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# Tell the Truth or Not? The Montero Mechanism for Emissions Control at Work

by Till Requate, Eva Camacho-Cuena, Kean Siang Ch'ng  
and Israel Waichman



# Tell the Truth or Not? The Montero Mechanism for Emissions Control at Work

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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, grandfathering and pure auctioning. We conducted 27 treatments with a total of 623 participants, controlling for the allocation mechanism, the number of firms, and the true maximal emission levels. We find that, in line with the theoretical predictions, firms over-report their maximal emissions under grandfathering and under-report them under pure auctioning, while under Montero's mechanism firms almost always report their maximal emissions truthfully. However, in terms of efficiency, the difference between Montero's mechanism and pure auctioning disappears when there is more than one firm in the market.

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

**Keywords:** mechanism design; environmental policy; permit trading; auctions; experiment

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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 marginal abatement costs 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 the issuance of 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 either use incentive payments financed by lump-sum taxes or make a surplus that is redistributed to the public in a lump-sum way. If, by contrast, the regulator is constrained by a balanced budget for the total incentive payments, only second-best outcomes can be induced (except in 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 or firms collude. 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 auctioned off to the firms at *a priori* individual prices. In equilibrium with truth-telling, these 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 the total auction revenues. 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 (naïve) mechanisms, where the regulator asks the firms to submit their (marginal) abatement cost schedules and then either auctions off permits or issues permits for free. 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. The three mechanisms that we are testing are: (i) issuing free permits proportionally to the maximal emissions reported (“grandfathering”), (ii) auctioning off emission permits (“pure auctioning”), and (iii) the (theoretically) incentive-compatible Montero mechanism. We conducted treatments with markets 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 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 pure auctioning.

While emission permit markets for major pollutants such as  $SO_2$  and  $CO_2$  are typically very large, examples with small numbers of firms to be regulated 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 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.

Our findings are as follows: We find that Montero's refunding mechanism works almost perfectly in all market sizes and with all initially assigned maximal emission levels. Firms learn fast, and their decisions quickly converge to the socially optimal equilibrium. Under grandfathering, firms over-report their actual (true) emissions, which is fully in line with theoretical predictions. Grandfathering is also the least efficient allocation mechanism in terms of overall abatement and damage costs. Under pure auctioning, again as predicted, firms under-report their true emissions. Yet in markets consisting of two or three firms, reported maximal emissions are close to the true values, and efficiency in these pure auctioning markets is almost perfect and no different from what it is under Montero's refunding mechanism. Thus, all in all, asking firms for their true maximal emissions and then auctioning off permits is as good as the fully incentive-compatible refunding mechanism in markets 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 leads to virtually first-best results.

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).

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 equations 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 discuss the general case in Appendix A. 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 marginal 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  $\sigma$ . The firm pays the regulator an amount  $\sigma L$  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 the auction revenues  $\beta(L)$  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

$$TC = C(L) + [1 - \beta(L)]\sigma L \quad (1)$$

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

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

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  $\sigma$  by  $D'(\tilde{L})$ , the firm's objective function will be given by

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

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

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

the solution of which is denoted by  $\tilde{L}$ . Given this, the firm will announce a marginal 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

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

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:

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

Plugging this 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:

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

By the weak convexity of the damage function, for any  $L$ , the pay-back 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 is simply  $C(L) + D(L)$ , 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 a marginal 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 auction revenues.

For multiple firms the mechanism works in a similar way. In this case, the regulator sets up a residual damage function for each firm representing the additional marginal damage caused by some firm  $i$ . Then the mechanism works as in the one-firm case. This implies that *a priori*, emission permit prices may differ across firms, but *ex post* they will be equal in equilibrium (for details, see Appendix A.1).

The most important theoretical result from Montero (2008) is that under the refunding mechanism, submitting the true marginal abatement cost function is always a *dominant strategy*. 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. Otherwise the mechanism would not work (see Herriges et al., 1994; Holmstrom, 1982).

### 3 Experimental Design and Procedure

This study sets out to test the Montero mechanism and to compare its performance with two well-known alternative naïve allocation mechanisms. In all these mechanisms, the regulator first asks the firms to report their abatement cost schedules and then either (i) allocates permits for free (“grandfathering”), (ii) auctions off permits but without refunding auction revenues (“pure auctioning”), or (iii) auctions off permits with optimal refunding according to Montero’s mechanism (“refunding”).

As the concept of submitting a whole function may be difficult to understand for participants 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 Appendix A.2 we show how to derive the residual demand and marginal damage functions that we have used in this study.

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.<sup>1</sup> Participants were told that they represented 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  $l_j$ . Furthermore, in the case of costly permit allocation (pure auctioning and refunding), the government would set individual prices  $\sigma_j$ , and in the case of refunding, would refund some of the auction revenues to the firms. 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 allocated (or auctioned) permits, permit price, and the share of refunding according to a specific rule.<sup>2</sup> 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

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<sup>1</sup>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.

<sup>2</sup>For instance, under *refunding* (and a two-firm market) 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.”

the other firms' decisions.<sup>3</sup> We also provided participants with a table for selected abatement levels and their respective abatement costs.

Formally, the firms' costs in the three different allocation mechanism, *grandfathering* (GRA), *pure auctioning* (AUC), and *refunding* (REF) are as follows:

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

where  $l_j$ ,  $\sigma_j$ , and  $\beta_j$  are individual emission permits, permit prices, and shares of refunding from the auction revenues, respectively. Note that these parameters are functions of the reported emissions profile denoted by  $(\tilde{e}_1^{\max}, \dots, \tilde{e}_n^{\max})$ .

To sum up, Table 1 shows the parameters and equilibrium predictions in the different treatments. In particular, it displays the maximal emissions initially assigned ( $e_i^{\max}$ ), the theoretical equilibrium prediction of the reported maximal emissions ( $\hat{e}_i^{\max}$ ), the associated emission permits assigned, permit price, abatement costs, and refunds.

- Table 1 about here -

## 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.<sup>4</sup> The experiment consists of 27 treatments varying the allocation mechanism (grandfathering, pure auctioning, and refunding), the number of firms (1, 2, or 3 firms), and the

<sup>3</sup>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).

<sup>4</sup>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

maximal emissions assigned to individual firms ( $e_i^{\max} = 18, 22$ , or  $26$  - mimicking both symmetric and asymmetric markets).

