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Abstract: We experimentally test the truth-telling mechanism proposed by Montero (2008) for eliciting firms’ abatement costs. We compare this mechanism with two well-known alternative allocation mechanisms, free and costly allocation of permits at the Pigouvian price. Controlling for the number of firms and the firms’ maximal emissions, we find that, in line with the theoretical predictions, firms over-report their maximal emissions under free allocation of permits and under-report these under costly allocation of permits. Under Montero’s mechanism, by contrast, firms almost always report their maximal emissions truthfully. However, in terms of efficiency, the difference between Montero’s mechanism and costly allocation disappears with industries including more than one firm.

Keywords: mechanism design, environmental policy, permit trading, auctions, experiment

JEL Classification: C92, D44, L51, Q28

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1 Introduction

The stylized social cost model consisting of monetarized environmental damage and abatement cost is the work-horse of environmental economics. The well-known rule for optimal pollution/abatement effort requires marginal abatement cost to align with marginal damage and to equalize across all polluters. The implementation of such an optimal allocation depends on the regulator having sufficient information about both (marginal) damage and polluters' (marginal) abatement cost schedules. While we now have a whole array of valuation methods to determine the external costs of pollution, and hence marginal damage, eliciting the polluters' private abatement cost seems to be more difficult. Before launching the sulfur dioxide trading program in the USA, the Environmental Protection Agency conducted a survey among the polluters affected to get an idea of the range of abatement costs and to set the emission cap accordingly. Not surprisingly for economists, firms over-reported (or over-estimated) their private costs. Consequently, emission prices were greatly over-estimated (Joskow et al., 1998; Rico, 1995), and the emission cap was set much too high relative to actual abatement costs.

It is well known that a regulator's choice of policy instrument affects firms' incentives to over- or under-report their private abatement costs. Suppose a regulator announces the implementation of an emission tax or the auctioning-off of tradable permits. If marginal damage is increasing and the regulator is expected to follow the Pigouvian optimality rule, then firms will have an incentive to under-report their private abatement costs. If, by contrast, the regulator announces to issue emission permits for free, firms are likely to over-report their costs (Kwerel, 1977; Montero, 2008).

Starting from Groves (1973) and Groves and Ledyard (1977), scholars have developed the theory of incentive compatible mechanisms. A major insight from this theory is that under incomplete information about agents' private preferences or costs, truthful revelation of such preference or cost parameters can be induced by choosing an appropriate scheme for paying/charging incentive payments to/from the agents. If a regulator is not constrained by balanced budget conditions, he or she can even induce first-best allocations by implementing truth-telling mechanisms. Hence, depending on the nature of the participation constraints, the regulator may use incentive payments or fees, either financed by lump-sum taxes or by (re-)distributing a resulting surplus in a lump-sum way back to consumers. If, by contrast, the regulator is constrained by a balanced budget for the total incentive payments, only second-best outcomes can be induced (except for special cases). Kwerel (1977) suggests a very simple mechanism for eliciting firms' marginal abatement cost functions. He proposes asking firms to submit their marginal abatement cost curves and, according to their reports, issuing emission permits complemented by subsidies to be paid for reducing emissions beyond what the holding of emission permits stipulates. Dasgupta et al. (1980) suggest a tax-subsidy scheme, extending Kwerel's mechanism to more general environments (such as non-competitive permit markets and heterogeneous pollutants), which induces truth-telling in dominant strategies. Montero (2008) shows, however, that Kwerel's mechanism works only under special conditions. He also indicates that the tax-subsidy scheme by Dasgupta et al. (1980) fails to allocate resources efficiently if aggregate permit supply is fixed. Montero then develops a general incentive-compatible mechanism for eliciting the firms' abatement costs and, in accordance with the firms' reports, regulating emissions in an optimal way. His mechanism is applicable to a wide range of settings, including situations where the pollution permit market is not perfectly competitive.

In a nutshell, Montero's mechanism works as follows: In a first step, the regulator asks the firms to submit their marginal abatement cost schedules, or equivalently, their demand functions for emission permits. Taking these reported marginal abatement cost curves as their true functions, the regulator aggregates these to obtain the aggregate marginal abatement cost curve (or equivalently, the aggregate demand for permits) and then sets the total emission cap by intersecting the resulting aggregate marginal abatement-cost curve with the marginal-damage curve. This yields an optimal emission cap which is then allocated to the firms at *a priori* individual prices. In equilibrium with truth-telling, these prices are equal across firms and correspond to the social marginal damage. In a final step, the regulator reimburses the firms individually by paying back a fraction of their permit expenditures. The auction rules assure that the permit allocation is *ex post* efficient. Note that under this mechanism, truth-telling is not only a Nash equilibrium but even an equilibrium in dominant strategies. Furthermore, firms pay a net amount equal to their contribution to pollution damages. In this sense, the mechanism is also *ex post* equitable from a polluter-pays-principle perspective. We describe this mechanism in detail in section 2.

In the present paper we make use of the controlled environment in the laboratory (e.g., Smith, 1980; 1982; Falk and Heckman, 2009) to test Montero's mechanism. We compare it with two well-known alternative mechanisms, where the regulator asks the firms to submit their (marginal) abatement cost schedules in a simultaneous bid auction to determine the price and amount of permits. Then, the regulator either allocates the permits for free ("free allocation") or charges firms the full costs of the permits at Pigouvian prices ("costly allocation").[1]

In the experiment, the cost schedule is the same for each firm, but maximal emissions are private information and vary across firms. In all three mechanisms investigated, the regulator asks firms to report their maximal emissions, then uses this information to determine emission caps and prices. Hence, in all three mechanisms the allocation of permits is determined by the same (simultaneous bid) auction. The three mechanisms that we are comparing are: (i) "free allocation", (ii) "(fully) costly allocation"(for short: "costly allocation"), where firms are required to fully pay for the permits, and (iii) the incentive-compatible Montero mechanism, where firms partially pay for the permits, referred to as "refunding". We conducted treatments with industries consisting of one, two, or three firms, where firms are assigned one of three different maximal emission levels. We restricted our experimental comparison of the three mechanisms to industries with a small number of firms (up to three) because in Montero's mechanism the share of refunded revenues decreases sharply with an increase in the number of firms, so that theoretically, when three or more firms are subject to regulation, there is hardly any difference between the Montero mechanism and auctioning off permits at the full Pigouvian

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[1] Sometimes "free allocation of permits" is referred to as "grandfathering". The latter suggests that free permits are allocated according to historical emissions. As the latter does not play any role in our experimental study, we avoid referring to "grandfathering". By contrast, "costly allocation" is often referred to as "auctioning". Since all three mechanisms considered here make use of a (simultaneous bid) auction, we prefer to talk about "fully costly allocation".

price.

While emission permit markets for major pollutants such as SO_2 and CO_2 are typically very large, examples with small number of firms do exist, notably regional pollution markets including locally restricted cases of air or water pollution (e.g., Borghesi, 2014; Muller et al., 2002; Sunnevåg, 2003). In this respect, Muller et al. (2002, p.72) note that in 2001 the Ontario Ministry of the Environment announced a mandatory cap on NO_x and SO_x emissions from six generation stations, all owned by a single firm (Ontario Power Generation). Borghesi (2014) describes tradable water pollution rights in Lake Dillon, Colorado, with only four municipal waste water treatment plants.

With respect to its theoretical foundations, this paper draws on the theory of incentive compatible mechanisms, notably Kwerel (1977), Dasgupta et al. (1980), and especially Montero (2008) (see Montero, 2005, 2007 for preliminaries and extensions). It is also linked to the literature on incentive mechanisms with imperfect information, notably Roberts and Spence (1976) and Spulber (1988), as those mechanisms also result in approximately optimal or second-best optimal allocations, even if the regulator does not know the abatement costs. Regarding the experimental literature, our paper adds to the now extensive work on emission trading and markets (see e.g., Plott, 1983; Cason, 1995; Cason and Plott, 1996; Ben-David et al., 1999; Muller et al., 2002; Cason and Gangadharan, 2006; recent papers are e.g., Stranlund et al., 2014; and Holt and Shobe, 2016; - see also the review articles by Muller and Mestelman, 1998; Bohm, 2003; and Sturm and Weimann, 2006).

Our findings are as follows: We find that Montero's refunding mechanism works almost perfectly in the three industry sizes implemented in our experimental setting and for different maximal emission levels. Firms learn fast, and their decisions quickly converge to the socially optimal equilibrium. Under free allocation of permits, firms over-report their true emissions, which is fully in line with theoretical predictions. Free allocation is also the least efficient allocation mechanism in terms of overall abatement costs and damage. Under costly allocation of permits, again as predicted, firms under-report their true emissions. Yet in industries consisting of two or three firms, reported maximal emissions are close to their true values, and efficiency in these industries under costly allocation is almost perfect and no different from the efficiency under Montero's refunding mechanism. The reason is that the pecuniary externalities imposed by any one bidder becomes very small, and hence untruthful bidding becomes unprofitable. Thus, all in all, asking firms for their true maximal emissions and then auctioning off permits at Pigouvian prices, i.e. at full costs, is as good as the fully incentive-compatible refunding mechanism in industries that are larger than a monopoly. This is good news since it indicates that merely asking firms for their emissions schedule and simply auctioning off permits at full costs leads to virtually first-best results.

In the remainder of the paper we proceed as follows: In section 2 we describe and explain the Montero mechanism in detail. In section 3 we describe the experimental design and procedure. In section 4 we formulate our hypotheses, and in section 5 we present our results. In the final section we draw our conclusions and give some outlines for further research. In the Appendix we adapt Montero's mechanism to the special functional forms chosen in our experiment and derive the necessary expressions for the equilibrium predictions for each of the mechanisms under consideration.

2 Theoretical Background of the Montero Mechanism

In the following we describe the Montero mechanism in more detail for the case $n = 1$. This is sufficient to grasp the main idea. We assume that the firm (and in general all firms involved) satisfy the following assumptions: Abatement costs, denoted by $C(e)$, are positive and decreasing in emissions e. Formally, $C(e) > 0$ for $e < e^{\max}$ and $C(e) = 0$, otherwise, where $e^{\max}$ is the business-as-usual emission level. Moreover, $-C'(e) > 0$ and $C''(e) > 0$ for $e < e^{\max}$. The social damage from pollution is evaluated by a social damage function $D(E)$, with $D'(E) > 0$ and $D''(E) \geq 0$, where E denotes the aggregate emissions (notably $E{=}e$ in the special case of one firm). Thus pollution damage is increasing and (weakly) convex.

Montero's mechanism works as follows:

a) The regulator asks the firm to submit its abatement cost schedule. The submitted schedule does not need to correspond to the true cost schedule.

b) The regulator treats the submission as if it is the true marginal abatement cost schedule and thus determines the "optimal" allocation of permits according to the rule "marginal abatement cost equals marginal damage." The optimal allocation induces an optimal aggregate emission level L and an optimal price σ. The firm pays the regulator an amount $\sigma \cdot L$ and receives L pollution permits in return (for several firms, the regulator auctions off a total number of permits L to the firms).

c) The firm receives a fraction of their permits' expenditure $\beta(L)$ so that an amount $\beta(L) \cdot \sigma \cdot L$ is returned to the firm after the auction.

