation through an ascending clock auction. **We find that the treatments with an initial free allocation of permits (grandfathering) perform closer to the first best investment pattern than the treatment with pure auctioning. This result is mainly driven by higher efficiency in permit allocation in the treatments with grandfathering.**

JEL Classification: C92; D44; L51; Q28; Q55

Keywords: environmental policy; abatement technology; taxes; permit trading; auctions

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1 Introduction

It is widely acknowledged today that 'market-based' pollution control instruments, such as emission taxes and tradable permits, are powerful and efficient tools for curbing pollution. At an early stage, Kneese and Schultze (1975) emphasized that one of the most important criteria for judging different pollution control policies is the extent to which these policies encourage firms to develop or adopt low-pollution technologies. Since then a large body of both theoretical and empirical research has been analyzing the impact of different policy instruments on both technological change and the diffusion of new technologies. The first attempts to rank environmental policy instruments were made by Downing and White (1986), Malueg (1989), Milliman and Prince (1989), and Jung et al. (1996).[1] Taking aggregate cost savings as the ranking criterion for pollution control policies, these studies, however, ignore the individual firms' incentives to adopt new technologies. Later, Kennedy and Laplante (2000) and Requate and Unold (2003, 2001) (for the case of adoption of new technology), and Montero (2002a,b) and Fischer et al. (2003) (for the case of technology innovation) argue that incentives provided by policy instruments to adopt (or develop) new technologies in equilibrium have to be considered in evaluating different pollution control policies. In other words, the number of firms that adopt the new technology in equilibrium should be determined endogenously. In particular, Requate and Unold (2003, 2001) study the incentives provided by emission taxes and tradable permits to adopt a given low-pollution technology. The authors show that if the regulator is well informed about the new technology[2] and firms are asymmetric, both instruments provide efficient incentives to invest in advanced abatement technology if the regulator levies a tax rate at the Pigouvian level or the equivalent emission cap, re-

[1]See Requate (2005) for a survey of incentives provided by environmental policy instruments to adopt and develop advanced abatement technology.

[2]This assumption comes close to the situation in European countries as a result of the Integrated Pollution Prevention and Control (IPPC) Directive 96/61. The IPPC legislation requires emission reduction and environmental improvements on the basis of what is achievable with the best techniques available to individual industrial sectors.

spectively. If firms are symmetric, however, Requate and Unold (2003) show that an ex ante setting of emission tax rates will fail to induce the first-best investment pattern. Although permits may theoretically lead to first-best investment, firms face a coordination problem that may prevent them from pursuing this course. Moreover, for both, symmetric and asymmetric firms, the authors establish the equivalence of grandfathered and auctioned permits with respect to technology adoption.

In this paper we study investment incentives from an experimental perspective. To this end we have conducted a series of economic experiments to simulate investment in a low-pollution technology when firms are regulated by emission permit markets. In particular, we investigate the impact of different allocations of property rights (free vs. costly allocation of permits) and different auction schemes on the efficiency of technology adoption.[3] In a nutshell, our experimental design is as follows: In a first step, subjects (firms) decide whether or not to buy a new technology that lowers their marginal abatement cost schedules, and in a second step, they participate in a permit auction. The main research issue is whether or not this two-step procedure induces i) an optimal allocation of investment decisions and ii) an efficient allocation of permits after the investment phase. Since symmetric firms face a coordination problem with respect to which firm will invest (Requate and Unold, 2003), we follow the asymmetric model of Requate and Unold (2001) by allocating different initial technologies to the firms, whereas the new technology is the same for all firms.

Furthermore, we have to specify the mechanisms for auctioning and re-allocating permits. In the theoretical literature these mechanisms are usually modeled as a black box. With the exception of Montero (2002a,b), firms are mostly assumed to behave as price-takers, and the auction clears the market. In a set-up with grandfathering, it is natural to choose a double auction for re-allocating the permits among the firms. Under costly allocation (so-called auctioning) we decided to implement an

[3]There are other studies investigating the impact of different auction designs or costly vs. free allocation of permits (for instance, Wråke et al., 2009), but to our knowledge, no other study had yet investigated this impact on technology adoption.

ascending clock auction. In addition, we conduct a third treatment where permits are grandfathered and then re-allocated through a (double) ascending clock auction.

Prior to this two-step procedure, we have the subjects participate in a treatment where the permit instrument is substituted by an emission tax. In such a case there is no interaction between the subjects. This treatment was conducted to make subjects familiar with the investment and abatement decisions depending on their abatement cost schedule.

Our main results are as follows: First, we find that in all three treatments the investment patterns are relatively close to the first-best investment pattern. We also find that the treatments with an initial free allocation of permits (grandfathering) perform closer to the first best allocation than the treatment with pure auctioning. Moreover, we find that the individual investment decision is mainly determined by the initial technology, while the risk attitude of subjects matters only in the treatment where permits are grandfathered and re-allocated through a double auction.[4] Secondly, with respect to the efficiency of the permit allocation we also find that free allocation (grandfathering) outperforms pure auctioning of permits. Furthermore, we observe that in the permit trading phase of all treatments, prices are higher and (net) trade volumes are lower than predicted by the theoretical equilibrium. Indeed, in the treatment with grandfathering and double auction we observe speculative trade, that is, some subjects buy and sell permits within the same trading round. This is quite striking since our design does not provide any reason to engage in arbitrage. Finally, we find that the treatments with grandfathering result in overall lower abatement costs (i.e. investment and abatement costs) than the treatment where permits are initially auctioned off. This result is mainly due to the better allocation of permits in our grandfathering treatments.

Our paper is organized as follows: The next section reviews the related literature. Section 3 outlines the underlying theoretical model. Section 4 describes the experi-

[4]For this purpose we asked the subjects to participate in a risk test (Holt and Laury, 2002) at the end of each treatment.

mental design and procedure, and section 5 sets out the results. Section 7 concludes.

2 Related Experimental Literature

As mentioned above, our study draws on the models of Requate and Unold (2001, 2003), who establish the dynamic (ax ante and ex post) optimality of tradable emission permits and the equivalence of auctioned permits and grandfathering.[5] Since Plott's (1983) first laboratory experiment on emissions trading, numerous experiments have been conducted on permit trading.[6] However, only a minority of them consider investment in low-pollution technology when firms participate in emission permit markets.

Ben-David et al. (1999) consider an emission permit market where firms produce a good by using capital and causing emissions. In their setting, firms can use one of three possible production technologies where permits and capital costs are inversely related (i.e. the cleanest technology is the most expensive one in terms of capital). In each round the firms can make an irreversible investment decision to become cleaner (but not vice versa). Surprisingly, the authors find that heterogeneity leads to lower efficiency from trade.

Hizen et al. (2001) and Kusakawa and Saijo (2003) also investigate investment with emissions trading, where trading is either bilateral or takes place using a double auction. These authors find that the irreversibility of investment and a time-lag in abatement reduce efficiency. Buckley et al. (2005, 2006) compare between implementation of cap-and-trade and baseline-and-credit (with and without varying production capacity) where emission rate is endogenously determined by the subjects. The authors find, in line with theory, that baseline-and-credit scheme results in higher aggregate output and emissions.

Finally, Gangadharan et al. (2010) examine the interaction between permit bank-

[5] Dynamic optimality refers to long-term abatement incentives including adoption (and also innovation through R&D) of new technologies.

[6] A summary of the literature is given in Muller and Mestelman (1998) and in Bohm (2003).

ing and (irreversible) investment in a cleaner technology. The authors consider an industry with asymmetric firms that differ with respect to production capacity and cleanliness. Permits are allocated for free and can be traded through a double auction. As in our model, the effect of investment in cleaner technology is asymmetric (dirty firms gain more by investing). In contrast to our design, information about investment is made public and given to all participants. The authors find that firms tend to over-invest and over-bank. Accordingly, the result is sub-optimal market performance.