We conducted 9 treatments with markets consisting of one firm (with firms assigned maximal emissions of  $e_i^{\max} = 18, 22$ , and  $26$  for each of the three allocation mechanisms). Further, we conducted 12 treatments with markets consisting of two firms (with firms assigned maximal emissions of  $18 \& 22, 18 \& 26, 22 \& 22$ , and  $22 \& 26$  for each of the three allocation mechanisms). Finally, we conducted 6 treatments with markets consisting of three firms, with symmetric ( $e_1^{\max} = e_2^{\max} = e_3^{\max} = 22$ ) and asymmetric maximal emissions ( $e_1^{\max} = 18, e_2^{\max} = 22, e_3^{\max} = 26$ ) for each of the three allocation mechanisms.

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 a market. 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. 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 (see screen shot in Figure B.1 in the Appendix). Finally, after all 20 payoff-relevant periods were over, four periods were randomly selected by the computer to determine the participant's final payoff.

Table 1 provides an overview of the different treatments and displays the number of observations, i.e. the independent markets, per treatment. For each allocation mechanism (*grandfathering*, *pure auctioning*, *refunding*), the top row shows the true maximal emissions  $e_i^{\max}$ . The second row displays the theoretical reported emission in Nash equilibrium (hereafter "Nash reports"). The table indicates that theory predicts considerable over-reporting under *grandfa-*

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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.

thering, slight under-reporting under *pure auctioning*, and truth-telling under *refunding*. The third row presents the resulting assigned emissions by the regulator (experimenter), given Nash reports. The respective 4th, 5th, and 6th rows show the resulting marginal damage, abatement cost, and total cost in Nash equilibrium (given Nash reports). It appears that under *grandfathering* Nash reports induce zero abatement cost but the highest social cost. Under *pure auctioning* Nash reports (and thus total social costs) differ only slightly from the true (optimal) values. The differences between minimal social cost and those resulting in Nash equilibrium get smaller with group size. Under *refunding*, social costs are minimized. Finally, Table 1 also indicates that predicted refunded (payback) shares get smaller with group size.

## 4 Hypotheses

In the following we formulate our research hypotheses. The theoretical predictions shown in Table 1 indicate that if we denote the theoretical Nash equilibrium under *grandfathering*, *pure auctioning*, and *refunding* by  $(\hat{e}_1^{GRA}, \dots, \hat{e}_n^{GRA})$ ,  $(\hat{e}_1^{AUC}, \dots, \hat{e}_n^{AUC})$ , and  $(\hat{e}_1^{REF}, \dots, \hat{e}_n^{REF})$ , we see that  $\hat{e}_j^{GRA} > e_j^{\max}$ ,  $\hat{e}_j^{AUC} < e_j^{\max}$ , and  $\hat{e}_j^{REF} = e_j^{\max}$ . In other words, under *grandfathering* and *pure auctioning* we expect firms to over-report and under-report their true maximal emissions, respectively. Under Montero's *refunding* mechanism, we expect firms to report their true maximal emission levels.

Hence we state our hypotheses as follows:

**Hypothesis 1:** Under *grandfathering*, firms will choose the reported maximal emissions according to the Nash equilibrium, i.e.  $\tilde{e}_j^{\max} = \hat{e}_j^{GRA}$ . Consequently, firms will significantly inflate their maximal emissions, formally  $\tilde{e}_j^{\max} > e_j^{\max}$ . The difference between reported and true emissions increases with the number of firms.

**Hypothesis 2:** Under *pure auctioning* of permits, firms will choose the reported maximal emissions according to the Nash equilibrium, i.e.  $\tilde{e}_j^{\max} = \hat{e}_j^{AUC}$ . Hence, firms will significantly under-report their maximal emissions, formally  $\tilde{e}_j^{\max} < e_j^{\max}$ . The difference between reported and true emissions decreases with the number of firms.

**Hypothesis 3:** Under Montero’s *refunding* mechanism, independently of the number of firms, the assigned maximal emissions  $e_j^{\max}$ , and the degree of asymmetry, firms will choose the reported maximal emissions according to the Nash equilibrium (i.e. firms will report their true maximal emissions), i.e.  $\tilde{e}_j^{\max} = \hat{e}_j^{REF} = e_j^{\max}$ .

Since in theory Montero’s mechanism will work for all arbitrary marginal abatement cost functions and for both symmetric and asymmetric firms, our conjecture is as follows:

**Hypothesis 4:** In each treatment, the differences between the reported maximal emissions and the theoretical equilibrium reports are independent of both the maximal emissions  $e_j^{\max}$  initially assigned and the degree of asymmetry.

## 5 Results

As an overview, Table 2 shows for each treatment in the second half of the experiment, i.e. for periods 11 through 20, the average reported maximal emissions, the average rate of deviation between the reported maximal emissions and (i) the corresponding true maximal emissions and (ii) the corresponding theoretical Nash equilibrium. In addition, Figure 1 show the evolution of the differences between the reported and the true maximal emissions for the different allocation mechanisms, numbers of firms, and assigned maximal emissions.<sup>5</sup>

Table 2 about here.

Figure 1 about here.

Table 2 and Figure 1 show that under *grandfathering*, participants over-report their maximal emissions. Moreover, this over-reporting seems to increase with the number of firms. Under *pure auctioning* and markets with one firm, participants under-report their maximal emissions. However, in markets with two or three firms it appears that reports are close to the true

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<sup>5</sup>Figures 1 and 2 (below) are especially important as they convey the economic significance of the results. This is important in the light of possible false rejections in multiple hypothesis testing (see List et al., 2016).



maximal emissions. Hence, increasing competition in the permit market reduces the firms' under-reporting of emissions. Finally, *refunding* seems to induce reporting of the true maximal emissions.

## 5.1 Reported maximal emissions

Let us now turn to testing the research hypotheses. For the following statistical tests, we compare indicators of independent markets (markets consisting of one, two, or three firms) averaged over the final 10 periods. Table 2 shows the results of a median test (one sample signed rank test) indicating whether the maximal emissions reported are systematically below or above (i) their true maximal emissions and (ii) their respective Nash-equilibrium preconditions (note that under both *grandfathering* and *pure auctioning* the Nash equilibrium reported maximal emissions are different from the true maximal emissions).<sup>6</sup> Under *grandfathering* we find that the reported maximal emissions are initially lower than the respective Nash-equilibrium predictions (Nash reports), but over time they converge to the equilibrium values. More precisely, for markets consisting of one or two firms we find that reported emissions in periods 11-20 are no different from their respective Nash-equilibrium predictions. But for markets with three firms, the values in period 20 are still lower than the equilibrium reports. Under *pure auctioning*, the maximal emissions reported correspond quite closely to their respective Nash-equilibrium predictions.