Under these rules, the firm decides which marginal abatement cost schedule to submit in order to minimize total pollution-related costs, which are given by

$$TC = C(L) + [1 - \beta(L)]\sigma L \tag{1}$$

In the following, we use $\tilde{C}(\cdot)$ to denote the reported abatement cost function, where $-\tilde{C}'(\cdot)$ represents the reported *marginal* abatement cost schedule. Then the regulator determines the number of permits to be issued according to the rule

$$-\tilde{C}'(L) = D'(L) \tag{2}$$

such that the number of permits can be written as $\tilde{L}(\tilde{C}(\cdot))$. Note that, based on the mechanism rules, if we replace the permit price σ by $D'(\tilde{L})$, the firm's objective function will be given by

$$\min_{\tilde{C}(\cdot)}\{C(\tilde{L}(\tilde{C}(\cdot))) + [1 - \beta(\tilde{L}(\tilde{C}(\cdot)))]D'(\tilde{L}(\tilde{C}(\cdot))) \cdot \tilde{L}(\tilde{C}(\cdot))\} \tag{3}$$

The firm's true abatement cost at this level of pollution is then given by $C(\tilde{L}(\tilde{C}(\cdot)))$. Since the firm's cost depends only on the number of permits being issued, we can reformulate equation (3) as

$$\min_{L}\{C(L) + [1 - \beta(L)]D'(L) \cdot L\} \tag{4}$$

the solution of which is denoted by $\tilde{L}$. Given this, the firm will announce an abatement cost schedule $\tilde{C}(\cdot)$ running through $C(\tilde{L})$, such that at $\tilde{L}$ the true and the announced functions coincide, i.e., $\tilde{C}(\tilde{L}) = C(\tilde{L})$. The rest of the announced schedule may or may not coincide with the true schedule.

Differentiating equation (4) with respect to L leads to the firm's cost minimizing first-order condition

$$C'(L) + [1 - \beta(L)][D''(L)L + D'(L)] - \beta'(L)D'(L)L = 0 \tag{5}$$

The regulator's task is to adjust the payback function $\beta(L)$ such that condition (5) matches the condition for the social optimum defined as the level of L that solves $C'(L) + D'(L) = 0$. For this to be the case, $\beta(L)$ needs to meet the following condition:

$$\beta'(L) + \beta(L)\frac{D''(L)L + D'(L)}{D'(L)L} = \frac{D''(L)}{D'(L)} \tag{6}$$

Plugging this condition into equation (5), that equation collapses to $C'(L) + D'(L) = 0$. Equation (6) can be viewed as a differential equation in L, which can be solved for $\beta(\cdot)$ to obtain the optimal payback function. The solution provided by Montero (2008, p.515) reads as follows:

$$\beta(L) = 1 - \frac{D(L)}{D'(L)L} \tag{7}$$

By the weak convexity of the damage function, for any L, the payback fraction $\beta(L)$ will adopt values in the unit interval. If we substitute the value of $\beta(L)$ into equation (4), we see that the firm's pollution-related total cost function simply collapses to $C(L) + D(L)$, which matches the regulator's objective function. Thus, the optimal payback function $\beta(\cdot)$ induces the firm to choose its emissions equal to the socially optimal level, and in the original mechanism it is optimal for the firm to announce an abatement cost schedule equal to its true schedule. Furthermore, the firm bears both the cost of pollution abatement and the damage from any remaining emissions.

To further clarify the mechanism, it is helpful to examine the range of values adopted by the payback function $\beta(\cdot)$ for special cases. Note that when the damage function is linear (i.e., $D(E) = d \cdot E$), it is optimal for the regulator to set $\beta(\cdot) = 0$. In this case, the mechanism is effectively equivalent to an emissions tax set equal to the constant marginal damage, which, from our previous analysis, we know to be optimal regardless of the abatement cost function. More generally, it will be optimal for the regulator to keep a portion of the revenue raised by the auction, but not all of it. For a quadratic damage function such as $D(E) = d \cdot E^2/2$, it is optimal for the regulator to set $\beta(\cdot) = 1/2$, i.e., to reimburse exactly half of the permit expenditures.

For multiple firms the mechanism works in a similar way. In this case, the regulator sets up a residual damage function $D'_j(l_j)$ for each firm j, representing the additional marginal damage caused by some firm j's emissions l_j. Then the mechanism works as in the one-firm case.

If for some reason other firms misrepresent their costs, a firm can still do no better than to announce its true costs. In other words, submitting the true marginal abatement cost function is always a *dominant strategy*. For the decision of any single firm, the mechanism therefore eliminates the role of expectations about other firms' actions and knowledge of the competitors' cost structures.

Montero also shows that for the general case of a strictly convex damage function, reimbursing nothing, i.e., setting $\beta(\cdot) = 0$, provides incentives to under-report marginal abatement cost schedules, while under free allocation, i.e., $\beta(\cdot) = 1$, firms will want to inflate their alleged marginal abatement costs. Note that Montero's mechanism is not budget-balanced, i.e., the regulator always keeps some of the revenues. One can also interpret it differently. Instead of charging the full cost of pollution, the regulator bribes the firm into telling the truth by refunding some of the auctioning revenues.

3 Experimental Design and Procedure

This study sets out to test the Montero mechanism and to compare its performance with two well-known alternative allocation mechanisms. In all these mechanisms, the regulator first asks the firms to report their abatement cost schedules. After that the regulator determines the amount and price of permits using a simultaneous bid auction, and then allocates emission permits proportionally to the maximal emissions reported. In particular, the regulator either (i) allocates permits for free, (ii) allocates them at full cost at the Pigouvian price, or (iii) allocates them at partial cost, by partially refunding permit expenditures according to Montero's mechanism.

As the concept of submitting a whole function may be difficult to understand for participants of a laboratory experiment with no experience of multi-unit auctions (see Ausubel, 2004; Klemperer, 2004) and the like, we set up a simple economic environment where the abatement cost schedule is the same for each firm but maximal emissions are private information and vary across firms. To this end, we restrict the class of marginal abatement cost functions to linear ones with equal slopes, such that

$$-C_j'(e) = a_j - be$$

This results in maximal, unregulated emissions $e_j^{\max} = a_j/b$. Under this setting, the only parameters the regulator needs to know are each firm's maximal emissions $e_j^{\max}$. We also assume the following quadratic damage function: $D(E) = 10 \cdot E^2/2$. In the Appendix we show how to derive the residual demand and marginal damage functions that we have used in this study.

Formally, the firms' costs in the three different allocation mechanism, *free allocation* ($FREE$), *costly allocation* ($COST$) and *refunding* (REF) are as follows:

$$\begin{aligned}
TC_j^{FREE} &= 10[e_j^{\max} - l_j]^2/2 \\
TC_j^{COST} &= 10[e_j^{\max} - l_j]^2/2 + \sigma l_j \\
TC_j^{REF} &= 10[e_j^{\max} - l_j]^2/2 + [1 - \beta_j]\sigma l_j
\end{aligned}$$

where l_j, and β_j denote individual emission permits and shares of refunding from the auction revenues, respectively, and σ is the price for emissions. Note that these parameters are functions of the reported maximal emissions profile denoted by $(\tilde{e}_1^{\max}, ..., \tilde{e}_n^{\max})$.

Procedure

We recruited a total of 623 undergraduate students from the Science University of Malaysia (mostly from Economics, Business Administration, and Mathematics) to participate in the experiment.[2] We implemented different treatments, testing for the performance of the three allocation mechanisms, under three different industry sizes (1, 2, and 3 firms) and three different maximal emissions (18, 22, and 26).[3]

We conducted a total of 27 treatments: For each of the three mechanisms there are three treatments with industries consisting of one firm with three different maximal emissions (of 18, 22, and 26). For each mechanism, there are four treatments with industries consisting of two firms and maximal emissions profiles of (18, 22), (18, 26), (22, 22), and (22, 26). Finally, for each mechanism there are two treatments with industries consisting of three firms and maximal emissions profiles of (18, 22, 26) and (22, 22, 22).

The computerized experiment was conducted using the z-Tree program (Fischbacher, 2007). The procedure was as follows: Upon entering the computer laboratory, participants were given approximately 20 minutes to read the instructions. Each participant represented a firm operating in an industry. Then the experiment started with three trial periods, followed by 20 payoff-relevant periods. In each period, the participant's computer screen was divided into two halves.[4] On the left-hand side there was a profit calculator where the participant could simulate the consequences of her own reported maximal emissions and the assumed reported maximal emissions of the other firms. On the right-hand side, the maximal assigned emission level was shown, and the participant was asked to enter her decision, i.e., the maximal emission level $\tilde{e}_j^{\max}$ that she decided to report. Finally, after all 20 payoff-relevant periods were completed, four

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[2] The participants were recruited (i) in lectures, and (ii) through advertisements posted in campus newspapers and in bus stops. In (i) students were told about the time, venue, and duration of the experiment and were asked to show up. In (ii) they received this information after calling the contact number announced in the advertisement. Participants were told that they would earn money in the experiment, but that their earnings would depend on their and others' decisions. The purpose of the experiment was not revealed to them. All participants were undergraduate students (2nd-4th year) from different disciplines: Economics, Business Administration, Mathematics, Biology, Physics, Chemistry, Chemical Engineering, Electric and Electronic Engineering, Computer Science, and Medicine.

[3] We chose these maximal emissions because they provide positive reports for all firms and all three mechanisms.

[4] See the decision's computer screen in Figure B.1 in the Appendix.

periods were randomly selected by the computer to determine the participant's final payoff.

Due to the complexity of the experiment, and since a context-free frame may pose further difficulties in understanding the mechanisms, we framed the experiment in the relevant field context.[5] Participants were told that they represent a firm which in the production process releases some emissions into the atmosphere (with default emissions equal to $e_j^{\max}$). They were further told that the government wanted to reduce total pollution and that reducing emissions was costly for each polluter. Abating a units of the pollutant would cost the firm $C(a) = 5a^2$.

Furthermore, participants were informed that the government requested them to report their default maximal emissions $e_j^{\max}$ and that, in accordance with all the reports, the government would issue individual emission levels l_j. Moreover, in the case of costly permit allocation (i.e., *costly allocation* and *refunding*), the government would set a permit price σ, and in the case of *refunding*, would refund some of the firm's expenditure for emission permits. In writing the instructions, we avoided persuasive language by, e.g., referring to the concept of "marginal damage," which would be necessary to explain the government's regulation rule. In particular, we explained the different mechanisms in general terms, telling participants that the regulator would determine the number of permits, permit price, and the share of refunding according to a specific rule.[6] To help participants learn about the relationship between their emission reports and the resulting number of permits, permit price, and reimbursement, participants were allowed to use a profit calculator to simulate the consequences of their own and the other firms' decisions.[7] We also provided participants with a table for selected abatement levels and their respective abatement costs.

- Table 1 about here -

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[5] In this connection, Loewenstein (1999) points out that cognitive psychologists assert that every form of problem-solving is context-dependent. Yet in a neutral context, the researcher cannot control for what the participant has in mind when making her decision. In the particular context of emissions-trading experiments, Sturm (2008) does not find that framing affects the outcome, while Cason and Raymond (2011) find lower compliance with regulation under environmental than under neutral framing.

[6] For instance, under *refunding* (and a two-firm industry) participants read that "the regulator will then pay you back approximately between 10% and 15% of your permit expenditure, and correspondingly to the other firm. The payback shares depend both on your and the other firm's reported maximum emissions."

[7] The inputs for the calculator are the reported maximal emissions by each of the firms. The calculator then shows the firm's payoff (and under *refunding* also the payback amount).

