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The optimal initial allocation of pollution permits: a relative performance approach

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Abstract The initial allocation of pollution permits is an important aspect of emissions trading schemes. We generalize the analysis of Böhringer and Lange (2005, Eur Econ Rev 49(8): 2041–2055) to initial allocation mechanisms that are based on inter-firm relative performance comparisons (including grandfathering and auctions, as well as novel mechanisms). We show that using firms' historical output for allocating permits is never optimal in a dynamic permit market setting, while using firms' historical emissions is optimal only in closed trading systems and only for a narrow class of allocation mechanisms. Instead, it is possible to achieve social optimality by allocating permits based only on an external factor, which is independent of output and emissions. We then outline sufficient conditions for a socially optimal relative performance mechanism.

Keywords Relative performance · Initial allocation · Pollution permits · Auctions · Rank-order contests

JEL Classification Q53 · Q58 · C72

1 Introduction

Tradable permit markets have become an important policy tool in the control of pollution. Schemes such as RECLAIM and the SO_2 market in the US have shown that tradable permits are a viable and cost effective market-based mechanism (e.g. Stavins 1998; Schmalensee et al. 1998). Yet there is still an active debate about how to allocate permit endowments among the participating firms at the beginning of each trading period. As Böhringer and Lange (2005) argue, some initial allocation mechanisms may create inter-temporal distortions and result in socially suboptimal outcomes.

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In this paper, we extend the results of Böhringer and Lange (2005) to accommodate most of the existing dynamic initial allocation mechanisms (including grandfathering and auctions, as well as novel mechanisms). We show that using firms' historical outputs for allocating permits is never optimal, while using firms' historical emissions is optimal only in closed trading systems and only for a narrow class of allocation mechanisms. Instead, it is possible to achieve social optimality by allocating permits based only on an external factor, which is independent of output and emissions. We outline sufficient conditions for a socially optimal relative performance mechanism and discuss the issues related to the choice of a suitable mechanism for initial allocation.

In our analysis, we discuss two types of mechanisms that are commonly considered for allocating initial endowments of permits. The first mechanism, which we call an Absolute Performance Mechanism (APM), involves permit allocations based on the *levels* of individual firm activity. The second mechanism, which we call a Relative Performance Mechanism (RPM), involves permit allocations based on how the levels of a firm's activity compare to the levels of other firms' activities, or on inter-firm *relative comparisons*. The distinction between these two mechanisms is crucial as firms' behaviour in the permit market is subject to whether firms' believe they are obtaining permits individually or, as under a RPM, as part of a game where a firm's allocation is dependent on other firms' actions. We show in this paper that a mechanism that allocates permits based on firms' absolute performance (APM), as used by Böhringer and Lange (2005), is a special case of a generalized relative performance mechanism (RPM), and thus that the two mechanisms share a number of optimality properties in a dynamic setting. We however argue that mechanisms which are based on relative performance might be superior over those based on absolute performance and offer a promising alternative to auctioning and grandfathering, namely a rank-order contest.

Both types of mechanisms have had important applications in existing tradable permit markets. Absolute performance mechanisms have been advocated in the form of relative emissions or intensity-based emissions caps (Fischer 2001, 2003; Ellerman and Wing 2003; Kuik and Mulder 2004; Pizer, 2005; Newell and Pizer, 2006).[1] In such a scheme *intra-firm* relative comparisons exist, where the performance of a given firm is evaluated relative to its own activity, but not relative to the activity of other firms. Rather than having a cap on absolute levels of emissions, an intensity-based cap involves a ceiling on the emissions intensity (i.e. emissions per one unit of output). This type of approach is becoming increasingly common, for example, Bode (2005) notes that a number of participants in the UK emissions trading scheme were given an intensity target. Furthermore, the Bush administration in the U.S. has strongly advocated this type of approach to tackle climate change (Kolstad 2005; Pizer 2005). When a trading system is based on emissions intensity, each firm can unilaterally increase both their output and emissions without changing emissions intensity and without any effect on other firms (the permit allocation is an adjustable grandfathering mechanism).