Next we employ a median test to learn whether the reported maximal emissions are systematically above or below the true maximal emissions. Under *grandfathering*, firms always over-report their true maximal emissions (differences between reported and true emissions are significantly different from zero at  $p < 0.01$  for all assigned maximal emissions in all treatments). By contrast, under *pure auctioning* firms under-report their true maximal emissions (differences between reported and true maximal emissions are significantly different from zero at  $p < 0.01$  for all maximal emissions in all treatments). Under *refunding*, we find that by

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<sup>6</sup>Figure B.2 in the Appendix illustrates the evolution of differences between maximal emissions reported and their corresponding equilibrium predictions.

and large the maximal emissions reported are not statistically different from their true values (equivalent to the Nash-equilibrium predictions).

Note that, in line with our theoretical predictions, under *pure auctioning* participants quickly reach the Nash equilibrium. Under *grandfathering*, again in line with theoretical predictions, participants largely over-report their true maximal emissions, but converge more slowly to the (inefficient) equilibrium. The likely reason for this slow convergence is that, while the optimal level for under-reporting under *pure auctioning* is not so far away from the true maximal emissions, under *grandfathering* the optimal level for over-reporting maximal emissions is between 2 and 4 times higher than the true maximal emissions.

We further use the Wilcoxon Rank Sum test to pairwise compare the absolute values of deviation rates between reported and true maximal emissions for each pair of treatments.<sup>7</sup> We find that for all group sizes, *grandfathering* always deviates further from the true value than either *pure auctioning* or *refunding* (at  $p = 0.000$ ). In markets with one or two firms, *pure auctioning* yields higher deviation rates between reported and true maximal emissions than *refunding* (at  $p = 0.009$  or lower level). However, in markets with three firms, there are no differences in deviation rates from true maximal emissions between *pure auctioning* and *refunding*. We can summarize our findings as follows:

### Result 1

- a) Under *grandfathering*, firms over-report maximal emissions. Yet, while firms initially report significantly lower maximal emissions than predicted by the Nash equilibrium, they converge to equilibrium over time. The speed of convergence to equilibrium is inversely related to the number of firms.
- b) Under *pure auctioning*, firms under-report their maximal emissions as predicted by the Nash equilibrium. When the number of firms in the market increases, the firms' reported maximal emissions get closer to their true maximal emissions.

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<sup>7</sup>In this and all following instances, we employed the `pairwise.wilcox.test` procedure in R - providing corrections for multiple testing within each group size. Moreover, we use the absolute values so that negative and positive deviations from true maximal emissions do not cancel out. The deviation rate is defined as the (absolute value of) the difference between reported and true maximal emissions divided by true maximal emissions.

- c) Under Montero’s *refunding* mechanism, firms report their true maximal emission levels. This finding is independent of the number of firms within a market and the degree of asymmetry between the firms.
- d) The rate of deviation between reported and true maximal emission is higher under grandfathering than under both pure auctioning and Montero’s refunding mechanism. This deviation rate is also higher under pure auctioning than under refunding with markets consisting of less than three firms. However, there are no differences in deviation rates between the two latter treatments for  $n = 3$ .

### 5.1.1 The effect of the maximal emissions

Next, we are interested in whether the rate of (the absolute value of) deviations between reported and true maximal emissions depend on the maximal emissions initially assigned. To this end, we use the Wilcoxon Rank Sum test to pairwise compare within each allocation method (*grandfathering*, *pure auctioning*, and *refunding*) and the given number of firms (markets with one, two, or three firms). Our results with one firm indicate that the rate of (absolute value of) deviations between the reported maximal emissions and the true values is not affected by maximal emission levels. Repeating the same test for markets with two firms we do not find systematic differences in the rate of (absolute value of) deviation from the true under *grandfathering* and *pure auctioning*. As for *refunding*, we find the highest rate of deviation in the symmetric group, where both members are assigned a maximal emission level of 22. Repeating the comparisons with markets of three firms, we find no difference between the symmetric and asymmetric allocations under *grandfathering* and *refunding*, but under *pure auctioning* we find a higher rate of deviation from the true maximal emissions in the symmetric than in the asymmetric treatment ( $p = 0.043$ ).

**Result 2** Overall, the maximal emissions initially assigned do not have a persistent effect on the rate of firms’ over- or under-reporting for any of the allocation mechanisms.

### 5.1.2 The effect of the number of firms

Finally we want to establish whether the rate of (absolute value of) deviation between reported and true maximal emissions depends on the number of firms. To this end, we use the Wilcoxon Rank Sum test to pairwise compare treatments with different numbers of firms within a given allocation mechanism. To keep all other things equal, we will only consider those symmetric treatments where each firm is assigned a default emission level equal to 22. We observe that under *grandfathering* the differences in deviation rates between firms' reported and true maximal emissions increases with the number of firms ( $p = 0.0003$  and  $p = 0.0008$  when comparing one- and two-firm treatments, and two- and three-firm treatments). However, under *pure auctioning* the opposite effect is observed, i.e. the difference between firms' reported and true maximal emissions decreases as the number of firms increases ( $p = 0.0000$  and  $p = 0.0002$  when comparing one- and two- firm treatments and two- and three-firm treatments). Under *refunding*, the evidence is mixed. The difference between firms' reported and true maximal emissions significantly decreases as we move from a one- to a two-firm treatment, whereas it increases when we move from a two-firm to a three-firm treatment ( $p = 0.0000$  and  $p = 0.0044$ , respectively). Now we can formulate the next result:

#### Result 3

- a) Under grandfathering, firms' over-reporting increases with the number of firms.
- b) Under pure auctioning, firms' under-reporting decreases with the number of firms.
- c) Under refunding, no persistent effect by the number of firms is observed on the difference between reported and true maximal emissions.

Summarizing, our hypotheses derived from the theoretical predictions are not refuted by the data. The only exception is that under pure auctioning and with three firms, we do not observe higher deviation rates between reported and true maximal emissions than under refunding.

## 5.2 Overall efficiency

So far, we have focused on the deviations between reported maximal emissions and 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.

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

where  $ER$  stands for efficiency ratio and  $SC$  for social costs consisting of abatement costs plus damage from pollution. Further,  $n$  denotes the number of firms in the market and  $m = GRA, AUC, REF$  is the index of the allocation mechanism. In addition,  $e_i^*$  is the socially optimal emission level of participant  $i$ , and  $e_i^m$  is the emission level given 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 of the three mechanisms rank as follows: *refunding* is lower than *pure auctioning*, which in its turn is lower than *grandfathering*. Accordingly, we expect the same ranking for our data, implying the efficiency ratio to be lower than one under *grandfathering* and *pure auctioning* and equal to one under *refunding*. Table 2 displays the efficiency ratios in the different treatments (averaged over periods 11-20), while Figure 2 illustrates the evolution of efficiency ratios in the different treatments.