In sum, Table 1 shows the parameters and equilibrium predictions in the different treatments. The top rows show the number of firms and the true maximal emissions $e_j^{\max}$. For each allocation mechanism (*free allocation*, *costly allocation*, and *refunding*) the first row displays the theoretical reported emissions in Nash equilibrium (hereafter "Nash reports"). Table 1 indicates that theory predicts considerable over-reporting under *free allocation*, slight under-reporting under *costly allocation*, and truth-telling under *refunding.* The second row presents the resulting assigned emissions by the regulator (experimenter), given Nash reports. The respective 3rd, 4th, and 5th rows show the resulting marginal damage, abatement cost, and total cost in Nash equilibrium (i.e., given Nash reports). It appears that under *free allocation* Nash reports induce zero abatement cost but the highest social cost. Moreover, under *free allocation* the differences between minimal social cost and those resulting in Nash equilibrium get larger with industry size. Under *costly allocation*, Nash reports (and thus total social costs) differ only slightly from the true values. In addition, under *costly allocation* the differences between minimal social cost and those resulting in Nash equilibrium get smaller with industry size.[8] Under *refunding*, social costs are minimized. Table 1 also indicates that in the case of *refunding*, predicted refunded (payback) shares get smaller with industry size. In addition, Table 1 displays the optimal reported maximal emissions under collusion (this option is only applicable for two and three firms). Finally, the bottom rows of the table indicate the number of independent industries per treatment.

4 Hypotheses

In the following we formulate our research hypotheses. As (true) maximal emissions are identical across allocation mechanisms, the question we ask is whether the different mechanisms lead to different reported maximal emissions. In particular, we want to learn whether Montero's *refunding* mechanism yields truth telling, whereas the other mechanisms do not, implying that

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[8] As explained in the introduction, the reason is that the pecuniary externalities imposed by any one bidder becomes very small and untruthful bidding becomes unprofitable. We thank an anonymous reviewer for this clarification.

Montero's refunding mechanism is more efficient than traditional schemes of permit allocation, such as free and (fully) costly allocation.

Our hypotheses are derived from the theoretical predictions shown in Table 1. These predications can be summarized as follows: Denoting the theoretical Nash equilibrium reporting profiles under *free allocation*, *costly allocation*, and *refunding* by $(\hat{e}_1^{FREE}, ..., \hat{e}_n^{FREE})$, $(\hat{e}_1^{COST}, ..., \hat{e}_n^{COST})$, and $(\hat{e}_1^{REF}, ..., \hat{e}_n^{REF})$, we see that

$$\hat{e}_j^{FREE} > e_j^{\max}, \quad \hat{e}_j^{COST} < e_j^{\max}, \quad \hat{e}_j^{REF} = e_j^{\max}.$$

In other words, if firms play Nash, they should over-report their true maximal emissions under *free allocation*, under-report these under *costly allocation* and tell the truth under Montero's *refunding* mechanism.

Our initial set of hypotheses is concerned with the deviations of the reported maximal emissions from their true values:

Hypothesis 1a: Under *free allocation*, firms' reported maximal emissions will be lower than or equal to the true maximal emissions (i.e., H0[1a]: $\tilde{e}_j^{FREE} \leq e_j^{\max}$).

Hypothesis 1b: Under *costly allocation*, firms' reported maximal emissions will be higher than or equal to the true maximal emissions (i.e., H0[1b]: $\tilde{e}_j^{COST} \geq e_j^{\max}$).

These one-sided hypotheses are formulated such that under both *free allocation* and *costly allocation*, we assume that firms report their true maximal emissions against the alternative that they play Nash (leading to a higher and lower reports than the truth under *free allocation* and *costly allocation*, respectively). We do not formulate an equivalent hypothesis for Montero's *refunding* mechanism since in this latter case, the two alternatives converge (i.e., truth telling is the Nash equilibrium).

Moreover, in case of rejecting these hypotheses, it would still be an open question whether reported maximal emissions differ from the Nash-equilibrium predictions (e.g., in the case of *costly allocation*, rejecting the initial hypothesis may also indicate that firms collude). So, for the case where the initial hypotheses are rejected, we formulate the following consequent set of (conditional) hypotheses under the assumption that firms play Nash.

Hypothesis 2a: Under *free allocation*, firms' reported maximal emissions are equal to the Nash equilibrium prediction (i.e., H0[2a]: $\tilde{e}_j^{FREE} = \widehat{e}_j^{FREE}$).

Hypothesis 2b: Under *costly allocation*, firms' reported maximal emissions are equal to the Nash equilibrium prediction (i.e., H0[2b]: $\tilde{e}_j^{COST} = \widehat{e}_j^{COST}$).

Hypothesis 2c: Under *refunding*, firms' reported maximal emissions are equal to the Nash equilibrium prediction (i.e., H0[2c]: $\tilde{e}_j^{REF} = \widehat{e}_j^{REF} = e_j^{\max}$).

In sum, the investigation of the initial hypotheses (1a-1b) would reveal whether the alternative allocation mechanisms leads to deviations of reported maximal emissions from the true maximal emissions (and thus may also disclose possible differences in reported emissions between the mechanisms). The examination of the consequent (conditional) hypotheses (2a-2c) would disclose whether deviations from truth telling (if it occurs) could stem from following equilibrium strategies, or rather from other non-equilibrium strategies such as attempting to collude.[9]

5 Results

In the following we report on the analysis of the experimental data. As an overview, Figure 1 shows the evolution of deviations of the reported maximal emissions from the true maximal emissions for the different allocation mechanisms, number of firms, and assigned maximal emissions.[10] In addition, for the second half of each treatment, i.e., for periods 11 through 20, Table 2

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[9] More precisely, rejecting the null hypotheses would indicate that reported maximal emission do not converge to Nash reports. However, not rejecting these hypotheses would not indicate that reported maximal emissions are equal to Nash reports, but that it merely cannot be excluded that reported maximal emissions are equal to Nash reports. Moreover, if the null hypothesis that reported maximal emissions are equal to Nash reports cannot be rejected, collusion is not excluded yet. In Section 5.1.1 we therefore explicitly test whether reported maximal emissions are equal to the "collusive-reports".

[10] Figures 1 and 2 (below) are especially important as they convey the economic significance of the results.

shows the average reported maximal emissions, the average percent deviations of reported maximal emissions from either the corresponding true maximal emissions or the corresponding Nash reports. Due to the relative complexity of the experiment, decisions in the initial periods may be confounded by confusion, stemming from participants making decisions in an unfamiliar environment (albeit the experiment started with three trial periods). Hence, our analysis centers on decisions after 10 periods of real-play, where participants are supposed to be already well acquainted with the environment.[11]

- Figure 1 about here -

- Table 2 about here -

Figure 1 and the third and fourth rows in Table 2 show that under *free allocation*, participants over-report their maximal emissions. Moreover, this over-reporting increases with the number of firms. Under *costly allocation* participants under-report their maximal emissions. However, in industries with two or three firms it appears that the maximal emissions reported are close to the true maximal emissions. Finally, *refunding* seems to induce reporting of the true maximal emissions independently of the the industry size.

5.1 Reported maximal emissions

In the following we formally test the research hypotheses. We start with our initial (one-sided) hypotheses 1a-1b. To this end we use a one-sample median test, considering the average reported maximal emissions in periods 11-20 in each industry as an independent observation. As we repeat this test for each of 18 treatments (i.e., for each of the *free allocation* and *costly allocation* treatments), we control for the false discovery rate in multiple testing using the Benjamini-Hochberg procedure (Benjamini and Hochberg, 1995).[12] Our findings indicate that under *free allocation* reported maximal emissions are significantly higher than their respective

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[11] Because of the design choice to pay participants for four randomly selected periods, there is no wealth accumulation effect due to previous periods' earnings.

[12] In this regard, see List et al. (2019) for a recent discussion of multiple testing in experimental economics.

true values and under *costly allocation* reported maximal emissions are significantly lower than their respective true values.[13] In sum, our initial results read as follows.

Result 1a: Under *free allocation*, firms' reported maximal emissions are higher than the true maximal emissions.

Result 1b: Under *costly allocation*, firms' reported maximal emissions are lower than the true maximal emissions.

Thus, we can reject our null hypotheses that under both *free allocation* and *costly* allocation firms report their true maximal emissions. In fact, the one-sided tests yield that the reported emissions under *free allocation* and *costly allocation*, respectively, are rather in the direction of the Nash-equilibrium predictions. Given these results, the question is whether reported maximal emissions are different from the Nash-equilibrium predictions. To this end, we now conduct a two-sided median test for each treatment under the null hypothesis that reported maximal emissions do not differ from their respective Nash reports. Using the multiple-testing Benjamini-Hochberg procedure for 27 treatments, we cannot reject for each of the treatments the hypothesis that the reported maximal emissions are equal to the Nash-equilibrium predictions.[14] We can now formulate the next set of (conditional) results.

Result 2a: Under *free allocation*, we cannot reject the hypothesis that firms' reported maximal emissions are equal to the Nash equilibrium prediction.

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[13] The results are significant when setting the false discovery rate at $p = 0.01$ for all treatments (except for *costly allocation* with a maximal emission profile of (18, 26) - but this turns significant when setting the false discovery rate at $p = 0.05$).

[14] The economic significance of the results is shown in Figure C.1 in the Appendix. This figure illustrates the evolution of differences between maximal emissions reported and their corresponding equilibrium predictions. In particular, it appears that under *free allocation* in industries with three firms, average reported maximal emissions are converging to the Nash reports. But unlike in the other treatments, we do not observe full convergence (i.e., average reported maximal emissions do not reach the Nash reports and then keep at a level very close to it). In fact, the original p-values (not adjusted for multiple testing) of the median test for the (18, 22, 26), and (22, 22, 22) treatments are $p = 0.0063$ and $p = 0.0074$, respectively. In fact, under *free allocation* with (22, 22, 22) we can marginally reject the hypothesis even when using the Benjamini-Hochberg procedure (and setting the false discovery rate at $p = 0.10$).

Result 2b: Under *costly allocation*, we cannot reject the hypothesis that firms' reported maximal emissions are equal to the Nash equilibrium prediction

Result 2c: Under *refunding*, we cannot reject the hypothesis that firms' reported maximal emissions are equal to the Nash equilibrium prediction

Results 1a-1b together with 2a-2c establish that reported maximal emissions are different across mechanisms. In particular, while we cannot reject the null hypothesis that under Montero's *refunding* firms report their true maximal emissions, we can reject it for *free allocation* and *costly allocation.* In fact, under the three allocation mechanisms, with the possible exception for *free allocation* with three firms in the industry[15], we cannot reject the hypothesis that firms' behavior in periods 11-20 is well predicted by the Nash equilibrium.

In sum, in industries consisting of one firm, we cannot reject the hypothesis that reported maximal emissions converge quite quickly to their respective Nash equilibrium predictions under the three allocation mechanisms. This result also holds in industries consisting of two and three firms under both *costly allocation* and Montero's *refunding* mechanism. However, under *free allocation* in industries consisting of two firms, we can reject convergence for periods 1-5, but cannot reject it for periods 6-10; and in industries with three firms, we can reject convergence in the first 10 periods, but cannot reject it for periods 11-15.[16] The likely reason for this slow convergence is that, while the Nash level for under-reporting under *costly allocation* is not so far away from the true maximal emissions, under *free allocation* the Nash level for over-reporting maximal emissions is between 2 and 4 times higher than the true maximal emissions.

Finally, the reader may be also interested in the comparison of average maximal emissions reported in the different allocation mechanisms (i.e., *free allocation*, *costly allocation*, and *refunding*). A first look at these values is provided at the top rows of the three panels of Table 2. Formally, we use the Conover-Iman test of multiple comparisons using rank sums (Dinno, 2017)

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[15] For further detail see Footnote 14.