3 Theoretical Background

This section presents the theoretical model that served as a basis for our experiment. The model outlined here is a discrete version of the model with a continuum of firms, as proposed by Requate and Unold (2001).

Consider an industry consisting of n polluting firms and K different initial technologies. Each firm $i = \{1, ..., n\}$ is endowed with one of these initial technologies and can invest in adopting the advanced technology a, the same for all firms. The firms' technologies are represented by their abatement cost functions $C^i(e_i, k)$ with $k = 1, ..., K, a$. For any targeted emission level e we assume $C^i(e, k) > 0$ for $e < \bar{e}_k$, where $\bar{e}_k$ is the baseline emission level of technology $k = 1, ..., K$, chosen in the absence of regulation. We denote this by $EMAX$. Investment in advanced abatement technology leads to lower marginal abatement costs, i.e. $-C^i_e(e, k) > -C^i_e(e, a)$ for all $e \leq \bar{e}_k$, where $-C^i_e(e, k) \equiv -\partial C^i_e(e, k)/\partial e$ is the marginal abatement cost, written for short as MAC. Denoting $k(i)$ as the technology initially owned by firm i, we assume, without loss of generality, that the firms' abatement cost functions are ordered from the dirtiest to the least dirty, i.e. $C^i(e, k(i)) \geq C^{i+1}(e, k(i+1)$ and $-C^i_e(e, k(i)) \geq -C^{i+1}_e(e, k(i+1)$. Installing the new technology causes a fixed cost $F > 0$, the same for all firms. Moreover, when setting the optimal policy, the regulator uses an increasing and convex social damage function, $D(E)$, that evaluates emissions in monetary terms. Here $E = \sum_{i=1}^{n} e_i$ denotes aggregate emissions.

A social planner minimizes total social costs with respect to emissions and the number of firms. When the fixed investment cost is independent of the initial technology, and if not all firms are supposed to adopt in equilibrium the advanced technology, it is always optimal for at least those firms with the highest abatement costs to invest, i.e. there will be some index j such that the firms $i = 1, ..., j$ will invest. Exploiting the fact that $C^i(e_i, a) = C^j(e_j, a)$ and $e_i = e_j$ for all $i \leq j$, the social planner's problem can therefore be written as

$$\min_{\{j, e_a, e_{j+1}, \ldots, e_n\}} \{j[C^j(e_a, a) + F] + \sum_{i=j+1}^{n} C^i(e_i, k(i)) + D(E)\}$$

where $E = je_j + \sum_{i=j+1}^{n} e_i$. Clearly for $i > j$, e_i depends solely on the type of technology k.

Using $AMAC^*(E, j)$ to denote the optimal *aggregate marginal abatement cost* when the first j firms have adopted the advanced abatement technology, the regulator will choose the optimal aggregate emission level E^*, satisfying

$$D'(E^*) = AMAC^*(E^*, j) \tag{1}$$

Assuming that a regulating authority uses tradable permits to control emissions, it will issue a number of permits, $L = E^*$, to enforce the aggregate emission level E^*. Using σ to denote the market price for permits, firm i with technology k will choose an emission level $e_i(\sigma, k)$ such that its marginal abatement cost equals the price of permits: $-C_e^i(e_i(\sigma, k), k(i)) = \sigma$.

Now, a firm with original technology i has an incentive to adopt the advanced technology a if and only if

$$C^i(e_i(\sigma, a), a) + F + \sigma[e_i(\sigma, a) - \hat{e}_i)] < C^i(e_i(\sigma, k), k) + \sigma[e_i(\sigma, k) - \hat{e}_i], \tag{2}$$

where $\hat{e}_i$ is firm i's initial endowment of permits (if any). Condition (2) indicates that investment will be profitable if the total cost (made up of abatement cost, expenditures on permits, and investment cost) is lower than the abatement cost plus expenditures for permits without investment. This condition crucially depends on the permit price and hence on the total supply of permits L chosen by the regulator. Even if firms are identical, it may be the case that in equilibrium some firms will adopt the new technology and some will not (see Requate and Unold, 2003). In fact, the price of permits and the number of firms are both determined endogenously. Requate and Unold show that socially optimal allocation can be theoretically implemented by issuing the *ex-ante* socially optimal number of emission permits for both a completely symmetric model (Requate and Unold, 2003) and an asymmetric model (Requate and Unold, 2001). In our experimental study, we therefore assume that the regulator issues the optimal number of permits. Requate and Unold (2001, 2003) also show that the social optimum can be decentralized, irrespective of whether permits are allocated for free (grandfathered) or are auctioned off. The type of auction or trading procedure under grandfathering are not specified in these papers. They merely assume that the permit market will always clear.

4 Experimental Design

The experiment was conducted in the experimental laboratory of the University of Kiel between December 2007 and June 2008 using the z-Tree experimental software (Fischbacher, 2007). Subjects were volunteer students with at least a Bachelor's degree in Economics. Earnings during the experiments were designated in Experimental Currency Units (ECUs) and converted into € at the end of the session. In the following sections we describe the treatments as well as the experimental procedure implemented.

4.1 Parameters and treatments

We chose five different technologies $T_1, ..., T_5$. Technology T_1 (technology T_5) implies the highest (lowest) marginal abatement cost (MAC) and the highest (lowest) business-as-usual emission level (EMAX). The firms' technologies are represented by stepwise, downward sloping marginal abatement cost functions depicted in Table 1. If there is no pollution control and the firms do not make any abatement effort, their default profit is $\Pi^0 = 1200$ ECU. The regulator issues a number of permits $L = 108$ (110) in case of grandfathering (auctioning).[7]

By investing a fixed amount of $F = 580$ ECU, any subject (firm) can adopt the new technology a, which has considerably lower levels of MAC and EMAX than even the most efficient initial technology.

With these parameters, only the firms with technologies T_1 and T_2 should invest in a socially optimal allocation. This is also an equilibrium with an optimal price of 55 ECU. However, other, less efficient equilibria exist.[8]

We conducted three different treatments implementing the following policy instruments:

- Auctioning-off permits through an ascending clock auction (AAC). We refer to this mechanism as *pure auctioning*.
- Grandfathering and re-allocating permits through a single-unit double auction (GDA)
- Grandfathering and re-allocating permits through an ascending clock auction (GAC)

[7]We originally had planned to issue $L = 110$ permits, which is the optimal emission level with a hypothetical damage function of $D(E) = \frac{E^2}{4}$ (as illustrated in Figure 1). To avoid integer problems, we reduced the number of permits to 108 in the case of grandfathering. Since the $AMAC$ curve is step function, the expected permit price lies between 40 and 50 ECU in both cases, and the small difference of 2 permits should not affect the results.

[8]For example, if one firm with technology T_3 invests and instead one firm with technology T_2 does not invest, no firm has a unilateral incentive to deviate from its investment decision.

MAC	Emissions (e_i) per technology type					
	T_1	T_2	T_3	T_4	T_5	a
0	20	18	16	14	12	7
10	19	17	15	13	11	6
20	18	16	14	12	10	5
30	17	15	13	11	9	4
40	16	14	12	10	8	3
50	15	13	11	9	7	2
60	14	12	10	8	6	1
70	13	11	9	7	5	0
80	12	10	8	6	4	0
90	11	9	7	5	3	0
100	10	8	6	4	2	0
110	9	7	5	3	1	0
120	8	6	4	2	0	0
130	7	5	3	1	0	0
140	6	4	2	0	0	0
150	5	3	1	0	0	0
160	4	2	0	0	0	0
170	3	1	0	0	0	0
180	2	0	0	0	0	0
190	1	0	0	0	0	0
200	0	0	0	0	0	0

Table 1: Marginal Abatement Cost (MAC) per technology type. $T_1, ..., T_5$ denote the initial technologies, while a denotes the advanced abatement technology.