Figure 2 about here

Using the Wilcoxon Rank Sum test to compare total efficiency ratios across each pair of treatments, we find that in markets consisting of one firm *grandfathering* is significantly less efficient than either *pure auctioning* or *refunding* ( $p = 0.0000$  in both comparisons) and that *pure auctioning* is less efficient than *refunding* ( $p = 0.0000$ ). For two and three firms, we

observe that *grandfathering* is significantly less efficient than either *pure auctioning* or *refunding* ( $p = 0.0000$  in both comparisons for the two groups sizes), but there is no significant difference in efficiency ratios between the latter two treatments.

Finally, we use the Wilcoxon Rank Sum test to find out whether the number of firms affects efficiency ratios in any given allocation mechanism. For comparability we only include markets where each firm is assigned a maximal emission level of 22. We find that under *grandfathering* efficiency decreases when comparing one-firm and two-firm markets ( $p < 0.0004$ ), but no significant decrease is observed when comparing two-firm and three-firm markets. Under *pure auctioning*, efficiency increases with the number of firms ( $p = 0.0000$  and  $p = 0.0001$  when comparing one-firm and two-firm markets and two-firm and three-firm markets, respectively). Under *refunding*, we do not observe any persistent market size effect on efficiency (efficiency decreases when comparing one-firm and two-firm markets and increases when comparing two-firm and three-firm markets,  $p = 0.0000$  and  $p = 0.0012$ , respectively). Now we can formulate our final result regarding overall efficiency.

#### **Result 4**

- a) Under grandfathering, efficiency is considerably lower than the optimum and weakly decreases with the number of firms.
- b) Under pure auctioning, efficiency is lower than the optimum in markets with one firm but increases with number of firms and with markets of two firms already gets very close to the optimum.
- c) Under Montero's refunding mechanism, efficiency is very close to the optimum independently of the number of firms. The number of firms has no persistent effect on efficiency.
- d) Finally, in markets with more than one firm, there is virtually no difference in efficiency between pure auctioning and refunding. The efficiency of these two mechanisms is always higher than that of grandfathering.

The intuition for Result 4 is as follows: As can be seen from the equations in Appendix A.3, the refunded shares decrease sharply with the number of firms, provided firms do not collude. 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 of more than three firms quickly converge to zero, hence theory predicts that under pure auctioning and refunding behavior (i.e. reporting of parameters) should converge to truthful reporting.

## 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, *grandfathering* and *pure auctioning* induce firms to over-report and under-report their maximal emissions, respectively. But even with only two firms in the market, *pure auctioning* 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 *grandfathering* was to be expected, the very minor difference between *pure auctioning* and *refunding* comes as a surprise. It shows that in markets with two or more firms the simpler auctioning mechanism without refunding works just as well as Montero’s truth-telling mechanism. 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 perfect efficiency.

These results provide additional empirical evidence for the advantage of pure auctioning over grandfathering (see e.g., Cramton and Kerr, 2002; Goeree et al., 2010). In fact, they emphasize the incentives to over-state maximal emissions under grandfathering and to under-state those under pure auctioning, while the latter fades 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 the subject for further research to investigate whether i) Montero’s mechanism works equally well and ii) the equivalence of refunding and pure auctioning 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 initial insights into the performance of Montero’s mechanism in practice, suggesting that the mechanism is especially powerful for markets with high market concentration. For large, highly competitive markets, notably carbon markets, the much simpler mechanism of pure auctioning performs equally well.

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

<b>Grandfathering</b>		$n = 1$	$n = 1$	$n = 1$	$n = 2$	$n = 2$	$n = 2$	$n = 2$	$n = 3$	$n = 3$
$e_j^{max}$		18	22	26	18	22	26	22	22	26
Reported Eq. $e_j^{max}$		36	44	52	58	62	70	66	70	74
Assigned Eq. Emissions $l_j$		18	22	26	18	22	26	22	22	26
Marginal Damage		180	220	260	400	400	540	440	480	480
Abatement Cost $C(l_j)$		0	0	0	0	0	0	0	0	0
Total Social Cost		1620	2420	3380	8000	8000	9680	9680	11520	11520
Observations (markets)		12	12	12	10	10	9	14	10	12
<b>Pure auctioning</b>		$n = 1$	$n = 1$	$n = 1$	$n = 2$	$n = 2$	$n = 2$	$n = 2$	$n = 3$	$n = 3$
$e_j^{max}$		18	22	26	18	22	26	22	22	26
Reported Eq. $e_j^{max}$		12.0	14.7	17.3	15.8	18.76	21.52	18.86	19.23	21.9
Assigned Eq. Emissions $l_j$		6.0	7.33	8.65	4.38	7.05	8.95	6.29	5.52	8.19
Marginal Damage (Price)		60.0	73.33	86.67	114.29	114.29	125.71	125.71	137.14	137.14
Abatement Cost $C(l_j)$		720	1075.56	1502.22	927.39	1117.87	1034.06	1234.69	1357.32	1585.90
Total Social Cost		900	1344.44	1877.78	2698.32	2698.32	3277.37	3259.59	3883.63	5465.74
Observations (markets)		12	12	12	10	10	10	15	10	12
<b>Refunding</b>		$n = 1$	$n = 1$	$n = 1$	$n = 2$	$n = 2$	$n = 2$	$n = 2$	$n = 3$	$n = 3$
$e_j^{max}$		18	22	26	18	22	26	22	22	26
Reported Eq. $e_j^{max}$		18	22	26	18	22	26	22	22	26
Assigned Eq. Emissions $l_j$		9	11	13	4.67	8.67	11.33	7.33	6.0	10.0
Marginal Damage (Price)		90	110	130	133.33	133.33	146.67	146.67	160	160
Abatement Cost $C(l_j)$		405	605	845	888.89	888.89	1075.56	1075.56	1280	1280
Payback share ( $\beta_j$ )		0.5	0.5	0.5	0.09	0.16	0.06	0.125	0.09	0.16
Total Social Cost		810	1210	1690	2666.67	2666.67	3226.67	3226.67	3840	5445
Observations (markets)		12	12	12	10	10	11	13	11	12

“ $e_j^{max}$ ” 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. All other values are calculated under the assumption that firms report according to the Nash-equilibrium prediction: “Assigned Eq. Emissions  $l_j$ ” denotes the emissions 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 market. 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 ( $\beta_j$ )” denotes the share of auction revenues paid back to the firms under *Refunding*. Finally, “Observations (markets)” are the number of independent markets per treatment.