[16] Further details on convergence are provided in Appendix C.1.

to compare between allocation mechanisms per industry size (i.e., separately for industries with one, two, or three firms). We find that for each industry size ($n = 1$, $n = 2$, and $n = 3$) average maximal emissions reported under *free allocation* are higher than under *refunding*, and that average maximal emissions reported under *refunding* are higher than under *costly allocation* (using the multiple-testing Benjamini-Hochberg procedure for the three pairwise comparisons per group size where false discovery rate is set at $p = 0.05$).[17]

5.1.1 The possibility of collusion

An interesting question that arises in the oligopoly markets with few firms is whether they try to collude, extracting a higher payoff than under non-cooperative Nash equilibrium. If firms try collusion under the permit allocation mechanisms studied here, they would solve the following problem.

$$\min_{\{\tilde{e}_i,\cdots,\tilde{e}_n\}} \{\sum_{i=1}^{n} [C_i(l_i) + \sigma \cdot [1 - \beta_i] l_i]\},$$

where σ, l_i and β_i represent the resulting permit price, the firm's number of allocated permits, and the refunding shares (in case of the *refunding* mechanism) chosen by the regulator in response to the reports $\tilde{e}_i$. Note that $\beta_i = 1$ under *free allocation* and $\beta_i = 0$ under *costly allocation*.

The theoretically optimal reported collusive maximal emissions are shown in Table 1. Note that the difference between collusive and Nash reported emissions is highest under *costly allocation*. The reason is that, when firms report lower maximal emissions, the regulator sets a lower emissions price. Thus, by collusion firms can induce an even lower price than under non-cooperative behavior. Also under *refunding* firms have an incentive to collude in reporting lower maximal emissions than their true values and thus push down the price (though less strong than under *costly allocation*, as part of their expenditure on emission permits will be refunded). By contrast, under *free allocation* in Nash-equilibrium firms report maximal emissions sufficiently high such that the regulator responds by allocating a number of permits that

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[17] The null hypothesis for the Conover-Iman test is that the probability of observing a randomly selected value from the first group that is larger than a randomly selected value from the second group equals one half (Dinno, 2017).

lead to zero marginal abatement costs. Thus, firms cannot do better than that by colluding, and the collusive reports are the same as the Nash reports.

Similar to the test of the conditional hypotheses 2a-2c, we now formally test whether the reported maximal emissions in each treatment differ from their respective collusive values. To this end, we use a median test, applying the multiple-testing Benjamini-Hochberg procedure for 12 treatments (since collusion is redundant in industries with one firm and also under *free allocation*). Our results indicate that we can reject the null hypothesis of collusion in all treatments under both, *costly allocation* and *refunding*, mechanisms.[18] Our conclusion is that Montero's *refunding* mechanism yields truth telling, even though collusion would lead to higher payoffs.

5.1.2 The effect of maximal emissions and number of firms

Next, we are interested in whether the percent deviations of reported emissions from true maximal emissions (i.e., [reported emissions - true emissions] / true emissions) depend on the maximal emissions initially assigned to the firms. To this end, we use the Conover-Iman test of multiple comparisons using rank sums (Dinno, 2017) within each allocation method (*free allocation*, *costly allocation*, and *refunding*) and the given number of firms (industries with one, two, or three firms).[19] Our results do not indicate that the maximal emissions profiles of the industries affect deviations from the true maximal emissions.[20]

Finally, we want to establish whether the percent deviations of reported emissions from true maximal emissions depend on the number of firms. For comparability we only include industries where each firm is assigned a maximal emission level of 22. Using the Conover-Iman

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[18] In particular, we can reject the null hypotheses of collusion when setting the false discovery rate at $p = 0.01$.

[19] Due to the small number of independent observations we use a non-parametric test. In particular, we compare between independent industries, e.g. in the $n = 2$ firm case, for each of the three allocation mechanisms we pairwise compare treatments with different true maximal emission profiles (treatments with (18, 22), (18, 26), (22, 22), and (22, 26)). We attain similar results when comparing maximal emission profiles for each industry size, pooling across allocation mechanisms (i.e., for each industry size, we pairwise compare whether percent deviations of reported emissions from true maximal emissions are different for maximal emission profiles under all allocation mechanisms). In line with our analysis, we control for the false discovery rate due to multiple testing using the Benjamini-Hochberg procedure.

[20] In particular, in all comparisons we observe only one significant difference, namely under *free allocation* between maximal emission profiles of (18, 22) and (18, 26). In all pairwise comparisons the false discovery rate is set at $p = 0.05$ (using the multiple-testing Benjamini-Hochberg procedure).

test of multiple comparisons using rank sums, our results indicate that under *free allocation* the percent deviations of reported emissions from true maximal emissions increase in industry size. By contrast, under *costly allocation* the percent deviations of reported emissions from true maximal emissions decrease in industry size.[21] However, under *refunding* no significant pattern emerges.

5.2 Overall efficiency

So far we have focused on the deviations of reported maximal emissions from their true values. Now we want to learn more about the welfare consequences of these deviations from truth-telling. Social costs are the firms' abatement costs plus the damage from emissions. Accordingly, we define the "efficiency ratio" as the ratio of theoretically minimal social cost divided by the cost resulting from observed behavior (reported emissions) in the experiment.

$$ER_n^m = \frac{SC_n(e_i^*)}{SC_n^m(e_i^m)} = \frac{\sum_{i=1}^n C_i(e_i^*) + D\left(\sum_{i=1}^n e_i^*\right)}{\sum_{i=1}^n C_i(e_i^m) + D\left(\sum_{i=1}^n e_i^m\right)} \tag{8}$$

where ER stands for efficiency ratio and SC for social costs consisting of abatement costs plus damage from emission. Further, n denotes the number of firms in the industry and m=$\{FREE$, $COST$, $REF\}$ is the index of the allocation mechanism. In addition, e_i^* is the socially optimal emission level of a firm i, and e_i^m is the emission level resulting from the reported maximal emissions by the firm i under mechanism m. The efficiency ratio takes the value of 1 if firms report their true maximal emission levels (as theoretically predicted by Montero).

It can be shown (see Appendix A.6) that, in equilibrium, the social costs under the three allocation mechanisms rank as follows: The social cost under *refunding* is lower than under *costly allocation* which in its turn is lower than the social cost under *free allocation.* Accordingly, we expect the same ranking for our data, implying the efficiency ratio to be lower than 1 under *free allocation* and *costly allocation* and equal to one under *refunding.*[22] Figure 2 illustrates

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[21] In particular, the effects of industry size under *free allocation* and *costly allocation* is observed even when setting the false discovery rate at $p = 0.01$ (using the multiple-testing Benjamini-Hochberg procedure).

[22] Concerning the social cost in equilibrium, theory predicts that under *free allocation* firms over-report their maximal emissions such that the regulator assigns an amount of permits that induces zero abatement costs.

the evolution of efficiency ratios in the different treatments, while the bottom rows of Table 2 display the efficiency ratios in the different treatments (averaged over periods 11-20).

- Figure 2 about here -

We use the Conover-Iman test of multiple comparisons using rank sums (Dinno, 2017) to compare efficiency ratios averaged over periods 11-20 within the given number of firms (industries with one, two, or three firms and different maximal emission profiles) and the maximal emissions in the industries. We find that for all industry sizes and maximum emission profiles, *free allocation* is significantly less efficient than both *costly allocation* and *refunding.* For industries with one firm, *costly allocation* is less efficient than *refunding.* However, for industries with two and three firms, we observe no systematic differences in efficiency ratios between *costly allocation* and *refunding.*[23]

Finally, we use the the Conover-Iman test to find out whether the number of firms affects efficiency ratios. For comparability we only include industries where each firm is assigned a maximal emission level of 22. We find that under *free allocation* efficiency decreases when comparing one-firm and two-firm industries, but no significant decrease is observed when comparing two-firm and three-firm industries. Under *costly allocation*, efficiency increases in industry size. Under *refunding*, we do not observe any monotone industry size effect on efficiency (as efficiency decreases when comparing one-firm and two-firm industries and increases when comparing two-firm and three-firm industries).[24]

Therefore, what matters is the aggregate maximal emission level in the industry. Hence, social costs are equal for equivalent aggregate maximal emissions. Under *refunding*, firms report their true maximal emissions. Since the different marginal abatement costs result from parallel shifts of the MAC-curves, the firms' abatement costs are equal. Thus, total emissions are also equal for equivalent aggregate maximal emissions. Under *costly allocation*, by contrast, firms under-report and therefore get the wrong amounts of permits allocated by the regulator. These amounts of permits, in general, do not induce equal marginal abatement costs, and hence also the abatement costs differ across firms. The higher the maximal emissions, the higher the abatement costs. Therefore, *costly allocation* does not induce equalization of marginal abatement costs, and therefore is not efficient.

[23] The observed differences between *free allocation* and both *costly allocation* and *refunding* (and when $n = 1$ between *costly allocation* and *refunding*) are attained when setting the false discovery rate at $p = 0.05$ (and also at $p = 0.01$), using the multiple-testing Benjamini-Hochberg procedure. We attain similar results when comparing allocation mechanisms for each industry size, pooling across maximal emissions (i.e., for each industry size, we pairwise compare whether efficiencies are different between the allocation mechanisms under all maximal emission profiles).

[24] These results are attained when setting the false discovery rate at $p = 0.05$ (and also at $p = 0.01$), using

In sum, we find that both Montero's *refunding* mechanism and *costly allocation* yield higher efficiency than *free allocation* in all industry sizes. In industries with one firm efficiency is higher under *refunding* than under *costly allocation*, but in industries with two or more firms, there is virtually no difference in efficiency between *refunding* and *costly allocation.* The intuition for this result is as follows: The refunded shares decrease sharply with the number of firms, provided firms do not collude.[25] For our quadratic cost and damage functions, the optimal refunded share is 50% in the case of one firm. However, optimal and thus predicted refunded shares are between 5% and 20% for the two-firm case, and between 1% and 10% for the three-firm case. Optimal refunded shares with more than three firms quickly converge to zero, hence theory predicts that under *costly allocation* reports converge to the true maximal emissions as the number of firms increases.

6 Concluding Remarks

Our experimental findings on the performance of Montero's seminal truth-telling mechanism indicate that it works extremely well. We also observe that, in line with theoretical predictions, *free allocation* and *costly allocation* induce firms to over-report and under-report their maximal emissions, respectively. But even with only two firms in the industry, *costly allocation* performs as well as Montero's *refunding* mechanism. Whereas in the face of the large over-reporting of maximal emissions in Nash equilibrium, the poor performance of *free allocation* was to be expected, the very minor differences in efficiency between *costly allocation* and *refunding* comes as a surprise. Indeed, it appears that asking firms about their true marginal abatement costs (maximal emissions) and auctioning off the corresponding number of permits is sufficient to assure almost full efficiency. This result holds although under both mechanisms, *costly allocation* and *refunding*, firms could increase their profits by tacitly colluding, i.e. by reporting lower maximal emissions than under Nash reports.

These results provide additional empirical evidence for the advantage of costly allocation

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the multiple-testing Benjamini-Hochberg procedure.

[25] For further detail on the refunded shares, see Appendix A.3.

through auctioning off permits over free allocation mechanisms such as grandfathering (see e.g., Cramton and Kerr, 2002; Goeree et al., 2010; Cason and de Vries, 2018). In fact, our findings emphasize the incentives to over-state maximal emissions under free permits' allocation and to under-state those under costly allocation (through auctioning off permits). Note that for larger industry size we find higher over-reports of true maximal emissions under *free allocation.* Under *costly allocation*, by contrast, under-reports fade out quickly as the number of firms gets larger.