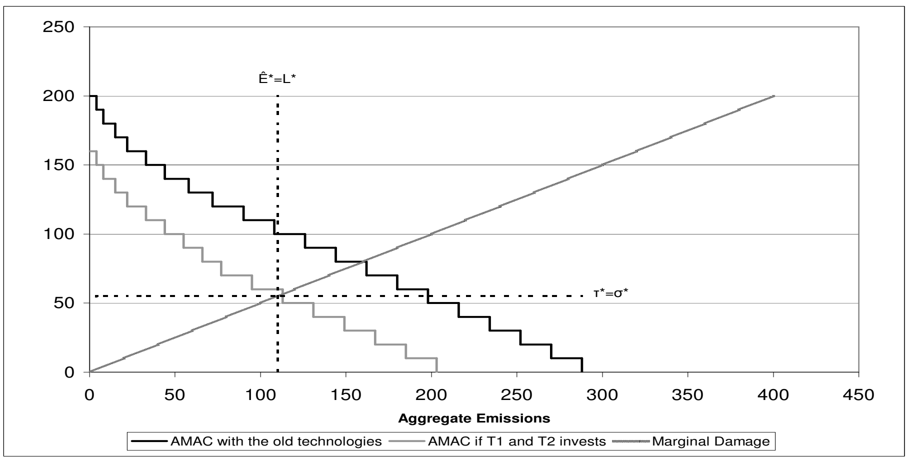

Figure 1: Socially optimal instrument level, tax and emission permits.

Typically, under a system of grandfathering (i.e. free allocation of permits), subjects can bilaterally trade the permits. To mimic this, it is natural to choose a single-unit double auction.[9] For costly allocation of permits (so-called auctioning), several designs might potentially be selected. We chose an ascending clock auction because it is simple to implement and to understand.[10]

Since the first two treatments (grandfathering with double auction and auctioning with ascending clock auction) differ with respect to two design features (free vs. costly allocation; double auction vs. ascending clock auction), it would not have been possible to assign differences in performance either for different allocation schemes or to different trading procedures. We therefore also conducted treatment GAC where permits were allocated for free and re-allocated via an ascending clock auction

4.2 Experimental procedure

Upon arrival at the laboratory, subjects were randomly assigned to one of the computer terminals. Instructions were then distributed and questions were answered.[11] The subjects were informed that communication was not allowed until the end of the session. In each session a group of 18 subjects participated mimicking polluting firms that are subject to regulation. Each subject was allowed to participate in only one session.

Each session consisted of two parts. In the first part, four rounds of a tax treatment were conducted. The purpose of this first part of the session was to make the subjects familiar with the pure investment decision without facing the strategic uncertainty induced by the auction, notably regarding the permit price. The design and the results of the tax treatments are shown in Appendix A. In the second part of the

[9] See **?** and **?**.

[10] We are aware that such uniform price auction might be inefficient since bidders may have an incentive to bid under their demand function in order to keep the clearing prices down. **?** proposes an alternative ascending-clock auction with Vickrey pricing that achieves full efficiency. However, as Cramton and Kerr (2002) state, in the absence of market power the inefficiency that results from an ascending clock auction with uniform pricing is likely to be insignificant and it is easier to implement.

[11] Instructions are included in the Appendix.

session subjects participated in one of three different treatments AAC, GDA, or GAC, to be precisely described below. In this second part subjects played six rounds of a one-shot game. Each round consisted of the following three stages:

Stage 1: Technology assignment and initial permit allocation Each subject is randomly assigned an initial technology $k = T_1, ..., T_5$, where four subjects each are endowed with technologies T_1, T_3, and T_5 and three subjects each with technologies T_2 and T_4. Moreover, in these treatments with grandfathering, i.e. GDA and GAC, permits are allocated depending on the firms' initial technology as displayed in table 2. Both the initial distribution of technologies and the criteria for permit allocation is common knowledge to the subjects.

Firm type	T_1	T_2	T_3	T_4	T_5
Number of firms	4	3	4	3	4
Permits allocated	8	7	6	5	4

Table 2: Firm type (according to the initial technologies), number of firms per type, and number of permits allocated to each firm in the treatments with grandfathering.

Stage 2: Investment decision Subjects simultaneously decide whether to keep the initial technology $k = T_1, ..., T_5$ or adopt to the new technology a and to pay the corresponding investment cost $F = 580$.

Stage 3: Permit auctioning Subjects participate in a permit auction (full compliance with the regulation was imposed and banking of permits was not allowed). The total number of auctioned (allocated) permits are fixed and known to the subjects during the experiment.

At the end of the session the final payoff to the subjects was computed by randomly choosing one round from the first part (tax treatment) and one round from the second part (permit treatment). Each session lasted approximately 2.5 hours and the average payoff was around €35.

In the following we will introduce the details of the implemented permit trading treatments:

In the *GDA treatment* a single-unit double auction is implemented. The permit market opens for three minutes for subjects to buy and sell permits. This they can do either by submitting bid(s) or offer(s), or by accepting standing bid(s) or offer(s). Every transaction refers only to one permit. However, subjects can trade as many permits as desired within the three minutes. Once the market is closed, the profit for firm i in round t is given by

$$\Pi_{i,t} = \begin{cases} \Pi^0 - C^i\left(e_{i,t}, a\right) - x - F & \text{if the firm invests in round } t, \\ \Pi^0 - C^i\left(e_{i,t}, k\right) - x & \text{if it does not invest in round } t, \end{cases}$$

where $k \in \{T_1, ..., T_5, a\}$ denotes the index of the abatement technology, and x is defined as $x = \sum_{j=1}^{J} \sigma_{i,j,t} Z_{i,j,t}$. Moreover, J is the number of trades, $\sigma_{i,j,t}$ is the price that subject i pays or receives in trade j, and $Z_{i,j,t} \in \{1, -1\}$ indicates whether he/she buys ($Z_{i,j,t} = 1$) or sells ($Z_{i,j,t} = -1$) a permit. Net trades sum up to $\sum_{j=1}^{J} Z_{i,j,t} = e_{i,t} - \hat{e}_i$ where $\hat{e}_i$ is subject $i's$ initial endowment of permits.

In the *AAC treatment,* permits are auctioned off through an ascending clock auction. In this procedure the initial price is set at 5 ECU. Subjects then have 40 seconds to place their demand for permits (their requested number of permits) at that price. If aggregate permit demand exceeds supply set by the regulator (108 permits), the price is increased by 10 ECU (so that the next price is 15 ECU, then 25 ECU, and so on). The auction then continues until the quantity required by the firms is smaller or equal to permit supply. If this is the case, the auction ends and each subject gets its demanded quantity at this last price.[12]

Finally, in the *GAC treatment* the procedure is similar to the AAC treatment, except that for the given price the subjects now have 40 seconds to place their demand (requested number of permits) *or* their supply (number of permits they offer). If

[12]If a subject does not submit her demand in time, the computer program automatically submits the subject's demand at the previous price. If the subject does not submit her demand at the initial price (5 ECU), the computer program automatically submits her maximum emission level. However, this hardly ever occurred.

aggregate demand is smaller or equal to aggregate supply, the auction ends and each bidder obtains his/her demanded quantity at this final price.[13]

The profit of firm i in round t for the treatments with ascending clock auction (AAC, GAC) is given by

$$\Pi_{i,t} = \begin{cases} \Pi^0 - C^i\left(e_{i,t}, a\right) - \sigma(e_{i,t} - \hat{e}_i) - F & \text{if the firm invests in round } t, \\ \Pi^0 - C^i\left(e_{i,t}, k\right) - \sigma(e_{i,t} - \hat{e}_i) & \text{if it does not invest in round } t, \end{cases}$$

where σ is now the uniform price resulting from the auction.

4.2.1 Eliciting risk attitudes

At the end of the session we conducted a test to elicit the subjects' risk attitudes. For this purpose we employed the low-payoff menu of paired lotteries (Holt and Laury, 2002), which ranks risk attitudes on a scale ranging from 1 (high degree of risk-loving) to 10 (high degree of risk-aversion). A coefficient of 4 denotes risk neutrality. Appendix B provides a detailed description of the menu. The distribution of risk coefficients in our sample is displayed in Figure 2.