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

	$n = 1$		$n = 1$		$n = 2$		$n = 2$		$n = 2$		$n = 3$		$n = 3$	
$E^{max}$	18	22	26	18	22	26	18	22	26	18	22	26	22	22
<b>Grandfathering</b>														
Reported $e^{max}$ ( $\hat{e}_j^{max}$ )	34.73 (2.67)	43.36 (3.01)	51.99 (0.03)	49.20 (9.11)	57.64 (7.62)	62.35 (7.08)	72.72 (8.66)	65.91 (11.92)	66.55 (7.42)	71.32 (11.23)	75.20 (17.13)	83.50 (6.88)	78.28 (9.87)	
Deviation from true (rate)	0.93 ***	0.97 ***	1.00 ***	1.73 ***	1.62 ***	2.46 ***	1.80 ***	2.00 ***	2.03 ***	2.96 ***	2.42 ***	2.21 ***	2.56 ***	
(significance)														
Deviation from Eq. (rate)	-0.04	-0.01	-0.00	-0.15 **	-0.07	0.01	0.04	-0.00	-0.05	-0.15 ***	-0.15 ***	-0.09 ***	-0.11 ***	
(significance)														
Efficiency	0.54	0.51	0.50	0.39 (0.07)	0.32 (0.08)	0.34 (0.12)	0.38 (0.10)	0.34 (0.12)	0.38 (0.10)	0.31 (0.06)	0.31 (0.06)	0.30 (0.18)	0.30 (0.18)	
(Std. Dev)	(0.08)	(0.06)	(0.00)											
<b>Pure auctioning</b>														
Reported $e^{max}$ ( $\hat{e}_j^{max}$ )	12.80 (1.90)	14.73 (0.23)	18.49 (2.31)	16.21 (1.42)	18.67 (1.15)	17.46 (1.51)	22.19 (2.00)	18.92 (2.28)	18.94 (1.26)	16.56 (0.74)	19.89 (0.71)	22.87 (1.67)	20.38 (1.27)	
Deviation from true (rate)	-0.29 ***	-0.33 ***	-0.29 ***	-0.10 ***	-0.15 ***	-0.03 ***	-0.15 ***	-0.13 ***	-0.14 ***	-0.08 ***	-0.10 ***	-0.12 ***	-0.07 ***	
(significance)														
Deviation from Eq. (rate)	0.07	0.00	0.07	0.03	-0.00	0.08	0.03 **	0.00	-0.02	-0.04 ***	-0.02 **	-0.02	0.00	
(significance)														
Efficiency	0.91	0.90	0.91	0.98 (0.01)	0.98	0.97 (0.01)	0.97 (0.01)	0.97 (0.02)	0.98 (0.01)	0.98 (0.01)	0.98 (0.01)	0.98 (0.01)	0.99 (0.02)	
(Std. Dev)	(0.03)	(0.07)	(0.03)											
<b>Refunding</b>														
Reported $e^{max}$ ( $\hat{e}_j^{max}$ )	17.77 (0.92)	22.07 (0.18)	15.90 (0.41)	17.45 (2.49)	21.27 (1.21)	19.52 (3.19)	25.16 (1.86)	21.48 (4.54)	21.86 (0.63)	17.63 (2.92)	21.86 (1.74)	25.67 (2.11)	21.48 (2.12)	
Deviation from true(=Eq.)	-0.01	0.00	-0.00	-0.03	-0.03 *	0.08 **	-0.03	-0.02	-0.01	-0.02	-0.01	-0.01	-0.02 *	
(significance)														
Efficiency	0.99	1.00	1.00	0.97 (0.02)	0.97 (0.02)	0.97 (0.03)	0.97 (0.03)	0.92 (0.12)	0.99 (0.01)	0.98 (0.02)	0.98 (0.02)	0.98 (0.02)	0.99 (0.02)	
(Std. Dev)	(0.02)	(0.01)	(0.02)											

“Reported  $e^{max}$  ( $\hat{e}_j^{max}$ )” is the maximal emissions reported by the firms, “Deviation from true (rate)” and “Deviation from Eq. (rate)” denote average rate of deviation between reported and either the true maximal emissions or the Nash equilibrium maximal emissions, respectively. Further, “(significance)” reports the significance level of a median test if the rate deviation of the reported emission from true maximal emissions or the Nash-equilibrium prediction are different from 0 (\*, \*\*, and \*\*\* indicate significance at the 10%, 5%, ad 1% levels). Efficiency is the ratio of optimal social costs (abatement costs + damage from emissions) to actual social costs.