For the initial test of Montero's truth-telling mechanism, we set up a very simple and readily comprehensible experiment. Participants were only asked to report one single parameter, their maximal emissions, while the slope (and hence the elasticity) of the marginal abatement costs was known to the regulator. A next step would be to allow for arbitrary marginal abatement cost functions where participants have to submit a whole abatement cost schedule or various parameters of it. It is thus subject for further research to investigate whether (i) Montero's mechanism works equally well and (ii) the equivalence of Montero's refunding mechanism and a costly allocation of permits still persists in more complex environments, for example when firms are asked to submit a full abatement cost schedule. Still, the simple design employed here provides useful insights into the performance of Montero's mechanism in practice, suggesting that this mechanism is especially powerful for industries with high market concentration. For large, highly competitive markets, notably carbon markets, the much simpler mechanism of allocating permits for the full Pigouvian price performs equally well.

To place our study in context, mechanisms (with and without refunding) as suggested by Kwerel (1977) and Montero (2008), i.e. asking firms to submit their abatement cost schedules and, according to their reports, allocating permits, are particularly useful when some jurisdiction wants to launch emission control of a pollutant or a region, formerly unregulated, and where the abatement costs are still unknown. While Montero's refunding mechanism ignores further trading on secondary markets, those are not ruled out. On the contrary, using the Montero mechanism as a start for new pollution control provides the right price signals for further trading of emission allowances. Moreover, refunding-like mechanisms may also be used to reform existing systems. Asking the firms about their abatement costs in an existing market and adjusting the number of permits accordingly may be helpful when it turns out that permits have been largely over-allocated, as is the case in the EU-ETS (e.g., Ellerman and Buchner, 2008; Laing et al., 2013). As we have seen, refunds get irrelevant in large markets, but help reduce pecuniary externalities exercised by large firms for strategic reasons.

Finally, besides serving as a 'testbed' for Montero's truth-telling mechanism, an experiment like ours can be used to train market participants in complex emission trading schemes such as auctioning with partial refunding. In fact, in 2002 a regional German industrial association in cooperation with a state government (Schleswig-Holstein, Germany) invited firms subject to EU-ETS emissions trading to participate in a simulated emissions market lasting for several months. This "framed field experiment" helped firms overcome biases against emissions trading and find efficient strategies. Hence, the development of experiments to test incentive compatible market designs in the experimental laboratory may also serve to increase welfare, not only by directly testbedding the instruments, thus helping regulators in the choice of instruments, but also by training firms and market participants.

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Table 1: Parameters and equilibrium predictions

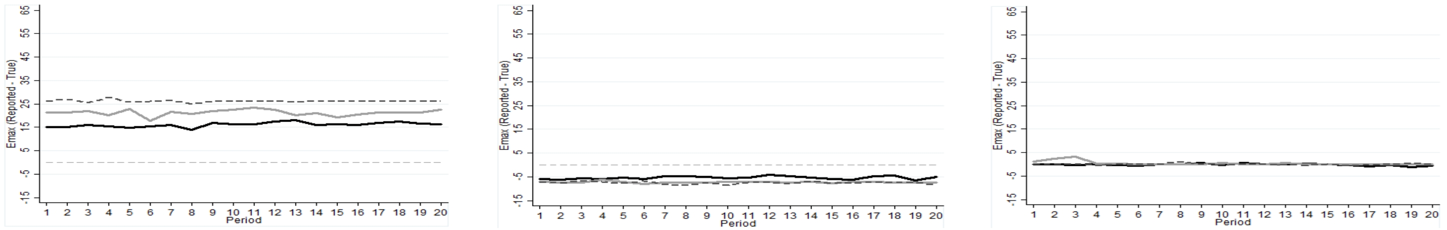
	$n=1$	$n=1$	$n=1$	$n=2$		$n=2$		$n=2$	$n=2$		$n=3$			$n=3$
e_j^{max}	18	22	26	18	22	18	26	22 22	22	26	18	22	26	22 22 22
Free allocation														
Reported Eq. e_j^{max}	36	44	52	58	62	62	70	66	70	74	84	88	92	88
Assigned Eq. Emissions l_j	18	22	26	18	22	18	26	22	22	26	18	22	26	22
Marginal Damage	180	220	260	400	400	540	540	440	480	480	660	660	660	660
Abatement Cost $C(l_j)$	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Social Cost	1620	2420	3380	8000		9680		9680	11520		21780			21780
Reported collusive e_j^{max}	-	-	-	58	62	62	70	66	70	74	84	88	92	88
Observations (i.e., industries)	12	12	12	10		9		14	10		12			15
Costly allocation														
Reported Eq. e_j^{max}	12.0	14.7	17.3	15.8	18.76	16.19	21.52	18.86	19.23	21.9	17.31	20.31	23.31	20.31
Assigned Eq. Emissions l_j	6.0	7.33	8.65	4.38	7.05	3.62	8.95	6.29	5.52	8.19	2.08	5.08	8.08	5.08
Marginal Damage (Price)	60.0	73.33	86.67	114.29	114.29	125.71	125.71	125.71	137.14	137.14	152.31	152.31	152.31	152.31
Abatement Cost $C(l_j)$	720	1075.56	1502.22	927.39	1117.87	1034.06	1453.11	1234.69	1357.32	1585.90	1267.72	1431.95	1606.18	1431.95
Total Social Cost	900	1344.44	1877.78	2698.32		3277.37		3259.59	3883.63		5465.74			5455.74
Reported collusive e_j^{max}	-	-	-	10	14	9.2	17.2	13.2	12.4	16.4	8.6	12.6	16.5	12.6
Observations (i.e., industries)	12	12	12	10		10		15	10		12			15
Refunding														
Reported Eq. e_j^{max}	18	22	26	18	22	18	26	22	22	26	18	22	26	22
Assigned Eq. Emissions l_j	9	11	13	4.67	8.67	3.33	11.33	7.33	6.0	10.0	1.5	5.5	9.5	5.5
Marginal Damage (Price)	90	110	130	133.33	133.33	146.67	146.67	146.67	160	160	165	165	165	165
Abatement Cost $C(l_j)$	405	605	845	888.89	888.89	1075.56	1075.56	1075.56	1280	1280	1361.25	1361.25	1361.25	1361.25
Payback share (β_j)	0.5	0.5	0.5	0.09	0.16	0.06	0.19	0.125	0.09	0.16	0.02	0.06	0.10	0.06
Total Social Cost	810	1210	1690	2666.67		3226.67		3226.67	3840		5445			5445
Reported collusive e_j^{max}	-	-	-	9.3	17.3	6.6	22.6	14.67	12	20	7.2	13.2	19.2	13.2
Observations (i.e., industries)	12	12	12	10		11		13	11		12			17

"e_j^{max}" denotes the maximal emissions assigned to the firm (unknown to the regulator), while "Reported Eq. e_j^{max}" indicates the Nash equilibrium prediction for the reported maximal emissions. The values in the rows below (until "Total Social Cost") are calculated under the assumption that firms report according to the Nash-equilibrium prediction: "Assigned Eq. Emissions l_j" denotes the emission permits assigned by the regulator, "Marginal Damage (Price)" indicates the marginal damage (and price of permits), "Abatement Cost $C(l_j)$" denotes the total abatement cost of the firm. "Total Social Cost" indicates the sum of total abatement costs plus the total pollution damage in a given industry. Note that under *Refunding*, the Nash equilibrium is the true report of the abatement cost, and the "Total Social Cost" is the theoretically minimum total social cost (first-best). "Payback share (β_j)" denotes the share of permit expenditures paid back to the firms under *Refunding*. "Reported collusive e_j^{max}" is the reported maximal emissions if firms collude (this only applicable for industries with at least two firms). Finally, "Observations (i.e., industries)" are the number of independent industries per treatment.

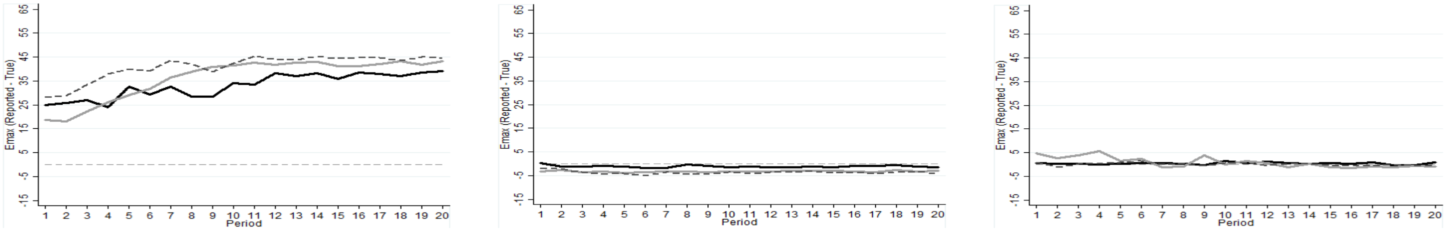
Table 2: Experimental results by treatment (Periods 11-20)

	$n=1$	$n=1$	$n=1$	$n=2$		$n=2$		$n=2$		$n=2$		$n=3$			$n=3$		
e_j^{max}	18	22	26	18	22	18	26	22	22	22	26	18	22	26	22	22	22
Free allocation																	
Reported e^{max} ($\widetilde{e}_j^{max}$)	34.73	43.36	51.99	49.20	57.64	62.35	72.72	65.91		66.55	68.62	71.32	75.20	83.50	78.37		
(std. dev)	(2.67)	(3.01)	(0.03)	(9.11)	(7.62)	(7.09)	(8.66)	(11.57)		(7.42)	(11.31)	(11.23)	(17.13)	(6.88)	(8.06)		
% deviation from true	0.93	0.97	1.00	1.73	1.62	2.46	1.80	2.00		2.03	1.64	2.96	2.42	2.21	2.56		
(significance)	***	***	***	***		***		***		***		***			***		
% deviation from Eq.	-0.04	-0.01	-0.00	-0.15	-0.07	0.01	0.04	-0.00		-0.05	-0.07	-0.15	-0.15	-0.09	-0.11		
(significance)															*		
Efficiency	0.54	0.51	0.50	0.39		0.32		0.34		0.38		0.31			0.30		
(std. dev)	(0.08)	(0.06)	(0.00)	(0.07)		(0.08)		(0.12)		(0.10)		(0.06)			(0.05)		
Costly allocation																	
Reported e^{max} ($\widetilde{e}_j^{max}$)	12.80	14.73	18.49	16.21	18.67	17.46	22.19	18.92		18.94	22.32	16.56	19.89	22.87	20.38		
(std. dev)	(1.90)	(0.22)	(2.55)	(1.42)	(1.15)	(1.51)	(2.00)	(1.64)		(1.26)	(0.84)	(0.74)	(0.71)	(1.67)	(0.70)		
% deviation from true	-0.29	-0.33	-0.29	-0.10	-0.15	-0.03	-0.15	-0.14		-0.14	-0.14	-0.08	-0.10	-0.12	-0.07		
(significance)	***	***	***	***		**		***		***		***			***		
% deviation from Eq.	0.07	0.00	0.07	0.03	-0.00	0.08	0.03	0.00		-0.02	0.02	-0.04	-0.02	-0.02	0.00		
(significance)																	
Efficiency	0.91	0.90	0.91	0.98		0.97		0.97		0.98		0.99			0.99		
(std. dev)	(0.03)	(0.01)	(0.03)	(0.01)		(0.01)		(0.02)		(0.01)		(0.01)			(0.02)		
Refunding																	
Reported e^{max} ($\widetilde{e}_j^{max}$)	17.77	22.07	25.90	17.45	21.27	19.52	25.16	21.48		21.86	26.45	17.63	21.86	25.67	21.48		
(std. dev)	(0.92)	(0.18)	(0.41)	(2.49)	(1.21)	(3.19)	(1.86)	(4.16)		(0.63)	(1.57)	(2.92)	(1.74)	(2.11)	(1.31)		
% deviation from true(=Eq.)	-0.01	0.00	-0.00	-0.03	-0.03	0.08	-0.03	-0.02		-0.01	0.02	-0.02	-0.01	-0.01	-0.02		
(significance)																	
Efficiency	0.99	1.00	1.00	0.98		0.97		0.92		0.99		0.98			0.99		
(std. dev)	(0.02)	(0.00)	(0.00)	(0.02)		(0.03)		(0.12)		(0.01)		(0.02)			(0.02)		