5 Results

We are particularly interested to see whether there are significant differences in performance between the different treatments regarding (i) optimal investment behavior, (ii) efficient allocations of permits (reflected in the total abatement costs given the investment decision), and (iii) minimization of total abatement cost. For most of the analysis, we employ the robust rank-order test (F-P test following Fligner and Poli-

[13]If demand is equal to supply, then each offerer also sells her offered quantity. However, if demand is smaller than supply, a random mechanism determines which of the offerers will sell their offered quantities and which will not.

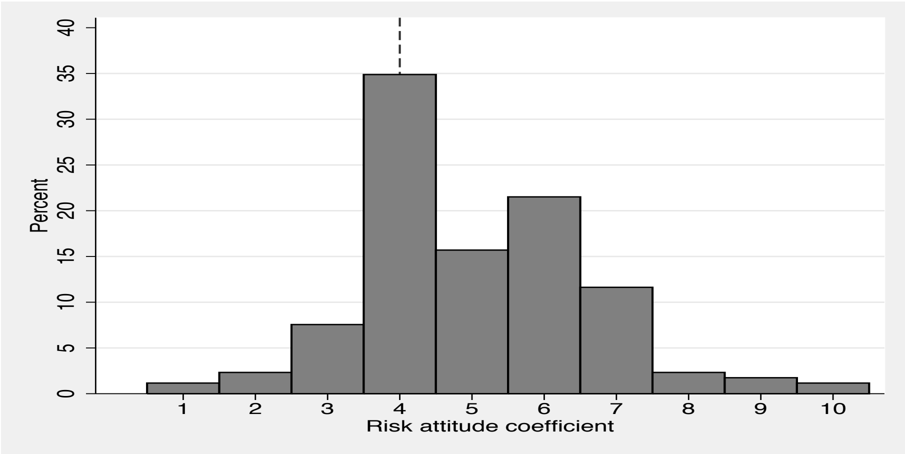

Figure 2: The distribution of the risk-attitude coefficients (average: 5.02, standard deviation: 1.58). Coefficients in the range 1-3 indicate risk loving, a coefficient of 4 indicates risk neutrality, and coefficients in the range 5-10 indicate risk aversion.

cello, 1981)[14] to compare between treatments. Since we employed 18 firms in each session and the firms are matched with different initial technologies each round, we treat every round in each session as an independence observation.

5.1 Investment behavior

We start by evaluating investment behavior. First we compare the aggregate investment patterns under the different treatments with the theoretical optimum. In a second step, we will study what factors drive individual firms' investment behavior.

5.1.1 Aggregate behavior

For all three implemented treatments, Figure 3 displays the firms' investment decisions depending on the assigned initial technology.

Note that in all treatments most of the firms using technologies T_1 and T_2 decide to adopt the low emission technology a, whereas the number of investing firms decreases as we move to technologies T_3, T_4 and T_5, i.e. those with initially lower baseline emissions and lower marginal abatement costs. In fact, although the observed investment

[14]The F-P test, like the popular Wilcoxon-Mann-Whitney (WMW) test, tests for the difference in medians of two samples. But, unlike the WMW test, it also works well for samples with different variances (see Feletovich, 2003).

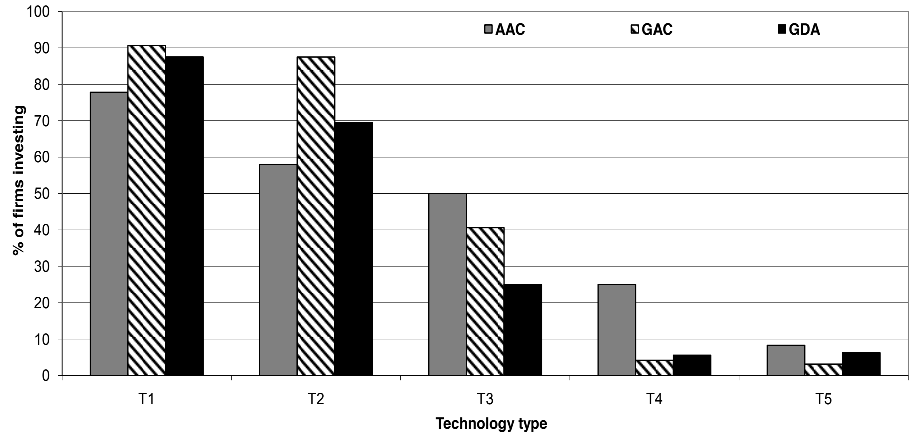

Figure 3: Percentage of firms investing in technology a per initial technology $k = T_1, ..., T_5$.

pattern is close to the socially optimal allocation (which is also an equilibrium)[15], we find that for all treatments implemented the observed investment patterns differ significantly (at the 5% level)[16] from the first-best investment pattern (where only those firms with technologies T_1 and T_2 should invest).

If we compare between treatments we find that in the ascending auction mechanism with and without grandfathering (i.e. comparing the AAC and the GAC treatments) the investment patterns differ significantly [17] In particular, for the AAC mechanism, where permits are initially auctioned off and no re-allocation mechanism is provided, we observe significant under-investment among the subjects having initially been endowed with relatively dirty technologies (T_1 and T_2) but over-investment among the subjects with initially relatively clean technologies (T_3, T_4 and T_5). In the later case the different sessions between between 8% and 50% of firms with the relatively clean technologies (T_3, T_4 and T_5) decided to invest. TILL, I DON'T LIKE THE WAY THIS (LAST) PARAGRAPH IS WRITTEN. HERE IS MY SUGGETSION.

Using an F-P test to compare between the different allocation mechansims (i.e. comparing the AAC and GAC treatments), we find that the

[15] In particular, averages of 70%, 86%, and 84% of the investment decisions in the AAC, GAC, and GDA treatments, respectively, follow the behavior predicted by the efficient equilibrium.

[16] We used a one-sample sign-rank test.

[17] Between 10% and 5% significnace level comparing the F-P test statistics with their simulated critical values for small samples (Feltovich, 2005).

GAC perform closer to the first best investment pattern than the AAC treatment.[18] **In other words, for the AAC mechanism, we observe significant under-investment among the subjects having initially been endowed with relatively dirty technologies (T_1 and T_2) and over-investment among the subjects with initially relatively clean technologies (T_3, T_4 and T_5).**

Finally we compare the effect of the permit re-allocation mechanism, once permits have been distributed for free among the firms. In other words, we compare the GAC and the GDA treatments. Employing the F-P test again, we do not find a significant difference in the subjects' investment behavior at the 10% level. We summarize our findings as follows.

Result 1a: *If permits are initially grandfathered, the observed investment pattern is closer to the socially optimal allocation compared with the investment pattern observed when permits are initially auctioned off.*

Result 1b: *With initial grandfathering, the market institution used to re-allocate permits within an industry (ascending clock vs. single-unit double auction) has no significant effect on the pattern of technology adoption.*

5.1.2 Individual behavior

To better understand the factors influencing investment behavior in the different treatments, we employ the random-effect Probit model to explain the subjects' investment probability in each treatment. As explanatory variables we include the initial technology assigned (a discrete variable ranging between 1 and 5 for the five initial technologies), the average price in the previous round, the risk-attitude coefficient ranging between 1 (high degree of risk-loving) and 10 (high degree of risk-aversion),

[18]Between 10% and 5% significnace level comparing the F-P test statistics with their simulated critical values for small samples (Feltovich, 2005).