However, the majority of distribution rules which have been discussed are relative performance mechanisms. The two most common RPMs include auctions (where firms' are allocated permits based on their relative bids) and grandfathering with a fixed cap (where firms' are allocated permits based on their relative emissions levels with respect to some fixed cap) (see Hahn and Noll 1982; Lyon 1982; 1986; Oehmke 1987; Milliman and Prince 1989; Van Dyke 1991; Franciosi et al. 1993; Parry 1995; Parry et al. 1999; Cramton and Kerr 2002).

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[1] We make a distinction between intensity-based caps and output-based allocation (although they do both act as an implicit output subsidy). In intensity rate-based mechanisms the emission cap is adjusted to maintain a constant emissions intensity and hence allocation is not dependent on other firms' behaviour (e.g. the levels of other firms' emissions and output choices). In contrast, output-based mechanisms alter the average allocation per unit of output to maintain a fixed emissions cap (allocation is dependent on firms' behaviour).

However, there is a large selection of RPMs that have not been extensively considered in the literature. For example, yardstick competition, where each firm's performance is assessed relatively to the performance of other firms has been suggested (Shleifer 1985; Franckx et al. 2005; Nalebuff and Stiglitz 1983a,b). Moreover, a novel RPM that could be envisaged to allocate permits is the use of contests or tournaments where firms spend resources in order to 'win' a proportion of the permit allocation (Moldovanu and Sela 2001, 2006).

Inter-firm comparisons using relative performance mechanisms have a number of general regulatory advantages which have been widely documented in the literature (Lazear and Rosen 1981; Holmström 1982; Green and Stokey 1983; Nalebuff and Stiglitz, 1983a,b; Mookherjee 1984; Shleifer 1985; Moldovanu and Sela 2001, 2006). Relative performance mechanisms can also be advantageous in an environmental context. Govindasamy et al. (1994) suggested the use of a tournament to control non-point pollution, and found that a RPM results in a number of desirable outcomes. Franckx et al. (2005) extended the work of Govindasamy et al. (1994) by using a different RPM, yardstick competition, and conducted the analysis in a more general environmental regulatory setting. They find that this RPM will be desirable when a large number of firms participate and common shocks (such as similar technology shocks or oil price changes) are experienced by all firms.

Rather fewer authors have focused on relative performance issues in emissions trading. Using a rent-seeking model, Malueg and Yates (2006) examine the effects of citizen participation in a permit market to determine the endowment and price of permits. They find that citizens' choice of lobbying and permit purchases in a market depends on the initial allocation mechanism chosen (auctioning or grandfathering). Finally, Groenenberg and Blok (2002) outline an initial allocation mechanism for a permit market that bases distribution on benchmarking the production process of each firm and find it eliminates a large amount of problems associated with existing allocation mechanisms.

For a number of decades the free allocation (grandfathering) of permits has been discussed as a feasible method of allocation (e.g. Tietenberg 1985). Indeed, the majority of actual emissions trading schemes to date use grandfathering as the primary allocation mechanism due to its political viability: market participants will always lobby for the free allocation of permits (Stavins 1998). Grandfathering might also be seen as offering a closer fit to existing regulatory approaches, since it does not involve any fundamental change in property rights compared with, for instance, a system of performance standards for polluting emissions. Grandfathering might also be preferred by governments on competition grounds, since the avoidance of a lump-sum distribution from industry to government can avoid disadvantaging domestic firms relative to their international competitors. On the negative side, grandfathering could be seen as rewarding firms who have engaged in relatively low pollution control efforts in the past. As grandfathering is a commonly used tool, the discussions regarding the effects of the mechanism have been widespread. In particular, Requate and Unold (2003) have shown that substantial innovation incentives exist for firms in a grandfathered emissions scheme. However, Goulder et al. (1997) found grandfathering to be a rather inefficient allocation mechanism compared to alternative allocation procedures. Recently, grandfathering has been adapted to include a dynamic element (Bode 2006; Böhringer and Lange 2005). In particular, Böhringer and Lange (2005) have discussed *updated grandfathering* which continually updates the free allocation of permits based on historical emissions and output.[2] They found that the dynamic allocation has to be carefully considered to reduce distortions in the product and permit market.