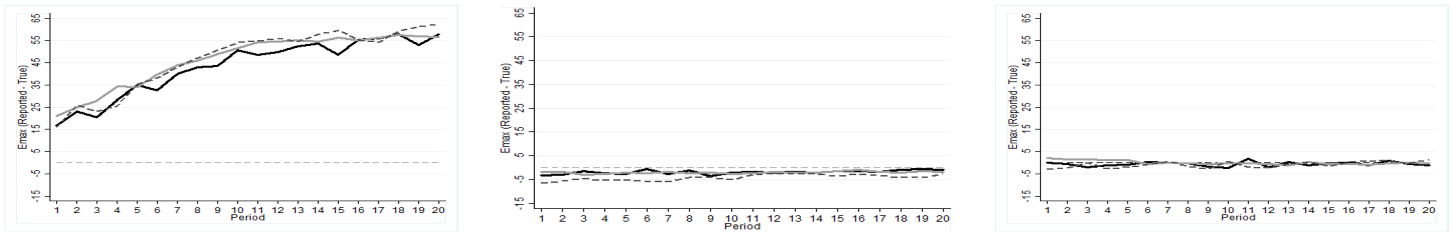
"Reported e^{max} ($\widetilde{e}_j^{max}$)" is the averaged maximal emissions reported by the firms, "% deviation from true" and "% deviation from Eq." denote the average percent deviation of reported maximal emissions from either the true maximal emissions or the Nash equilibrium maximal emissions, respectively (e.g., [reported emissions - true emissions]/true emissions). Further, "(significance)" reports the significance level of a median test if the percent deviations of the reported maximal emissions from either the true maximal emissions or the Nash-equilibrium predictions are different from 0 (*, **, and *** indicate results attained when setting the false discovery rate at $p = 0.10$, $p = 0.05$, and $p = 0.01$, respectively, using the multiple-testing Benjamini-Hochberg procedure). Efficiency is the average ratio of optimal social costs (abatement costs + damage from emissions) to actual social costs.



(a) Free allocation (n=1) (b) Costly allocation (n=1) (c) Refunding (n=1)

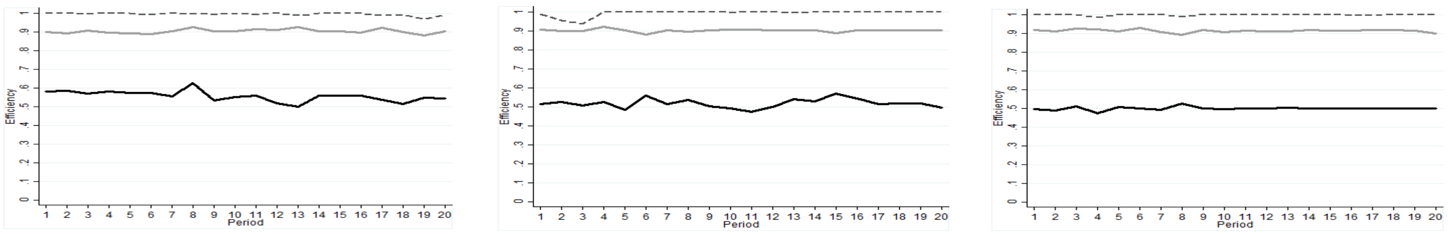


(d) Free allocation (n=2) (e) Costly allocation (n=2) (f) Refunding (n=2)



(g) Free allocation (n=3) (h) Costly allocation (n=3) (i) Refunding (n=3)

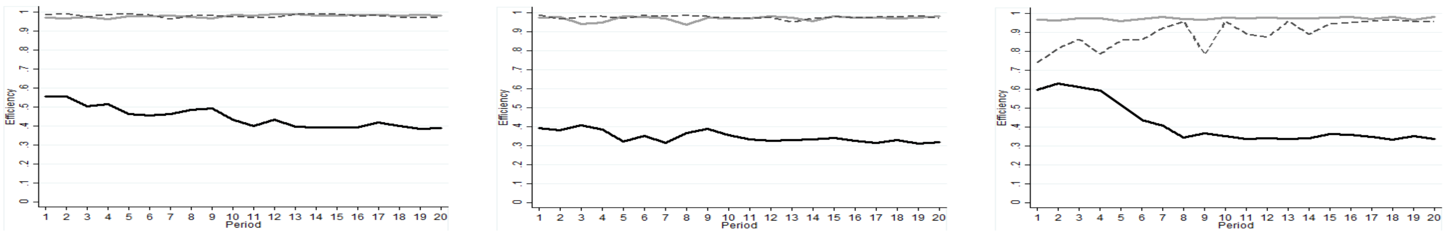
Figure 1: Evolution of deviations of reported maximum emissions from the corresponding true maximal emissions by allocation method, number of firms, and maximal emissions initially assigned (the horizontal dashed line indicates no deviation)



(a) Emax: 18

(b) Emax: 22

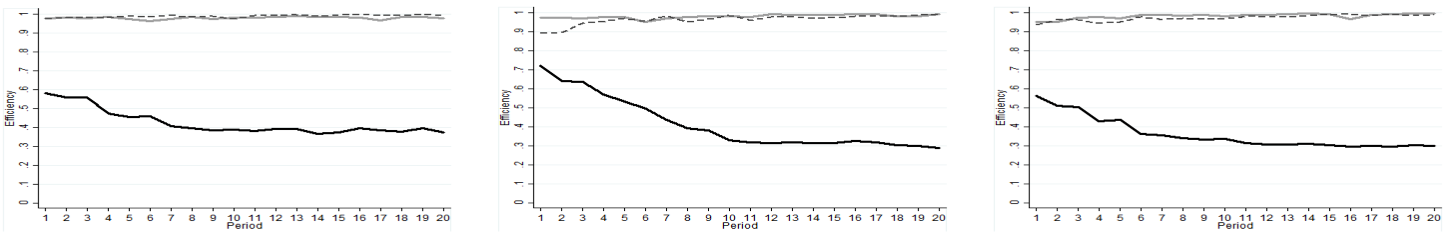
(c) Emax: 26



(d) Emax: (18, 22)

(e) Emax: (18, 26)

(f) Emax: (22, 22)



(g) Emax: (22, 26)

(h) Emax: (18, 22, 26)

(i) Emax: (22, 22, 22)

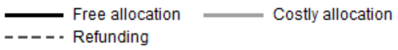


Figure 2: Evolution of efficiencies in the different treatments

Efficiency is defined on the industry level as the ratio of the minimum social cost divide by the actual social cost. Social cost is the sum of the firms' total abatement costs plus the total damage from pollution.

A Appendix

A.1 Sketch of the Montero mechanism with multiple firms

For multiple firms, Montero's mechanism proceeds similarly to the single-firm case. The regulator informs the firms about the auction rules, and then the following steps are taken: Each firm j submits an abatement cost schedule $\tilde{C}_j(e_j)$ from which we can derive the direct demand function for permits $e_k(\sigma)$. For each firm j, the regulator then sums up the collection of submissions from the other firms k except j for all $k \neq j\}$ to obtain the aggregate inverse demand excluding firm j, denoted by $\tilde{C}_{-j}(\tilde{E}_{-j})$ where $\tilde{E}_{-j} = \sum_{k \neq j} e_k$, and aggregate demand function $\tilde{E}_{-j}(\sigma) = \sum_{k \neq j} e_k(\sigma)$. Next we invert the marginal damage function to obtain a virtual supply function for permits, i.e., $S(\sigma) = D'^{-1}(\sigma)$. For each firm j, the regulator uses $\tilde{E}_{-j}(\sigma)$ to compute a residual supply function as

$$S_j(\sigma) = S(\sigma) - \tilde{E}_{-j}(\sigma) \tag{A.1}$$

with residual marginal damage function for firm j given by $D'_j(e_j) = D'(E) - \tilde{C}'_{-j}(E_{-j})$. Then for each firm the regulator clears the auction by determining the number of permits l_j and the personal price σ_j for each bidder according to the rule $-\tilde{C}'_j(l_j) = D'_j(l_j) = \sigma_j$. Firm j spends $\sigma_j \cdot l_j$, obtains l_j pollution permits, and receives back a fraction of its expenditures on permits according to the rule

$$\beta_j(l_j) = 1 - \frac{D_j(l_j)}{D'_j(l_j) \cdot l_j} \tag{A.2}$$

where $D_j(l_j)$ is the integral of the residual marginal damage function $D'_j(\cdot)$ between 0 and l_j. The firm then receives a rebate of $\beta_j(l_j) \cdot \sigma_j \cdot l_j$.

A.2 The optimal allocation and payback functions for linear marginal abatement cost and linear marginal damage

In this part of the appendix we derive the optimal emission quantities and payback functions for the case of linear marginal abatement cost curves of the type

$$-C'(e_j) = a_j - b_j e_j \tag{A.3}$$

and a marginal damage function

$$D'(E) = dE \tag{A.4}$$

To calculate the residual marginal damage curve, we have to invert (A.3) and (A.4). Setting

$$-C'(e_j) = a_j - b_j e_j = \sigma \tag{A.5}$$

and solving for e_j yields

$$e_j(\sigma) = \frac{a_j - \sigma}{b_j} \tag{A.6}$$

In the same way, setting $D'(E) = dE = \sigma$ and solving for E, gives us the aggregate supply curve

$$S(\sigma) = \frac{\sigma}{d} \tag{A.7}$$

Now substituting (A.6) and (A.7) into (A.1) we obtain:

$$e_j = S_j(\sigma) = \frac{\sigma}{d} - \sum_{k=1,k\neq j}^{n} \frac{a_k - \sigma}{b_k} = \left[\frac{1}{d} - \sum_{k=1,k\neq j}^{n} \frac{1}{b_k}\right]\sigma - \sum_{k=1,k\neq j}^{n} \frac{a_k}{b_k} = A_j p - B_j \tag{A.8}$$

with $A_j = \frac{1}{d} - \sum_{k=1,k\neq j}^{n} \frac{1}{b_k}$ and $B_j = \sum_{k=1,k\neq j}^{n} \frac{a_k}{b_k}$. Now we invert (A.8) by solving for σ to obtain the residual marginal damage function as

$$\sigma = D_j'(e_j) = \frac{e_j + B_j}{A_j} \tag{A.9}$$

Integrating this, we obtain

$$D_j(e_j) = \frac{e_j/2 + B_j}{A_j} e_j \tag{A.10}$$

Substituting the emissions with the allocated allowances, i.e., $l_j = e_j$, and substituting the above expressions into (A.2) we obtain

$$\beta_j(l_j) = 1 - \frac{D_j(l_j)}{D'_j(l_j) \cdot l_j} = 1 - \frac{l_j/2 + B_j}{l_j + B_j} = \frac{l_j/2}{l_j + B_j} \tag{A.11}$$