Treatment	AAC	GAC	GDA
Technology (t)	-0.71***	-1.42***	-1.07***
	(0.13)	(0.35)	(0.18)
Risk-attitude coef.	-0.02	-0.19	0.40**
	(0.12)	(0.19)	(0.18)
Average price ($t-1$)	0.02**	-0.01	0.03
	(0.01)	(0.02)	(0.03)
Period	-0.09	-0.53	0.15
	(0.09)	(0.30)	(0.22)
Cons	1.31	7.74**	-2.32
	(0.95)	(2.58)	(3.36)
$\widehat{\Sigma_u}$	0.98	0.53	0.83
	(0.26)	(0.49)	(0.27)
$\widehat{\rho}$	0.49	0.22	0.41
	(0.13)	(0.31)	(0.15)
Wald-$\chi^2(4)$	30.88***	16.71***	35.66***

Table 3: Random-effect Probit estimations of the different treatments (std. err. are given in parentheses). The dependent variable: investment in round t. **, and *** denote significance at the 5%, and 1% levels, respectively.

and the round number.[19]

First we study the effect of the initial technology on the probability to invest. Since firms endowed with dirtier technologies gain more from adopting the new technology, we expect the firms' investment probability to decrease when initially being endowed with a cleaner technology. The results reported in Table 3 confirm our hypotheses for all implemented treatments. However, this effect differs among the different mechanisms. In the mechanisms with freely allocated permits (GDA and GAC) the role of the technology is much stronger than in the AAC treatment where permits are auctioned-off and must be purchased.[20]

Secondly, since the permit price observed in the market is the only information the subjects have about previous aggregate investment, it is natural to conjecture that firms will be more likely to invest if they expect high prices in the permit market. Therefore, our hypotheses is that a higer permit price in one round will increase the firms' investment probability in the next round. However, this hypothesis is

[19]We omitted the data of two subjects from the AAC, and GAC treatments and one subject from the GDA treatment who did not fill in the risk test.

[20]A t-test show a statistically significant difference between the coefficients for the technology among treatments.

only confirmed when permits are initially auctioned off and are note given away for free (AAC treatment). One possible explanation is that the initial grandfathering allocation is closer to the final allocation and therefore reduces the firms' dependence on the auction compared to the situation where firms have to purchase all the permits.

Finally, investment reduces the firms' dependency on the permit price and might thus be perceived as a kind of insurance against unfavorable scenarios. Thus, we expect risk aversion to influence the firms' investment decisions. We observe, however, that a higher degree of risk aversion increases the investment probability only when permits are initially grandfathered and re-allocated through a double auction (GDA treatment). This result could signal systematic differences in the auction mechanism implemented: discriminatory vs. uniform pricing. Whereas in the double auction traders observe a range of transactions prices as trading takes place, in the ascending-clock auction all permits are traded at a single price, which may be perceived as a less noisy signal by the firms. We can summarize our findings as follows:

Result 2a: *The firms' initial technology is the main determinant of their investment decisions, and therefore, those firms with higher marginal abatement cost have a higher the probability to adopt the new technology.*

Result 2b: *A higher permit price in the previous round only affects the firms' investment decisions when permits are initially auctioned off (i.e. under AAC), but not in the case of initial grandfathering (i.e. under GAC and GDA).*

Result 2c: *When permits are initially grandfathered and re-distributed among firms through a double auction (i.e. under GDA), investment increases as firms are more risk averse.*

5.2 The permit market

TILL, HERE I THINK THAT WE SHOULD DIFFERENTIATE THIS SECTION FROM THE EFFICIENCY - I MARK IN BOLD THE PARTS WHICH I THINK SHOULD NOT BE THERE

In this section we investigate the performance of the different permit trading institutions implemented. One important aspect is to analyze whether a given trading institution is able to reflect the firms' investment decision by the permit price. MY SUGGESTION: **In this section we charecterize the different treatments according to prices and trading volume. One important aspect is whether these prices and volumes reflect the industry's technological level (or the firms' investment pattern).**

Note that in order to evaluate market efficiency, we cannot use the theoretically optimal equilibrium price computed in section 4 as a benchmark, since that price results from the theoretically optimal investment pattern[21]. **But we have already seen that firms do not behave optimally concerning technology adoption. Therefore, in order to evaluate the permit-market performance, we calculate the theoretical equilibrium prices and trade volumes given the observed investment pattern. Table 4 shows the observed average prices and volumes in the first two columns**[22] **and the efficient prices and volumes expected in the last two columns. I THINK THAT WE SHOULD NOT SPEAK ABOUT EFFICIENCY IN THIS SUBSECTION SINCE WE HAVE A SECTION ONLY ABOUT THAT**.

MY SUUGESTION, Note that in order to evaluate the observe **permit prices and volumes**, we cannot use the theoretically optimal equilibrium price and volumes

[21] If only firms of type T_1 and T_2 invest in the advanced technology, we expect an equilibrium permit price equal to 55 ECU. See Figure 1.

[22] The reported prices and volumes are averaged across sessions and rounds within a given treatment.

Treatment	Observed		Expected	
	Price	Volume	Price	Volume
AAC	55.00	103.81	45.45 − 53.63	108
	(11.83)	(5.32)	(8.20 − 9.24)	(−)
GAC	60.00	32.87	49.16 − 59.16	35
	(10.69)	(5.66)	(8.86)	(3.42)
GDA	64.84	44.16	49.16 − 59.16	35.41
	(10.01)	(10.56)	(7.93)	(3.77)

Table 4: Comparison of mean observed prices and trade volumes of permits with the expected prices and trade volumes, given the firms' investment pattern (std. dev. are given in parentheses).

computed in section 4 as a benchmark, since that price results from the theoretically optimal investment pattern[23]. But we have already seen that firms do not behave optimally concerning technology adoption. Therefore, we **should** calculate the theoretical equilibrium **prices and trade volumes** given the observed investment pattern. Table 4 shows the observed average prices and volumes in the first two columns[24] and the efficient **(expected)** prices and volumes in the last two columns.

Table 4 shows that in all treatments the permit market suffers from significant over- pricing, that is, the observed prices are higher than the expected price reflecting the technologies used by the firms. This is particularly true in those treatments with grandfathering (GAC and GDA treatments). Looking at the observed volumes, we find lower volumes than expected in those treatments using the ascending-clock auction to allocate (AAC treatment) or re-allocate (GAC treatment) permits, whereas excess volumes are observed when trade takes place via double auction (GDA treatment). However, in this last case it is important to distinguish between total and net trade volumes. Whereas the net trade volume refers to the permit variation, that is, the difference between the permits held at the beginning and at the end of the auction, the total trade volume refers to the total number of transactions. The difference between net and total volume can be considered as *speculative trading*,

[23]If only firms of type T_1 and T_2 invest in the advanced technology, we expect an equilibrium permit price equal to 55 ECU. See Figure 1.

[24]The reported prices and volumes are averaged across sessions and rounds within a given treatment.

Treatment	Observed volume		Expected volume
	Net	Total	
GDA	30.83	44.16	35.41
	(7.95)	(10.56)	(3.77)

Table 5: Mean (std. dev.) of observed net trading in comparison with total trading in the GDA treatment.

defined as one subject buying and selling permits in the same round in order to gain from price volatility within a given trading period. From Table 5 we observe that speculative trading represents around 30% of total volume. Indeed, the net volume observed is lower than expected, which is in line with the other two implemented mechanisms. Moreover, also the observed price variance is higher than expected. In fact, from tables 4 and 5 we find a negative relationship between price dispersion and net trading.[25]

We summarize our findings on the permit market performance as follows:

Result 3a: *Given the firms' investment pattern all permit trading mechanisms suffer from over-pricing and insufficient (net) trading.*

Result 3b: *When the double auction mechanism is used to re-allocate permits among firms, speculative trading emerges and generates excess volume in the permit market.*

Let us finally take a closer look into speculative behavior. As indicated above, we define a *speculator* as a trader who sells and buys permits within the same round. In this respect we can say that firms tried to engage in arbitrage. In contrast to other financial assets, an emission permit can be considered as a production input. Therefore we would expect that the production technology influences the decision to speculate. Table 6 summarizes the results of a random effect Probit estimation

[25]In a related experimental setting, Ben-David et al. (1999) also observe that price variability is inversely related to trade volume and recommend a uniform price auction in order to increase market liquidity.

looking for factors that influence speculative trading. Interestingly, it is mainly the risk attitude that drives speculation: the lower the risk aversion, the higher the probability to speculate. By contrast, the initial technology, the investment decision, and also the previous round's permit price have no significant impact on speculative trade.