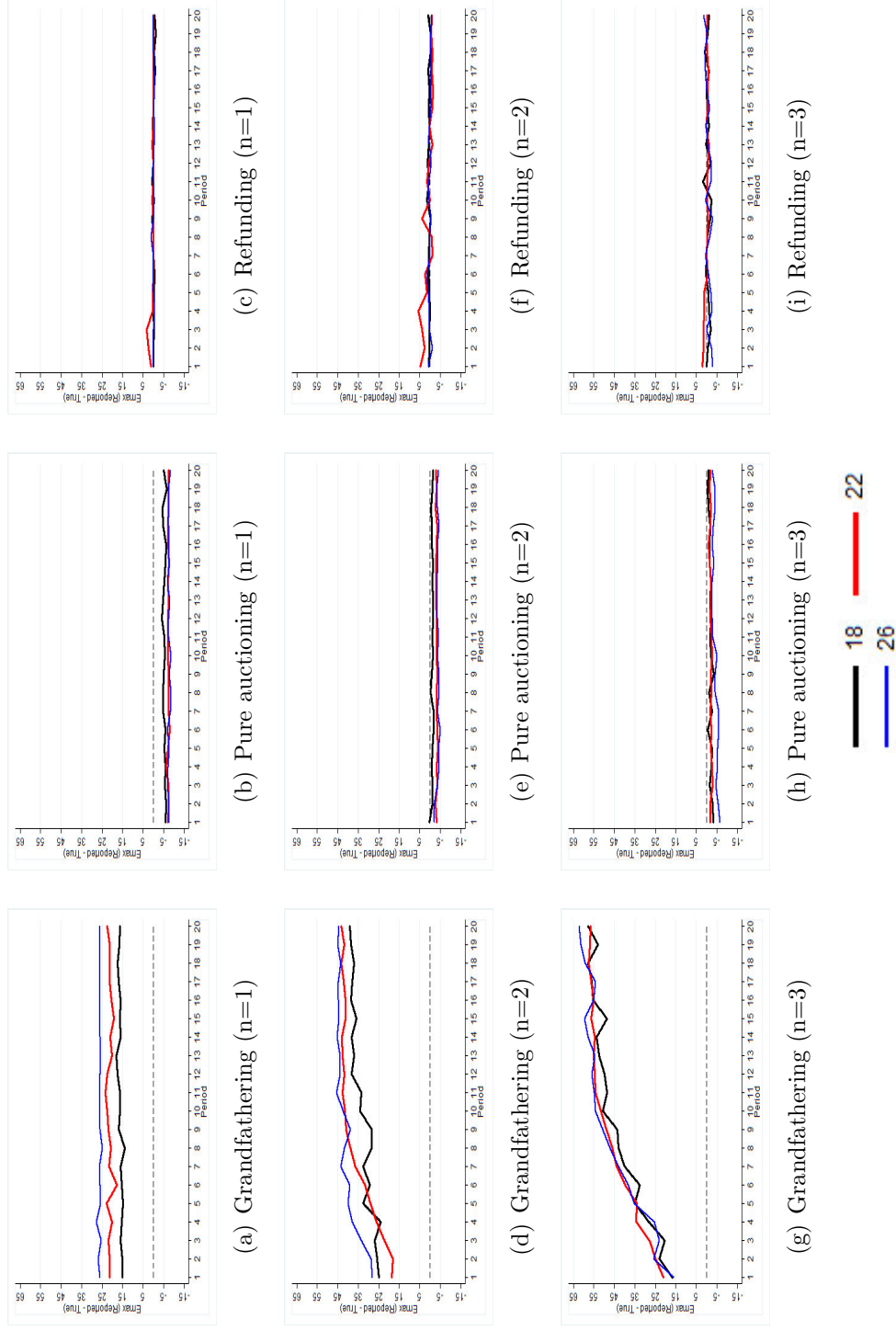


Figure 1: Evolution of deviations between reported maximum emissions and the corresponding true maximal emissions by allocation method, number of firms, and maximal emissions initially assigned (the horizontal dashed line indicates no deviation)

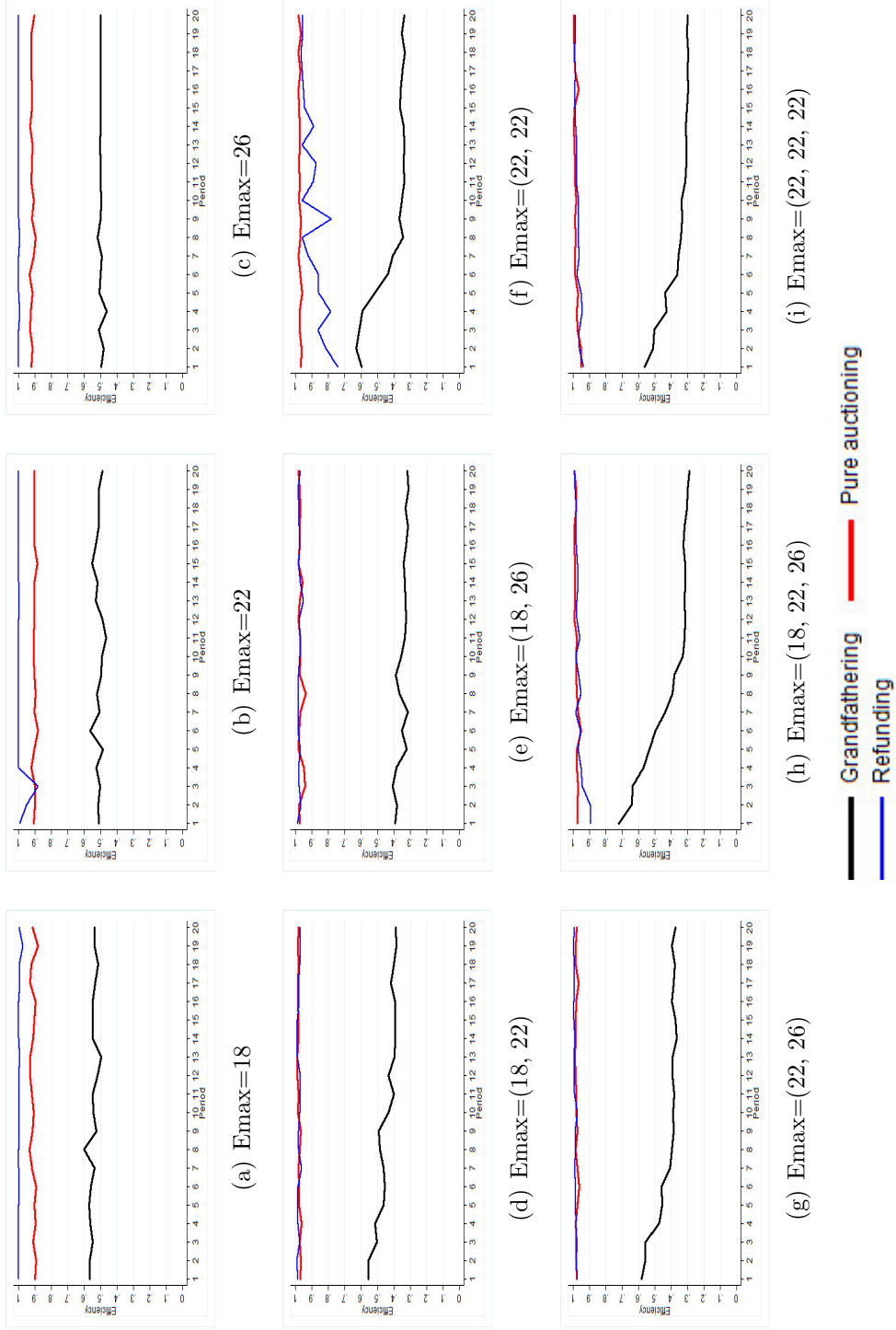


Figure 2: Evolution of efficiencies in the different treatments



# A Appendix

## A.1 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:

a) Each firm  $j$  submits a marginal abatement cost schedule  $-\tilde{C}_j(e_j)$  from which we can derive the direct demand function for permits  $e_k(\sigma)$ .

b) For each firm  $j$ , the regulator then sums up the collection of submissions from the other firms  $k$  except  $j$ , i.e.  $\{-\tilde{C}'_k(e_k), \text{ for all } k \neq j\}$  to obtain the aggregate inverse demand excluding firm  $j$ , denoted by  $-\tilde{C}'_{-j}(E_{-j})$  where  $\tilde{E}_{-j} = \sum_{k \neq j} e_k$ , and aggregate demand function  $\tilde{E}_{-j}(\sigma) = \sum_{k \neq j} e_k(\sigma)$ .

c) Next we invert the marginal damage function to obtain a virtual supply function for permits, i.e.  $S(\sigma) = D'^{-1}(\sigma)$ .

d) 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

$$D'_j(e_j) = D'(E) - \tilde{C}'_{-j}(E_{-j})$$

e) Then for each firm the regulator clears the auction by determining the number of permits  $l_j$  and the personal price  $\sigma_j$  for each bidder according to the rule

$$-\tilde{C}'_j(l_j) = D'_j(l_j) = \sigma_j$$

f) 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

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

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  $\beta_j(l_j) \cdot \sigma_j \cdot l_j$ .