For $n = 1$ it is now easily verified that the optimal emissions are

$$L^* = E^* = \frac{a}{b + d}$$

and the payback is

$$\beta^*(L^*) = \frac{1}{2}$$

For $n = 2$ we obtain

$$\begin{aligned} l_1^* &= \frac{a_1 b_2 + d(a_1 - a_2)}{b_1 b_2 + d(b_1 + b_2)} \\ l_2^* &= \frac{a_2 b_1 + d(a_2 - a_1)}{b_1 b_2 + d(b_1 + b_2)} \end{aligned}$$

and

$$\begin{aligned} \beta_1^*(l_1^*) &= \frac{b_2(a_1 b_2 + d(a_1 - a_2))}{2(a_2 b_1 + a_1 b_2)(b_2 + d)} \\ \beta_2^*(l_2^*) &= \frac{b_1(a_2 b_1 + d(a_2 - a_1))}{2(a_1 b_2 + a_2 b_1)(b_1 + d)} \end{aligned}$$

For $n = 3$ we obtain

$$l_1^* = \frac{a_1 b_2 b_3 + d(a_1(b_2 + b_3) - a_2 b_3 - a_3 b_2)}{b_1 b_2 b_3 + d(b_1 b_2 + b_2 b_3 + b_1 b_3)}$$

analogously for l_2^* and l_3^*. For the payback we obtain

$$\beta_1^*(l_1^*) = \frac{b_2 b_3 (a_1 (b_2 b_3 + d(b_2 + b_3)) - d(a_2 b_3 + a_3 b_2))}{2(a_1 b_2 b_3 + a_2 b_1 b_3 + a_3 b_2 b_3)(b_2 b_3 + d(b_2 + b_3))}$$

Similarly for $\beta_2^*(l_2^*)$ and $\beta_3^*(l_3^*)$.

A.3 Equilibria under the Montero mechanism

In this and the following sections, we derive the equilibria for the parameters in our treatment, i.e., we choose $b_i = 10$, $d = 10$, while a_i varies. We work out the case for $n = 2$. The cases $n = 1$ and $n = 3$ are similar. The socially optimal emissions for those parameters are given by

$$e_i^* = \frac{2a_i - a_j}{30}, \qquad i, j = 1, 2; j \neq i$$

Since truth-telling is a dominant strategy in Montero's mechanism, reported equilibrium emissions are given by

$$\hat{e}_i = e_i^{\max} = a_i/10, \qquad i, = 1, 2$$

and the resulting optimal (minimal) social costs are

$$SC^{REF} = \frac{(a_1 + a_2)^2}{60} \tag{A.12}$$

The paybacks are given by

$$\beta_i^* = \frac{2a_i - a_j}{4(a_i + a_j)}$$

For our parameters we obtain the following payback shares:

	β_1^*	β_2^*	β_3^*
$a_1 = 180$, $a_2 = 220$	0.09	0.16	–
$a_1 = 180$, $a_2 = 260$	0.06	0.19	–
$a_1 = 220$, $a_2 = 220$	0.125	0.125	–
$a_1 = 220$, $a_2 = 260$	0.09	0.16	–
$a_1 = 180$, $a_2 = 220$, $a_2 = 260$	0.015	0.056	0.096
$a_1 = 220$, $a_2 = 220$, $a_2 = 220$	0.056	0.056	0.056

We see that asymmetries between firms in an industry induces an even stronger asymmetry in the paybacks. On the other hand, the payback shares go quickly to zero as the number of firms grows.

A.4 Equilibria under free allocation

Under free allocation, again let $\hat{e}_i^{\max}$ denote the reported maximal emissions. The corresponding intercept of the (reported) marginal abatement cost function would then be $\hat{a}_i = 10\hat{e}_i^{\max}$. Since the regulator treats the reported $\hat{a}_i$ as if they were the true parameters and allocates emissions l_i according to the rule

$$-\hat{C}'(l_i) \equiv \hat{a}_i - 10l_i = 10(l_1 + l_2) \equiv D'(l_1 + l_2),$$

setting $\hat{a}_i = 10\hat{e}_i^{\max}$ and solving this equation system for $i = 1, 2$ yields

$$l_i = \frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}, \qquad i = 1, 2, \quad j \neq i \tag{A.13}$$

Substituting this expression into the firm's (participant's) payoff function yields

$$\Pi_i(\hat{e}_i^{\max}, \hat{e}_j^{\max}) = \Pi_i^0 - C_i\left(\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right) = \Pi_i^0 - \frac{1}{20}\left(A_i - 10\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right)^2$$

In Nash equilibrium, player i takes the action of player j as given and maximizes his/her payoff with respect to $\hat{a}_i$. The first-order condition is then given by

$$3a_i = 20\hat{e}_i^{\max} - 10\hat{e}_j^{\max} \qquad i = 1,2, \quad j \neq i$$

Solving this equation system yields

$$\hat{e}_i^{\max} = \frac{2a_i + a_j}{10} \qquad i = 1,2, \quad j \neq i$$

and thus the implied intercepts are given by

$$\hat{a}_i = 2a_i + a_j \qquad i = 1,2, \quad j \neq i$$

The resulting assigned emissions $\hat{e}_i$ are determined according to the following rule:

$$\hat{a}_i - 10\hat{e}_i = 2a_i + a_j - 10\hat{e}_i = 10(\hat{e}_i + \hat{e}_j) \qquad i = 1,2, \quad j \neq i$$

Solving this system yields $\hat{e}_i = a_i/10 = e_i^{\max}$. So there is zero abatement. The resulting social cost is then given by

$$SC^{FREE} = SC(\hat{e}_1, \hat{e}_2) = D(e_1^{\max} + e_2^{\max}) = 5(e_1^{\max} + e_2^{\max})^2 = 5(a_1/10 + a_2/10)^2 \qquad \text{(A.14)}$$

For example, for $a_1 = 180$, $a_2 = 220$ we obtain $\hat{e}_1^{\max} = 58$, $\hat{e}_2^{\max} = 62$. All other values in Table 1 are calculated in a similar fashion. This also applies to $n = 1$ and $n = 3$.

For $n = 3$ we obtain

$$l_i = \frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}, \qquad i = 1,2, \quad j,k \neq i \qquad \text{(A.15)}$$

For the Nash equilibrium of reported $\hat{e}_i^{\max}$ we obtain

$$\hat{e}_i^{\max} = \frac{2a_i + a_j + a_k}{10}, \qquad i = 1,2,3 \quad j,k \neq i$$

A.5 Equilibria under costly allocation

Again we work out the case for $n = 2$ only. The cases for $n = 1$ and $n = 3$ can be calculated in the same way. The regulator again takes the firms' reports $\hat{e}_i^{\max}$ as if they were the true reports and sets the allowed emissions according to (A.13). Given this reaction and observing that $\sigma = D'(l_1 + l_2) = 10(l_1 + l_2) = 10\left(\frac{2\hat{e}_1^{\max} - \hat{e}_2^{\max}}{3} + \frac{2\hat{e}_2^{\max} - \hat{e}_1^{\max}}{3}\right) = 10(\hat{e}_1^{\max} + \hat{e}_2^{\max})/3$, the firms' payoff function becomes

$$\begin{aligned}
\Pi_i(\hat{e}_1^{\max}, \hat{e}_2^{\max}) &= \Pi_i^0 - C_i(l_i) - \sigma l_i \\
&= \Pi_i^0 - \frac{1}{20}\left(a_i - 10\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right)^2 - 10\frac{(\hat{e}_1^{\max} + \hat{e}_2^{\max})}{3}\left(\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right)
\end{aligned}$$

Again, in Nash equilibrium player i takes the action of player j as given and maximizes his payoff with respect to $\hat{a}_1$. The first-order condition is then given by

$$\begin{aligned}
\frac{2}{3}\left(a_1 - 10\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right) - \frac{10}{3}\left(\frac{2\hat{e}_i^{\max} - \hat{e}_j^{\max}}{3}\right) - \frac{20}{3}\frac{(\hat{e}_i^{\max} + \hat{e}_j^{\max})}{3} &= 0 \qquad \Leftrightarrow \\
6a_1 - 80\hat{e}_i^{\max} + 10\hat{e}_j^{\max} &= 0 \qquad i = 1, 2, \quad j \neq i
\end{aligned}$$

Solving for $\hat{e}_i^{\max}$, $\hat{e}_j^{\max}$ yields

$$\hat{e}_i^{\max} = \frac{(8a_i + a_j)}{105}$$

For example, for $a_1 = 180$, $a_2 = 220$ we obtain $\hat{e}_1^{\max} = 15.8$, and $\hat{e}_2^{\max} = 18.5$ or $\hat{a}_1 = 158$ and $\hat{a}_2 = 185$. The assigned emissions are then given by

$$\hat{e}_i = \frac{(5a_i - 2a_j)}{105}$$

and the resulting social costs are then given by

$$SC^{COST} = \frac{173a_1^2 + 248a_1a_2 + 173a_2^2}{8820} \tag{A.16}$$

All other values in Table 1 are calculated in a similar fashion. This also applies to $n = 1$ and

$n = 3$. For $n = 3$ we have

$$\begin{aligned}
\Pi_i(\hat{e}_1^{\max}, \hat{e}_2^{\max}, \hat{e}_3^{\max}) &= \Pi_i^0 - C_i\left(l_i\right) - \sigma l_i \\
&= \Pi_i^0 - \frac{1}{20}\left(a_i - 10\frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}\right)^2 \\
&\quad -10\frac{(\hat{e}_1^{\max} + \hat{e}_2^{\max} + \hat{e}_3^{\max})}{4}\left(\frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}\right)
\end{aligned}$$

The first-order condition with respect to $\hat{e}_i^{\max}$ is

$$\frac{3}{4}\left(a_i - 10\frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}\right) - \frac{30}{4}\frac{(\hat{e}_1^{\max} + \hat{e}_2^{\max} + \hat{e}_3^{\max})}{4} - \frac{10}{4}\left(\frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}\right) = 0$$

Solving for $\hat{e}_i^{\max}$ yields

$$\hat{e}_i^{\max} = \frac{3}{52}(14a_i + a_j + a_k)$$

The resulting assigned emissions are given by

$$\hat{e}_i = \frac{3}{52}(14a_i + a_j + a_k)$$

The resulting symmetric equilibrium for $a_1 = 220$ is then given by $\hat{e}_i^{\max} = 20.3077$ or $\hat{a}_i = 203.077$.