Furthermore, it is interesting to observe that speculators did not manage to outperform non-speculators. On average speculators even earned a lower profit than those who bought or sold only once.[26] Our findings give rise to the next results:

Result 3c: *The lower is the individual's risk-aversion, the higher the probability that he/she will engage in a speculative behavior in the permit market.*

Result 3d: *On average speculators earn a lower profit than non-speculators.*

6 Efficiency comparison

TILL; I CHANGED THE NUMBERS OF THE RESULTS IN THIS SECTION TO BE 4a, 4b and 4c. I THINK THAT IT IS MORE CONSISTENT WITH THE RESULTS BEFORE:

An important issue, being also of political interest, is to compare the different allocation and trading schemes with respect to efficiency. A typical efficiency measure to test the performance of mechanisms in economic experiments is the ratio of the theoretical minimal social cost divided by the social cost induced by the observed behavior in the experiment. In the mechanisms considered here, two sources for potential inefficiencies occur: suboptimal investment decisions and suboptimal permit

[26]The mean profit (average profit per round) obtained by those subjects doing speculative (non speculative) trading is 702.86 ECU (785.60 ECU). The result is significant at the 1% significance level (using an F-P test or a t-test).

Variable	Coef. (Std. Err.)
Technology (t)	-0.11
	(0.12)
Risk-attitude coef.	-0.28**
	(0.14)
Investment (t)	-0.54
	(0.37)
Average price ($t-1$)	0.04
	(0.02)
Period	-0.00
(0.18) Cons	-0.98
	(2.80)
Subjects	35
$\widehat{\Sigma_u}$	0.97
	(0.24)
$\widehat{\rho}$	0.48
	(0.12)
Wald-$\chi^2(5)$	15.44***

Table 6: Random-effect Probit estimation of the GDA treatment. The dependent variable: speculation in round t (std. err. are given in parentheses). **, and *** denote significance at the 5%, and 1% levels, respectively, and "n.s" means not significant at the 10% or lower level.

	AAC	GAC	GDA
ER^{Permit}	0.68 (0.11)	0.81 (0.04)	0.84 (0.06)
ER^{Invest}	0.92 (0.04)	0.93 (0.02)	0.92 (0.03)
ER^{Total}	0.79 (0.06)	0.86 (0.03)	0.85 (0.05)

Table 7: Mean (Std. Dev.) of the different efficiency ratios

allocations through auction or bilateral trade. It is therefore instructive to decompose these two sources for potential inefficiencies.

6.1 Efficiency in the permit market

We begin by looking at the efficiency of permit allocation. For this purpose, we denote the total variable abatement cost as *TVAC*, i.e. *TVAC*$= \sum_{i=1}^{n} C^i(e_i, \kappa(i))$, where $\kappa(i) \in \{k(i), a\}$ is the actual technology used by firm i after the investment decision. Let $\kappa = (\kappa(1), ..., \kappa(n))$ be the technology profile after the investment stage. Further $\kappa^{obs} = (\kappa^{obs}(1), ..., \kappa^{obs}(n))$ is the *observed* technology profile while $\kappa^* = (\kappa^*(1), ..., \kappa^*(n))$ is the *efficient* one. **Additionaly, (INSTEAD OF FURTHER)** we use $e^{obs} = (e_1^{obs}, ..., e_n^{obs})$ to denote the observed emission-permit allocation, and $e^*(\kappa)$ to denote the optimal emission-permit allocation contingent on a given the technology profile κ. Then $TVAC(e^{obs}, \kappa^{obs}) = \sum_{i=1}^{n} C^i(e_i^{obs}, \kappa^{obs}(i))$ is the observed *TVAC*, while $TVAC(e^*(\kappa^{obs}), \kappa^{obs}) = \sum_{i=1}^{n} C^i(e_i^*(\kappa^{obs}), \kappa^{obs}(i))$ is the theoretically minimal *TVAC* contingent on the observed investment profile κ.

Permit-market efficiency is now defined by the ratio of the *expected TVAC contingent on the observed investment profile* to the *observed TVAC*, formally:

$$ER^{Permit} = \frac{TVAC(e^*(\kappa^{obs}), \kappa^{obs})}{TVAC(e^{obs}, \kappa^{obs})}$$

The permit-market efficiency-ratios resulting from our three allocation mechanisms are displayed in the first row of Table 7.

A pairwise application of an F-P-test shows that grandfathering outperforms auctioning independently of how the permits are reallocated.[27] By contrast, once permits are issued for free, there is no significant difference between the auction mechanisms. More precisely GDA and GAC do not differ at the 10% level. An explanation for the good show of grandfathering in comparison with pure auctioning (i.e. without free allocation) may be that the initial allocation under grandfathering generates some kind of anchoring effect, since compared with auctioning, the initial allocation is not so far away from the efficient one. We summarize our findings as follows:

Result 4a: *Grandfathering with initial allocation of permits proportional to the maximal emission levels (EMAX) leads to higher final permit-market efficiency than pure auctioning.*

Note that I WOULD OMIT AND START LIKE THAT: The fact that grandfathering with ascending clock auction (GAC) outperforms pure auctioning (AAC) contradicts the celebrated theoretical result stating that the final allocation of permits is independent of the initial allocation. Although this is not the particular focus of this paper, our results show in passing that this theoretical result does not necessarily hold, but rather that the final allocation is biased through the initial one. CAN WE GIVE OTHER REFERENCES? THERE MUST BE RELATED RESEARCH RESULTS. WE COULD WRITE THEN: "this is in line with the findings of XX and YY who found that".

6.2 Efficiency of investment

In a next step we investigate investment efficiency. To separate this from the allocation efficiency, we look at the counter-factual total abatement cost, including investment, that will result if an efficient allocation emerges through permit trading. For this purpose we define: $I = (I_1, ..., I_n)$ with $I_i \in \{0, 1\}$ as the investment

[27] At the 1% significance level.

pattern, where $I_i = 1$ if subject i invests and $I_i = 0$, otherwise. Further we write $I^* = (I_1^*, ..., I_n^*)$ for the optimal investment pattern, and $I^{obs} = (I_1^{obs}, ..., I_n^{obs})$ for the observed one. Clearly I^* and I^{obs} induce the corresponding technology profiles κ^* and κ^{obs}. Then we can define *efficiency ratio of investment* as the ratio between the *lowest* possible total abatement cost, including investment cost, and the *observed* total abatement cost, given the counterfactual that emissions are allocated efficiently.

$$ER^{Invest} = \frac{TVAC(e^*(\kappa^*), \kappa^*) + F_{i=1}^n I_i^*}{TVAC(e^*(\kappa^{obs}), \kappa^{obs}) + F_{i=1}^n I_i^{obs}}$$

In the second row of Table 7 we see that the investment efficiency ratio**s circles around (INSTEAD: are around)** 93% **for (INSTEAD: in)** all treatments. In fact, an F-P test shows that there no significant difference between any pair of treatments. This is surprising since in Result 1a we found that the investment patterns do significantly differ. The reason for this puzzle is that under the AAC treatment there is under-investment among those subjects with initial technologies T_1 and T_2 and over-investment by those with T_3, T_4, and T_5. The total number of firms investing, however, is close to the efficient number. Therefore the suboptimal investment pattern does not impact so much on investment efficiency. We summarize our result as follows:

Result 4b: *There is no significant difference between all mechanisms with respect to investment efficiency.*

6.3 Overall efficiency

Finally we look at *total efficiency,* measured as the ratio of the lowest possible total abatement cost divided by the observed total abatement cost.

$$ER^{Total} = \frac{TVAC(e^*(\kappa^*), \kappa^*) + F_{i=1}^n I_i^*}{TVAC(e^{obs}, \kappa^{obs}) + F_{i=1}^n I_i^{obs}}$$

The results are displayed in the third row of Table 7. Here we see again free allocation of permits (GDA and GAC) outperforms pure auctioning.[28], while there is no significant difference between GDA and GAC. The reason that free allocation performs better than pure auctioning obviously results from corresponding permit-market efficiency.[29] We summarize our result as follows:

Result 4c: *Mechanisms with free allocation of permits (grandfathering) leads to higher final total efficiency than pure auctioning.*

7 Concluding Remarks

The aim of this study was to investigate by methods of experimental economics whether emission permit markets provide efficient incentives for polluting firms to adopt cleaner technologies. In particular, we have been interested in the performance of different institutional frameworks, notably the choice of the initial allocation of permits (costly vs. free) and the choice of auction design and how these affect investment incentives.