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[2] See Fischer (2001) for static analysis of output-based permit allocations.

Another important aspect of the mechanisms in question involves multi-period choice problems in pollution permit markets. Several studies have focused on general design considerations for multi-period permit markets (Cronshaw and Kruse 1996; Rubin 1996; Kling and Rubin 1997; Schennach 2000; Leiby and Rubin 2001; Yates and Cronshaw 2001), yet only a few studies have focused on the initial allocation of permits in this setting. In the context of the electricity sector, Bode (2006) finds considerable variation in the distributional impacts among different allocation mechanisms within a dynamic emissions trading scheme. Jensen and Rasmussen (2000) model a number of allocation mechanisms in a dynamic setting and find that welfare and employment vary drastically across allocation mechanisms.

The work which is the most relevant to our paper is by Böhringer and Lange (2005), who compare the efficiency of dynamic permit allocations based on output, emissions and a lump-sum transfer. In comparing efficiency, they make a distinction between markets that are open (i.e. when firms can trade outside the domestic market) and closed (i.e. when participating firms cannot trade in permits outside the domestic market). This distinction is important to policy analysis as tradable permit markets are becoming increasingly varied in size and scope and have the potential to have either an open or closed market structure. They find in a closed market it is optimal to allocate permits on criteria not related to output, whereas for an open market, an efficient allocation occurs when the permits are distributed using a lump-sum approach. However, in their treatment of the initial allocation mechanism, Böhringer and Lange (2005) assume that the permit distribution to a firm is based *only* on firms' absolute levels of output and emissions, so that other firms's actions do not affect the allocation of a given firm. Yet, given the fixed emission cap considered by Böhringer and Lange (2005), the permit allocation to a firm is also crucially dependent on the behaviour of rival firms. This is because a fixed emissions cap implies that if in the current period rival firms, say, increase their output and emissions relative to a given firm, then the current-period aggregate output and emissions increase, thus decreasing the proportion of future permits that each firm can receive per each unit of current output and emissions. As the result, even if a given firm does not alter its own choices, its own future allocation of permits will change. Thus we argue that the initial allocation process considered by Böhringer and Lange (2005) should take into account other firms' actions and thus should be modelled as a relative performance mechanism.

Our paper therefore attempts to extend Böhringer and Lange (2005) by implementing a more general design of a dynamic initial allocation mechanism, which allows for the allocation of permits to be based on each firm's choices *relative to other firms*. Following Böhringer and Lange (2005), we consider allocation mechanisms which are based on choices of output and emissions, but in addition we consider possible permit allocations based on an "external" factor which is independent of output and emissions. This allows us to create an encompassing model for most existing types of initial allocation mechanisms such as grandfathering, auctioning and contests. We show that a RPM can efficiently (socially optimally) allocate pollution permits if the criteria used to compare firms is based on such an external factor, in a contest. Given the variety of potential external factors, we suggest a number of criteria that a regulator may take into account when choosing a suitable factor. We also argue in favour of a new mechanism, which involves an inter-firm contest designed to achieve two goals simultaneously—that is, the primary goal of efficiency and some secondary goal, such as generating revenue, achieving health and safety targets, noise reduction, reduction of other pollutants, etc. Given the political economy problems with both auctions and grandfathering as a way of initially allocating permits, this new mechanism may well be of interest to policy makers.