A.6 Ranking of social costs

Comparing (A.14), (A.16), and (A.12) we obtain

$$\begin{aligned}
SC^{FREE} - SC^{COST} &= \frac{134a_1^2 + 134a_2^2 + 317a_1a_2}{4410} > 0 \\
SC^{COST} - SC^{REF} &= \frac{13a_1^2 + 13a_2^2 - 23a_1a_2}{4410} > \frac{13a_1^2 + 13a_2^2 - 26a_1a_2}{4410} = \frac{13(a_1 - a_2)^2}{4410} > 0
\end{aligned}$$

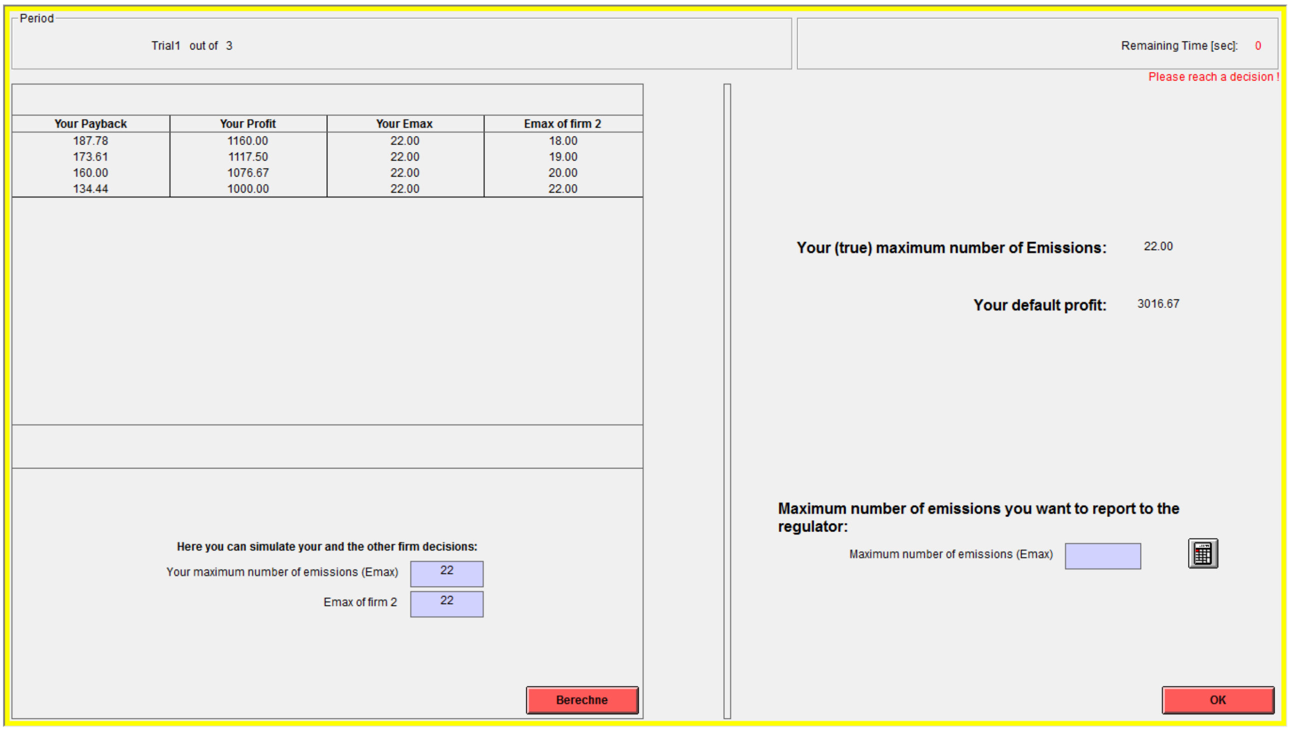
Thus we have

$$SC^{FREE} > SC^{COST} > SC^{REF} \tag{A.17}$$

Note that SC^{REF} is equal to the minimum (optimal) social costs.

For $n = 1$ and $n = 3$ the results are equivalent.

B Decision Screen



Trial1 out of 3

Remaining Time [sec]: 0

Please reach a decision !

Your Payback	Your Profit	Your Emax	Emax of firm 2
187.78	1160.00	22.00	18.00
173.61	1117.50	22.00	19.00
160.00	1076.67	22.00	20.00
134.44	1000.00	22.00	22.00

Here you can simulate your and the other firm decisions:

Your maximum number of emissions (Emax) 22

Emax of firm 2 22

Your (true) maximum number of Emissions: 22.00

Your default profit: 3016.67

Maximum number of emissions you want to report to the regulator:

Maximum number of emissions (Emax)

Figure B.1: Example of a decision computer screen

This is an example of the computer screen in the *refunding* (22, 22) treatment. The screen is divided into two halves. On the left-hand side there is a profit calculator where the participant can simulate the consequences of his/her own reported maximal emissions and the assumed reported maximal emissions of the other firms. On the right-hand side, the assigned maximal emission level is shown, and the participant is asked to report her maximal emission level.

C Further Analysis, Tables, and Figures

C.1 Convergence to equilibrium

Given Results 2a-2c, it is of interest to learn if possible convergence to the Nash reports occurs early in the experiment or rather later. More precisely, we are interested in whether we could reject the hypothesis that reported maximal emissions are equal to the Nash reports early in the experiment.[i] Therefore, we repeat the median tests used to test hypotheses 2a-2c (using the multiple-testing Benjamini-Hochberg procedure for 27 treatments), but now for earlier periods. We start with average reported maximal emissions over periods 1-5: For size of $n = 1$, in all treatments (i.e., under the three allocation mechanisms and the three initially assigned maximal emissions - a total of 9 treatments) we cannot reject the null hypothesis that reported maximal emissions are equal to the Nash reports. For size of $n = 2$, and periods 1-5, we cannot reject that reported maximal emissions are equal to the Nash reports in each of the *costly allocation* and *refunding* treatments. However, the reported maximal emissions differ from their respective Nash reports in 3 out of 4 *free allocation* treatments.[ii] Yet, already in periods 6-10, we cannot reject that the reported maximal emissions do not significantly differ from the Nash reports. Finally, for $n = 3$, in periods 1-5 we cannot reject that firms play equilibrium in the *costly allocation* and *refunding* treatments. However, we can reject that firms play Nash-equilibrium for the two *free allocation* treatments in periods 1-5 and also 6-10.[iii] Finally, in periods 11-15, we cannot reject that reported maximal emissions are equal to Nash reports in any treatment under any allocation mechanism.[iv]

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[i] We rejected that reported maximal emissions are different from either the true or the collusive reports. Notebly, not rejecting the hypothesis that reported maximal emissions are equal to the Nash reports does not indicate that the latter are equal to each other. Yet, this would indicate that we cannot rule out convergence to Nash reports.

[ii] This is observed when setting the false discovery rate at $p = 0.05$ (but not at $p = 0.01$).

[iii] This is observed even when setting the false discovery rate at $p = 0.01$. The only other (marginally significant) difference from Nash reports in periods 6-10 ($n = 3$) occurs in one *costly allocation* treatment (when setting the false discovery rate at $p = 0.10$).

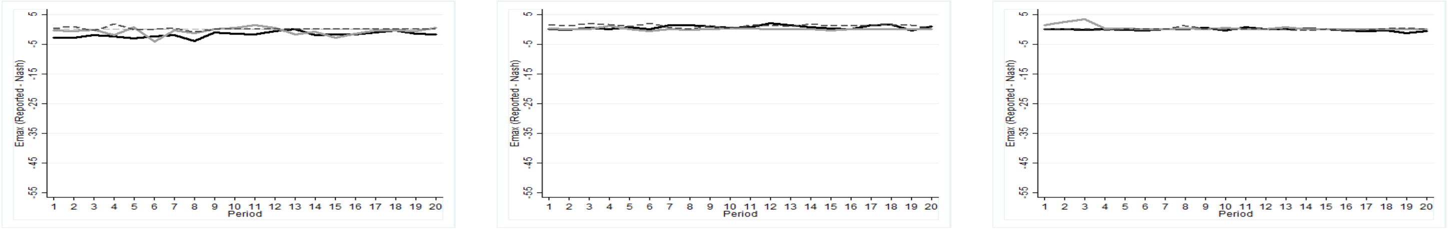
[iv] More precisely, under *free allocation* and industry of (22, 22, 22) we can marginally reject convergence when setting the false discovery rate at $p = 0.10$ (but not at $p = 0.05$).

C.2 Further tables and figures

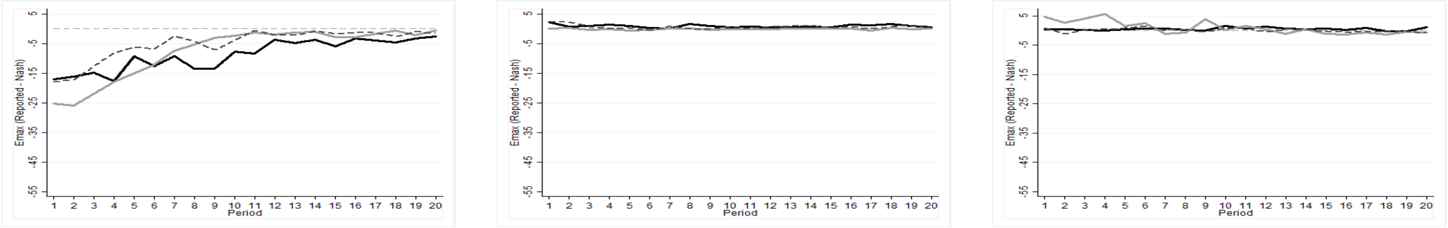
Table C.1: Random effect estimations

	Percent deviations from true Emax			Percent deviations from Eq.		
	Size $n = 1$	Size $n = 2$	Size $n = 3$	Size $n = 1$	Size $n = 2$	Size $n = 3$
Free allocation	0.95***	1.65***	2.12***	-0.03**	-0.14***	-0.22***
	(0.02)	(0.07)	(0.07)	(0.01)	(0.03)	(0.02)
Costly allocation	-0.31***	-0.15***	-0.09***	0.04**	-0.01	-0.02
	(0.01)	(0.03)	(0.01)	(0.02)	(0.03)	(0.01)
Emax dummies	Yes	Yes	Yes	Yes	Yes	Yes
Period dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.01	0.10**	0.20***	-0.00	0.05	0.06***
	(0.01)	(0.05)	(0.04)	(0.01)	(0.03)	(0.01)
Observations	2160	5320	4980	2160	5320	4980

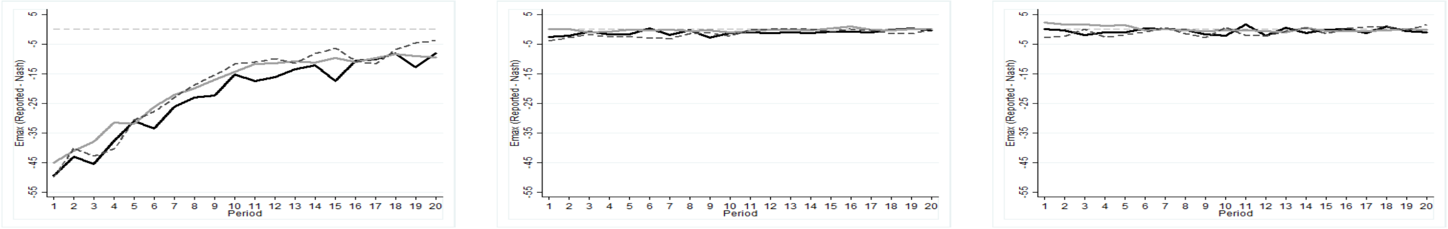
"Emax dummies" denote the technology profiles (e.g., (18), (18, 26), (18, 22, 26)). In addition, *, **, and *** indicate significance at the 10%, 5%, ad 1% levels.



(a) Free allocation (n=1) (b) Costly allocation (n=1) (c) Refunding (n=1)



(d) Free allocation (n=2) (e) Costly allocation (n=2) (f) Refunding (n=2)



(g) Free allocation (n=3) (h) Costly allocation (n=3) (i) Refunding (n=3)

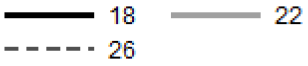


Figure C.1: Evolution of deviations of reported maximal emissions from the corresponding *Nash-equilibrium prediction*, by allocation method, number of firms, and initially assigned maximal emissions (the horizontal dashed line indicates no deviation)