We find that the firms' overall performance with respect to investment under tradable permits is remarkably good, even though we observe some under-investment by inefficient firms and some over-investment by less inefficient firms.[30] **However this deviation from the first-best has little impact on the investment efficiency measured by the ratio of minimal total abatement cost, including investment costs, and observed total abatement cost, contingent on a counterfactual efficient allocation of permits. I FIND THIS CONFUSING. MY**

[28]These differences are significant at the 1% level.

[29]Note that the total efficiency cannot simply be written as the product of permit-market efficiency and investment efficiency, the reason being that $E - Ratio^{invest}$ and $E - Ratio^{total}$ contain the investment cost while $E - Ratio^{permit}$ does not. To relate $E - Ratio^{permit}$ and $E - Ratio^{invest}$ to $E - Ratio^{total}$ we had to normalize the product $E - Ratio^{permit} \times E - Ratio^{invest}$ by the factor $\frac{{}_{i=1}^{n} AC_i(e_i^{obs}, \kappa_i^{obs})}{{}_{i=1}^{n} AC_i(e_i^{obs}, \kappa_i^{obs}) + {}_{i=1}^{n} I_i^{obs} F} / \frac{{}_{i=1}^{n} AC_i(e_i^{*}(\kappa^{obs}), \kappa_i^{obs})}{{}_{i=1}^{n} AC_i(e_i^{*}(\kappa^{obs}), \kappa_i^{obs}) + {}_{i=1}^{n} I_i^{obs} F}$ the values of which, however, are of no further interest.

[30]A similar result has been found by Gangadharan et al. (2010).

SUGGESTION: The good showing of the treatments with grandfathering in comparison with the pure auctioning treatment regarding the first best investment pattern does not necessary imply that the treatments with grandfathering outperform the pure auctioning concerning the adoption of new technology. In fact, when looking at the investment efficiency (given optimal permit allocation) we do not find differences between the treatments.

HERE IS AGAIN PART THAT I DONT LIKE: In contrast to theoretical predictions, we find however that the treatments with an initial free allocation of permits (grandfathering) performs better than pure auctioning. I SUGGEST THE FOLLOWING: However, regarding the efficiency in allocation of permits (for a given technological level), we find that the treatments with an initial free allocation of permits (grandfathering) performs better than pure auctioning. The reason may consist in the fact that due to proportionally allocating the permits to the business-as-usual emission levels, the initial allocation under grandfathering is much closer to the efficient one than is the case under pure auctioning. On the other hand, once permits are allocated for free, we do not observe any difference in the allocation mechanism, i.e. it does not matter whether permits are traded by a double oral auction or are allocated to an ascending bid auction. This result is remarkable because it justifies abstraction from the particular auction design, as performed in many theoretical papers and textbooks.

Regarding total abatement cost, i.e. abatement and investment costs, the treatments using grandfathering scheme outperform the treatment using the pure auctioning scheme. This result is driven by the higher permit-market efficiency. This is particularly interesting in light of most economists preference of auctioning over grandfathering (see, for instance, Cramton and Kerr, 2002).[31] The reason for the good

[31]There are nevertheless strong reasons to favor auctioning over grandfathering because auction revenues can contribute to lowering the costs of raising public funds that arise elsewhere through distortionary taxes. This effect as known as the 'weak double dividend' (see Goulder, 1995).

showing of the grandfathering scheme may be that if permits are initially allocated in a corrective way (i.e. firms which pollute more receive more permits), it reduces the dependency of the firms on the auction results.

In our experimental design we endowed the firms with asymmetric technologies and all firms are relatively small compared to the whole market, and thus have little market power. Montero (2002a,b) has shown that the initial allocation does affect the firms' investment decisions if firms can exercise market power on either the permit or the output market. While for the European CO_2 market even the large utilities are relatively small compared to the whole CO_2 emission permit market, in other existing permit markets, notably the American SO_2 market (see Rico, 1995), large buyers and sellers of permits exist. Further research is therefore needed to cast light on the question whether institutional design matters with respect to investment incentives when firms do exercise market power. In this respect, it may be interesting to draw on the design by Godby et al. (1999) and Godby (2000) to investigate the incentives for adopting a low-pollution technology. Another issue we still know little about is the way in which the degree of asymmetry among firms affects investment efficiency. As stressed by Requate and Unold (2003), complete symmetry may induce a coordination problem with respect to which firms will invest and which will not. Strategic uncertainty may induce both over- and under-investment. Even in our experiment with its rather asymmetric firms, strategic uncertainty could not be eliminated completely. This uncertainty increases with greater symmetry among the firms. In the light of the relative paucity of experimental literature in this area, a systematic investigation of this issue is certainly worth pursuing.

References

Ben-David, S., Brookshire, D. S., Burness, S., McKee, M., Schmidt, C., 1999. Heterogeneity, irreversible production choices, and efficiency in emission permit markets.

Journal of Environmental Economics and Management 38, 176–194.

Bohm, P., 2003. Experimental evaluations of policy instruments. In: Mäler, K.-G., Vincent, J. R. (Eds.), Handbook of Environmental Economics, Vol. 1. Elsevier, pp. 437–460.

Buckley, N. J., Mestelman, S., Muller, R. A., 2006. Implications of alternative emission trading plans: Experimental evidence. Pacific Economic Review 11, 149–166.

Buckley, N. J., Muller, R. A., Mestelman, S., 2005. Baseline-and-credit style emission trading mechanisms: An experimental investigation of economic inefficiency. Department of Economics Working Papers 2005-04, McMaster University.

Cramton, P., Kerr, S., 2002. Tradeable carbon permit auctions: How and why to auction not grandfather. Energy Policy 30, 333–345.

Downing, P. B., White, L. J., 1986. Innovation in pollution control. Journal of Environmental Economics and Management 13, 18–29.

Feletovich, N., 2003. Nonparametric tests of differences in medians: Comparison of the Wilcoxon-Mann-Whitney and Robust Rank-Order tests. Experimental Economics 6, 273–297.

Feltovich, N., 2005. Critical values for the robust rank-order test. Communications in Statistics - Simulation and Computation 34, 525–547.

Fischbacher, U., 2007. z-Tree: Zurich toolbox for ready-made economic experiments. Experimental Economics 10, 171–178.

Fischer, C., Parry, I. W. H., Pizer, W. A., 2003. Instrument choice for environmental protection when technological innovation is endogenous. Journal of Environmental Economics and Management 45, 523–545.

Fligner, M. A., Policello, G. E., 1981. Robust rank procedures for the Behrens-Fisher problem. Journal of the American Statistical Association 76, 162–168.

Gangadharan, L., Farrell, A., Croson, R., Forthcoming, 2010. Investment decisions and emissions reductions: Results from experiments in emissions trading. In: List, J. A., Price, M. (Eds.), Handbook on Experimental Economics and the Environment. Edward Elgar Publishing Ltd., Cheltenham, UK and Northampton, MA.

Godby, R., 2000. Market power and emission trading: Theory and laboratory results. Pacific Economic Review 5, 349–363.