Our contribution is thus twofold. First, we extend the results of Böhringer and Lange (2005) to a wider class of mechanisms, so-called *relative performance mechanisms*, such as grandfathering with fixed cap, yardsticks, auctions, contests, etc. Although such mechanisms create a situation where firms' choices are interdependent, the general intuition of Böhringer and Lange (2005) holds in the Nash equilibrium of the ensuing game. That is, for a wide range of mechanisms, for the initial allocation to be cost-efficient, it should not depend on firms' outputs, and may depend on firms' emissions only in limited circumstances. Second, we propose that the lump-sum distribution advocated by Böhringer and Lange (2005) can be implemented better with a relative performance mechanism based on an external factor. Such a cost–efficient mechanism allows the regulator to achieve a secondary target, such as raising revenue,—thus "killing two birds with one stone".

To the best of our knowledge, this is the first paper to introduce a generalised RPM into a permit market which allows us to model most existing relative-based mechanisms and has the added advantage of encompassing APMs. The paper is organised as follows: Sect. 2 outlines our model and presents the social optimality conditions and firm's optimisation problem. A socially optimal dynamic initial allocation mechanism, when the market experiences both exogenous and endogenous permit prices, is considered in Sect. 3. Section 4 discusses the external factor, while Sect. 5 concludes.

2 The model

We follow Böhringer and Lange (2005) and consider a multi-period partial equilibrium model. The technology of a firm i ($i = 1, 2, \ldots, n$) at time t ($t = 1, 2, \ldots$) is given by a cost function $c_{it}(e_{it}, q_{it})$, where q_{it} is the firm's output level, and e_{it} the firm's emissions resulting from production. Costs c_{it} are assumed to be twice differentiable and convex, with $\frac{\partial c_{it}}{\partial e_{it}} \leq 0$, $\frac{\partial c_{it}}{\partial q_{it}} > 0$, $\frac{\partial^2 c_{it}}{\partial e_{it}^2}, \frac{\partial^2 c_{it}}{\partial q_{it}^2}, -\frac{\partial^2 c_{it}}{\partial e_{it} \partial q_{it}} \geq 0$ and $\frac{\partial^2 c_{it}}{\partial q_{it}^2} \cdot \frac{\partial^2 c_{it}}{\partial e_{it}^2} - \left(\frac{\partial^2 c_{it}}{\partial e_{it} \partial q_{it}}\right)^2 > 0$.

The firm sells its output in a competitive product market at a price of p_t. Finally, the firm is regulated by a competitive emissions-trading program and receives an initial allocation of permits A_{it}.

We further assume that each firm i also "produces" a factor z_{it} which has no direct relevance in the product and emissions market, and thus is outside the regulator's interests and/or jurisdiction. This "external" factor is "produced" by each firm *independently* of output and emissions at a cost $v_{it}(z_{it})$ (possibly zero), with $\frac{dv_{it}}{dz_{it}} \geq 0$. While this external factor is irrelevant to the product and emissions market, it may determine firms' permit allocations A_{it} in a manner to be specified later.

2.1 The generalised allocation mechanism

Böhringer and Lange (2005) considered a mechanism whereby pollution permits are allocated based on the *levels* of firm's historical production q_{it} and emissions e_{it}.[3] We first extend this mechanism by assuming that in addition to output and emissions, some "external" factor may play a role in how many permits will be allocated to a given firm, but this factor has no relevance to the product and emissions market, and thus is beyond the interest or jurisdiction

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[3] Böhringer and Lange (2005) considered a number of historical observation periods, $l = (1, 2 \ldots, s)$. For expositional simplicity, we restrict our model to $l = 1$ (the historical period is simply the previous period). It is straightforward to generalise our model to $l > 1$ historical observation periods.

of the regulator (and it is this factor which determines the lump-sum allocations in the model of Böhringer and Lange 2005).

Examples of a possible external factor include population size in a firm's locality, a firm's socially responsible activities, a firm's emissions of other pollutants, a random event such a lottery draw and so on. We denote such external factors as z_{it}. While we will discuss the external factor more in Sect. 4, it is worth noting here that the nature of the external factor determines both the cost of this factor to the firm, as well as the degree of firm's control over this factor. For example, population size is both beyond the firm's control and it is "free" to the firm. On the other hand, lottery tickets can be bought by firms, or can be allocated to firms by the regulator (and thus are beyond firms' control). In contrast, in a permit auction, both success and costs of each firm's bid depends on the bids of other participating firms.