Montero shows that this mechanism is incentive-compatible – i.e. firms will find it optimal to submit their true marginal abatement cost function – regardless of what other firms do. Showing this analytically involves replacing  $D'(L)$  in the single-firm case by  $D'_j(l_j)$  for each firm in the general case, so that firm  $j$ 's objective function is

$$\min_{l_j} \{C_j(l_j) + D'_j(l_j) \cdot l_j - \beta_j(l_j) D'_j(l_j) l_j\} \quad (\text{A.3})$$

By plugging (A.2) into (A.3) it follows, similarly to the single-firm case, that firm  $j$ 's total pollution related costs amount to  $C_j(l_j) + D_j(l_j)$ , and the firm will submit a marginal abatement cost function as if choosing emissions  $l_j$  to minimize these costs, leading to the condition  $-C'_j(l_j) = D'_j(l_j)$ . The rules of the mechanism therefore result in each firm's behavior being determined by

$$-\tilde{C}'_j(l_j) = -C'_j(l_j) = D'_j(l_j) = \sigma_j \quad (\text{A.4})$$

Montero (2008, p.504) explains this condition as “...basically informing the firm that, whatever (abatement cost function) it chooses to submit to the regulator, that report, together with the other firms, will be used efficiently.” Importantly, Equation (A.4) suggests that it is optimal for firm  $j$  to reveal its true cost function, regardless of what other firms do. If for some reason other firms misrepresent their costs,  $D'_j(l_j)$  will be incorrect from an efficiency perspective, but firm  $j$  can still do no better than to announce its costs according to (A.4). 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, reim-

bursing nothing, i.e. setting  $\beta(\cdot) = 0$ , provides incentives to under-report marginal abatement cost schedules, while under grandfathering, i.e.  $\beta(\cdot) = 1$ , firms will want to inflate their alleged marginal abatement costs.

## 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 pay-back functions for the case of linear marginal abatement cost curves of the type

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

and a marginal damage function

$$D'(E) = dE \quad (\text{A.6})$$

To calculate the residual marginal damage curve, we have to invert (A.5) and (A.6). Setting

$$-C'(e_j) = a_j - b_j e_j = \sigma \quad (\text{A.7})$$

and solving for  $e_j$  yields

$$e_j(\sigma) = \frac{a_j - \sigma}{b_j} \quad (\text{A.8})$$

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

$$S(\sigma) = \frac{\sigma}{d} \quad (\text{A.9})$$

Now substituting (A.8) and (A.9) into (A.1), i.e.

$$S_j(\sigma) = S(\sigma) - \tilde{E}_{-j}(\sigma)$$

we obtain:

$$e_j = S_j(\sigma) = \frac{\sigma}{d} - \sum_{k=1, k \neq j}^n \frac{a_k - \sigma}{b_k} = \left[ \frac{1}{d} - \sum_{k=1, k \neq j}^n \frac{1}{b_k} \right] \sigma - \sum_{k=1, k \neq j}^n \frac{a_k}{b_k} = A_j p - B_j \quad (\text{A.10})$$

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.10) by solving for  $\sigma$  to obtain the residual marginal damage function as

$$\sigma = D'_j(e_j) = \frac{e_j + B_j}{A_j} \quad (\text{A.11})$$

Integrating this, we obtain

$$D_j(e_j) = \frac{e_j/2 + B_j}{A_j} e_j \quad (\text{A.12})$$

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

$$\beta_j(l_j) = 1 - \frac{D_j(l_j)}{D'_j(l_j) \cdot l_j} = 1 - \frac{l_j/2 + B_j}{l_j + B_j} = \frac{l_j/2}{l_j + B_j} \quad (\text{A.13})$$

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

$$\begin{aligned}\beta_1^*(l_1^*) &= \frac{b_2(a_1b_2 + d(a_1 - a_2))}{2(a_2b_1 + a_1b_2)(b_2 + d)} \\ \beta_2^*(l_2^*) &= \frac{b_1(a_2b_1 + d(a_2 - a_1))}{2(a_1b_2 + a_2b_1)(b_1 + d)}\end{aligned}$$

For  $n = 3$  we obtain

$$l_1^* = \frac{a_1b_2b_3 + d(a_1(b_2 + b_3) - a_2b_3 - a_3b_2)}{b_1b_2b_3 + d(b_1b_2 + b_2b_3 + b_1b_3)}$$

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

$$\beta_1^*(l_1^*) = \frac{b_2b_3(a_1(b_2b_3 + d(b_2 + b_3)) - d(a_2b_3 + a_3b_2))}{2(a_1b_2b_3 + a_2b_1b_3 + a_3b_2b_3)(b_2b_3 + d(b_2 + b_3))}$$

analogously 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

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

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

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

and the resulting optimal (minimal) social costs are

$$SC^{REF} = \frac{(a_1 + a_2)^2}{60} \tag{A.14}$$

The paybacks are given by

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

In the case of symmetry we have  $\beta_i^* = 1/8$ ,  $i = 1, 2$ . (Compare this to  $\beta_i^* = 1/2$  for  $n = 1$  and  $\beta_i^* = 1/18$  for  $n = 3$ ).

For asymmetric parameters we obtain

	$\beta_1^*$	$\beta_2^*$	$\beta_3^*$
$a_1 = 180, a_2 = 220,$	0.09	0.16	—
$a_1 = 180, a_2 = 260,$	0.06	0.19	—
$a_1 = 220, a_2 = 260,$	0.09	0.16	—
$a_1 = 180, a_2 = 220, a_3 = 260$	0.015	0.056	0.096

We see that the asymmetry in parameters induces 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 grandfathering

For the grandfathering mechanism, again let  $\hat{e}_i^{\max}$  denote the reported maximal emissions. The corresponding intercept of the (reported) marginal abatement cost function would then be  $\hat{a}_i = 10\hat{e}_i^{\max}$ .