Godby, R., Mestelman, S., Muller, R. A., 1999. Experimental tests of market power in emission trading markets. In: Petrakis, E., Sartzetakis, E., Xepapadeas, A. (Eds.), Environmental Regulation and Market Power: Competition, Time Consistency and International Trade. Edward Elgar Publishing Ltd., Cheltenham, United Kingdom, pp. 67–94.

Goulder, L. H., 1995. Environmental taxation and the 'double dividend': A reader's guide. International Tax and Public Finance 2, 157–183.

Hizen, Y., Kusakawa, T., Niizawa, H., Saijo, T., 2001. Two patterns of price dynamics were observed in greenhouse gases emissions trading experiments: An application of point equilibrium. Working paper, Institute of Social and Economic Research, Osaka University.

Holt, C. A., Laury, S. K., 2002. Risk aversion and incentive effects. American Economic Review 92, 1644–1655.

Jung, C., Krutilla, K., Boyd, R., 1996. Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives. Journal of Environmental Economics and Management 30, 95 111.

Kennedy, P. W., Laplante, B., 2000. Environmental policy and time consistency: Emissions taxes and emissions tradings. In: Petrakis, E., Sartzetakis, E. S., Xepapadeas, A. (Eds.), Environmental Regulation and Market Power. Edward Elgar Publishing inc., Hants, England, pp. 116–144.

Kneese, A. V., Schultze, C. L., 1975. Pollution, Prices and Public Policy. Brokings, Washington, D.C.

Kusakawa, T., Saijo, T., 2003. Emissions trading experiments: Investment uncertainty reduces market efficiency. In: Sawa, T. (Ed.), International Frameworks and Technological Strategies to Prevent Climate Change. Springer-Verlag, New York, pp. 45–65.

Malueg, D. A., 1989. Emission credit trading and the incentive to adopt new pollution abatement technology. Journal of Environmental Economics and Management 18, 52–57.

Milliman, S. R., Prince, R., 1989. Firms incentives to promote technological change in pollution control. Journal of Environmental Economics and Management 17, 247–265.

Montero, J.-P., 2002a. Market structure and environmental innovation. Journal of Applied Economics 5, 293–325.

Montero, J.-P., 2002b. Permits, standards, and technology innovation. Journal of Environmental Economics and Management 44, 23–44.

Muller, R. A., Mestelman, S., 1998. What have we learned from emissions trading experiments? Managerial and Decision Economics 19, 225–238.

Plott, C. R., 1983. Externalities and corrective policies in experimental markets. The Economic Journal. 93, 106–127.

Requate, T., 2005. Dynamic incentives by environmental policy instruments - a survey. Ecological Economics 54, 175–195.

Requate, T., Unold, W., 2001. On the incentives created by policy instruments to adopt advanced abatement technology if firms are asymmetric. Journal of Institutional and Theoretical Economics 157, 536–554.

Requate, T., Unold, W., 2003. Environmental policy incentives to adopt advanced abatement technology: Will the true ranking please stand up? European Economic Review 47, 125–146.

Rico, R., 1995. The U.S. allowance trading system for sulfur dioxide: An update on market experience. Environmental and Resource Economics 5, 115–129.

Wråke, M., Myers, E. C., Mandell, S., Holt, C. A., Burtraw, D., 2009. Pricing strategies under emissions trading: An experimental analysis. Working Papers 2009:1, Swedish National Road & Transport Research Institute (VTI).

A The Tax Treatments

Every experimental session started with a tax treatment ("Part I" in the instructions). Only then did it proceed with the auction treatment. The structure of the tax treatment is similar to that of the permit auction treatments, the only difference being that the government imposes a tax per emission that is equal for all firms (instead of participating in an auction). The idea of conducting the tax treatment is to make subjects familiar with the setting (but without the uncertainty involved in the auctions). Also, the tax treatment enables us to evaluate whether the subjects have understood the setting before we proceed with the actual experiment.

Under the assumption that the regulator anticipates the new technology, we set the *ex-ante* optimal tax rate equal to $\tau = 55$. According to the above settings, the profit of firm i in round t is the following:

$$\Pi_{i,t} = \begin{cases} \Pi^0 - C^i\left(e_{i,t}, a\right) - \tau e_{i,t} - F & \text{if invested in round } t, \\ \Pi^0 - C^i\left(e_{i,t}, k\right) - \tau e_{i,t} & \text{if did not invest in round } t, \end{cases}$$

where $k = T_1, ..., T_5$ and a denotes the advanced abatement technology.

Since the tax treatment is basically a maximization problem, non-optimal decisions by the subjects are considered 'errors'. Consequently, we identify two types of error, (i) a non-optimal abatement decision, i.e., a firm abates more or fewer units than is optimal under the given tax rate and (ii) a non-optimal investment decision, i.e., either a firm invests although it shouldn't, or a firm doesn't invest although it should. Table A.1 shows the percentage of errors in the first and last rounds of the treatment.

	% of investment errors	% of abatement errors
First round	19.12	26.87
Last round	7.85	8.79

Table A.1: Percentage of errors in the first and the last rounds of the tax treatments (a total of 126 subjects).

Table A.1 illustrates that the percentage of errors is substantially lower in the last round in comparison with the first round, implying that at the end of the treatment the subjects have a much better grasp of the economic situation. At the end of the treatment, fewer than 10% of the decisions made by the subjects are classified as erroneous.

B Holt and Laury's (2002) Menu of Paired Lottery

Holt and Laury's (2002) low payoff menu of paired lottery (see Figure B.1) requires subjects to choose between two lotteries: A and B. The 'safer' lottery A includes a probability of winning a high payoff of €2 and a (complementary) probability of wining a low payoff of €1.6.[32] Similarly, the 'riskier' lottery B includes a probability of winning a high payoff of €3.85 and a (complementary) probability of wining a low payoff of €0.1. The probabilities of wining the high (and low) payoffs are the same for both lotteries. The probability of winning the high payoff gradually increases during the lottery-choice menu in increments of 10%, proceeding from a 10% probability of wining the high payoff and a 90% probability of of wining the low payoff in the first lottery-choice, to a 100% probability of winning the high payoff and a 0% probability of winning the low payoff in the last choice of the menu. As the probability of winning the high payoff in both lotteries increases, subjects are expected to switch from A to B since the expected value in lottery B increases more than it does in lottery A. For instance, a risk-neutral subject who chooses the lottery according to the highest expected value will choose A exactly four times before switching to B. Consequently, from the pattern of choices observed, a risk-attitude coefficient is computed which corresponds to the number of consecutive choices in lottery A before switching to lottery B.

[32] In the original study by Holt and Laury (2002) the payoffs are in US$.

Number	Option A	Option B	Your Decision (A or B)
1	1/10 of €2.00, 9/10 of €1.60	1/10 of €3.85, 9/10 of €0.10	
2	2/10 of €2.00, 8/10 of €1.60	2/10 of € 3.85, 8/10 of €0.10	
3	3/10 of €2.00, 7/10 of €1.60	3/10 of €3.85, 7/10 of €0.10	
4	4/10 of €2.00, 6/10 of €1.60	4/10 of € 3.85, 6/10 of €0.10	
5	5/10 of €2.00, 5/10 of €1.60	5/10 of €3.85, 5/10 of €0.10	
6	6/10 of €2.00, 4/10 of €1.60	6/10 of €3.85, 4/10 of €0.10	
7	7/10 of €2.00, 3/10 of €1.60	7/10 of €3.85, 3/10 of €0.10	
8	8/10 of €2.00, 2/10 of €1.60	8/10 of €3.85, 2/10 of €0.10	
9	9/10 of €2.00, 1/10 of €1.60	9/10 of €3.85, 1/10 of €0.10	
10	10/10 of €2.00, 0/10 of €1.60	10/10 of €3.85, 0/10 of €0.10	

Figure B.1: Holt and Laury's (2002) menu of paired lottery