Thus, the allocation mechanism based on absolute performance (APM) is given by

$$A_{it}^{\mathrm{APM}} = \lambda_{q,it}^{t-1}\tilde{h}(q_{i(t-1)}) + \lambda_{e,it}^{t-1}\tilde{g}(e_{i(t-1)}) + \lambda_{z,it}^{t-1}\tilde{f}(z_{i(t-1)}) \tag{1}$$

where $\tilde{h}$, $\tilde{g}$, $\tilde{f}$ are increasing and continuously differentiable functions, and $\lambda_{q,it}^{t-1}$, $\lambda_{e,it}^{t-1}$, $\lambda_{z,it}^{t-1} \geq 0$ are the weights (in period t) placed on period $t-1$'s performance. The weights reflect the relative importance of a particular activity, and can vary across time periods and across firms.

We extend Eq. 1 by allowing for firms' performance to be evaluated in comparison to other firms, i.e. how a given firm i's performance at time t in production q_{it}, emissions e_{it}, an external factor z_{it} compares relatively to the performance of every other firm $-i = \{1, \ldots, i-1, i+1, \ldots, n\}$. Formally, firm i's performance at time t in output relatively to other firms' output q_{-it} is given by a relative performance function $h = h(q_{i(t-1)}, q_{-i(t-1)})$. Similarly, relative performance in emissions and external factor are given by $g = g(e_{i(t-1),} e_{-i(t-1)})$, and $f = f(z_{i(t-1),} z_{-i(t-1)})$, respectively. We assume $h_i = \frac{\partial h}{\partial q_{it}}$, $g_i = \frac{\partial g}{\partial e_{it}}$, $f_i = \frac{\partial f}{\partial z_{it}} > 0$ so that, for given levels of other firms' performance, higher levels of emissions, output, and the external factor result in a larger permit allocation. We also assume that $h_{-i} = \frac{\partial h}{\partial q_{-it}}$, $g_{-i} = \frac{\partial g}{\partial e_{-it}}$, $f_{-i} = \frac{\partial f}{\partial z_{-it}} \leq 0$, so that for a given level of firm's performance, its allocation does not increases if other firms' increase their levels of emissions, output, or the external factor.[4]

We take a rather general view of the relative allocation functions. That is, to allow for uncertainty over allocations, we treat these functions as *expectations* over possible realisations. Thus allocations can be distributed using deterministic rules (such as yardstick competitions) devised by the regulator, as well as by lotteries, auctions, or contests. For analytical tractability, we assume that the relative allocation functions h, g, f are continuously differentiable.[5] For example, a firm's relative allocation can be determined continuously based on how its own output compares to aggregate output, e.g. $h(q_{i(t-1)}, q_{-i(t-1)}) = \alpha \frac{q_{it}}{q_{it} + \sum_{-i} q_{-it}}$. Another example of a continuous relative allocation function includes Tullock-type (winner takes all) contest allocations, where a firm's expected amount of permits is given by all participating firms' outputs as follows: $h(q_{i(t-1)}, q_{-i(t-1)}) = \beta \frac{q_{it}^r}{q_{it}^r + \sum_{-i} q_{-it}^r}$—i.e. the size of the permit lot β multiplied by the probability of winning the contest (see Skaperdas 1996).

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[4] Instead, one can assume that h_i and g_i are negative.

[5] Our argument will not change if we relax the assumption of continuity to include relative performance mechanisms such as winner-pay and all-pay auctions involving discontinuities in firms' payoff functions. To deal with such discontinuities, one typically assumes that all firms face commonly known continuously differentiable distribution of firms' "types", and that all firms follow symmetric strictly increasing and differentiable strategy, so that each firm's expected payoff function becomes continuously differentiable.