Under the grandfathering rule, the participants submit their  $\hat{e}_i^{\max}$ . 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

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

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

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

Solving this equation system yields

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

and thus the implied intercepts are given by

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

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

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

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

$$SC^{GRA} = SC(\hat{e}_1, \hat{e}_2) = 5(e_1^{\max} + e_2^{\max})^2 = 5(a_1/10 + a_2/10)^2 \quad (\text{A.16})$$

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

$$l_i = \frac{3\hat{e}_i^{\max} - \hat{e}_j^{\max} - \hat{e}_k^{\max}}{4}, \quad i = 1, 2, \quad j, k \neq i \quad (\text{A.17})$$

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

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

## A.5 Equilibria under pure auctioning

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.

As under *grandfathering*, the regulator takes the firms' reports  $\hat{e}_i^{\max}$  as if they were the true reports and sets the allowed emissions according to (A.15). 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

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

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

$$SC^{AUC} = \frac{173a_1^2 + 248a_1a_2 + 173a_2^2}{8820} \quad (\text{A.18})$$

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

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

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.16), (A.18), and (A.14) we obtain

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

Thus we have

$$SC^{GRA} > SC^{AUC} > SC^{REF} \tag{A.19}$$

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

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

## B Further Tables and Figures

Table B.1: Random effect models by market size

	rate of deviation from true Emax			rate of deviation from Eq.		
	Size $n = 1$	Size $n = 2$	Size $n = 3$	Size $n = 1$	Size $n = 2$	Size $n = 3$
Grandfathering	0.94*** (0.02)	1.54*** (0.07)	1.99*** (0.07)	0.01 (0.01)	0.04 (0.03)	0.10*** (0.02)
Pure Auctioning	0.29*** (0.01)	-0.00 (0.02)	-0.01 (0.01)	0.05*** (0.02)	-0.05 (0.03)	-0.03** (0.02)
Period dummies	Yes	Yes	Yes	Yes	Yes	Yes
Constant	0.03*** (0.01)	0.21*** (0.03)	0.27*** (0.04)	0.03*** (0.00)	0.11 (0.02)	0.07*** (0.01)
Observations	2160	5320	4980	2160	5320	4980

Period
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)

Emax of firm 2


**Berechne**

**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)



**OK**

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 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.

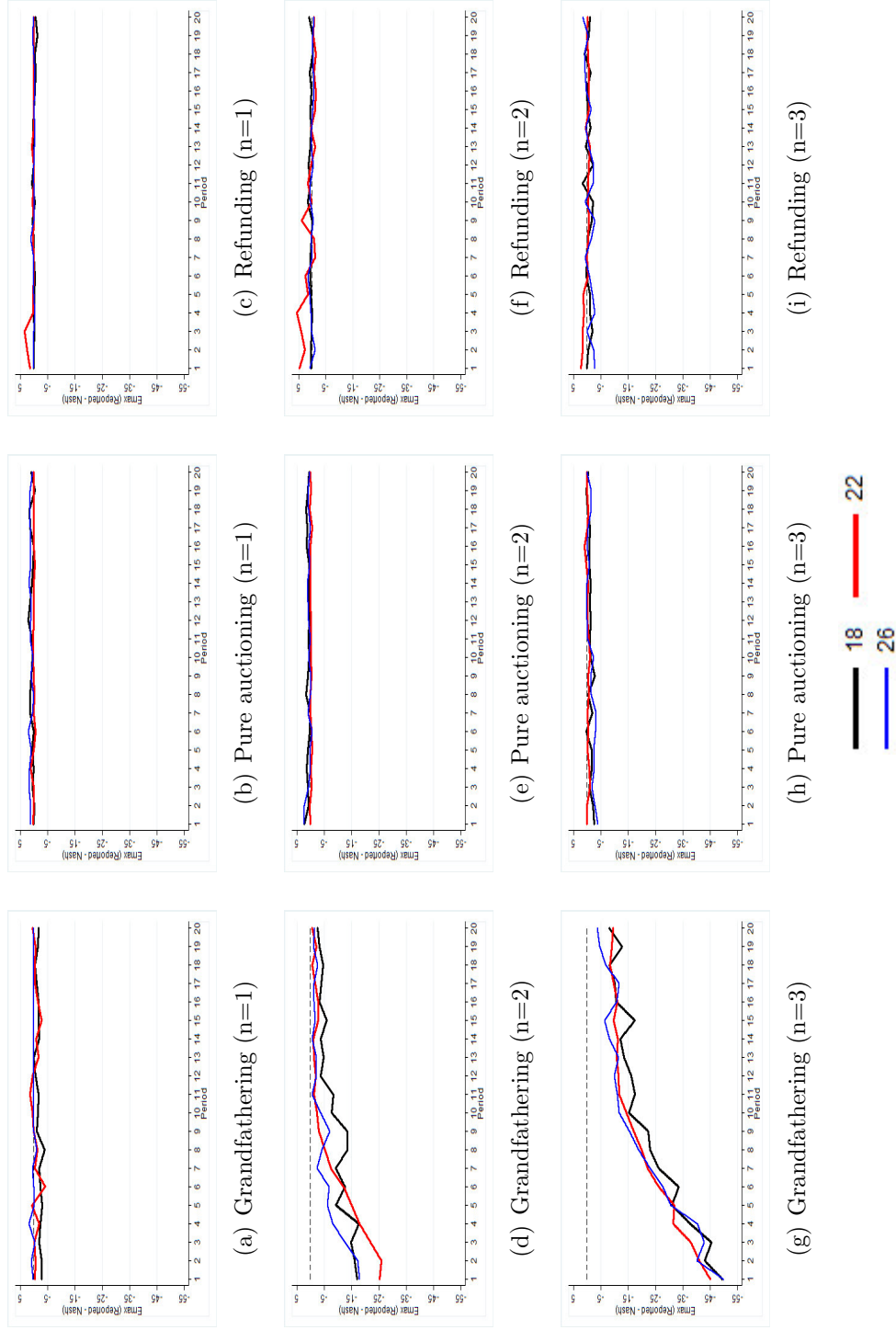


Figure B.2: Evolution of deviations between reported maximal emissions and the corresponding Nash prediction, by allocation method, number of firms, and initially assigned maximal emissions (the horizontal dashed line indicates no deviation)