Thus, the permit allocation for firm i at time t, according to the generalized Relative Performance Mechanism is

$$A_{it}^{\mathrm{RPM}} = \lambda_{q,it}^{t-1} h(q_{i(t-1)}, q_{-i(t-1)}) + \lambda_{e,it}^{t-1} g(e_{i(t-1)}, e_{-i(t-1)}) + \lambda_{z,it}^{t-1} f(z_{i(t-1)}, z_{-i(t-1)}) \quad (2)$$

Comparing this relative performance allocation mechanism to that based on absolute performance (1), one can observe the following:

Remark 1 If $h_{-i} \equiv g_{-i} \equiv f_{-i} \equiv 0$ then a relative performance allocation mechanism reduces to an absolute performance allocation mechanism.

In other words, the absolute performance mechanism considered by Böhringer and Lange (2005) is a special case of relative performance mechanism when firm i's allocation is independent of the remaining firms' actions. In this case, the remaining firms' actions have no impact on firm i's allocation, and a firm i can obtain permits by optimally choosing q_{it}, e_{it} and z_{it}, *without* considering other firms' actions.

Note that Böhringer and Lange (2005) implicitly assume that the grandfathering mechanism is an absolute performance mechanism. However, with a fixed emission cap, for a given behaviour of other firms, if a particular firm increases/decreases its output and/or emissions, that would affect the aggregate output and emissions of domestic firms, ultimately affecting how many permits both that firm and all other firms will receive. Thus, it is implicit in Böhringer and Lange (2005) that the factor weights will change each period to reflect changes in the aggregate activities. To see this, suppose that at time t a fixed amount of permits $\bar{E}_t$ is allocated among n firms proportionally to each firm's output q_{it}. In other words, each firm i receives an allocation $\gamma_t q_{it}$, where $\gamma_t = \frac{\bar{E}_t}{q_{it}+\sum_{-i} q_{-it}}$. Thus, the output weight γ_t has to be adjusted each period to reflect changes in aggregate production. It is easy to see that such a fixed cap grandfathering mechanism is a RPM with $h(q_{i(t-1)}, q_{-i(t-1)}) = \bar{E}_t \frac{q_{it}}{q_{it}+\sum_{-i} q_{-it}}$.

When a relative performance mechanism is used, firm i's choices affect the number of permits allocated to firm $j \neq i$, and thus affect firm j's profits, and vice versa. In other words, a RPM creates a situation where firms choices are *interdependent*. In such a situation, a rational firm will make its choices strategically, by taking into account the anticipated actions of its rivals. The relative performance permit allocation mechanism thus results in a game among participating firms, which leads firms' behaviour to be typically different from their behaviour when faced with an APM. To explore the distortionary effect of such behaviour, we first need to consider the socially optimal situation.

2.2 The socially optimal outcome

We now consider the regulator's point of view. Following Böhringer and Lange (2005) we assume that the regulator cares about profits and costs associated with the production of output and emissions of the specific pollutant, as well as the trade in the pollution permits, but is not interested in the external factors such as population size, lottery draws, or auction bids (we will come back to this assumption in Sect. 4). Thus, the regulator's objective is to maximise (minimise) the aggregate profit (cost) that all the domestic firms incur while producing the product of the regulator's interests or jurisdiction whilst being constrained by the emissions program.

When trade in emissions permits is not restricted to the regulator's jurisdiction, firms can import/export emissions across the system's borders. From a regulator's point of view, this is a (small) *open* emissions trading system, where the permit price is exogenously determined, and the aggregate emissions in the jurisdiction are not capped. This may occur when the market is open to transactions from other (possibly larger) schemes. For example, in the European Union Emissions Trading Scheme (EU-ETS), member states allocate permits domestically, but firms in each member state can trade permits with firms in other member states.

In such a system, the regulator's objective takes into account the balance of the trade in the emission permits. Thus, given the set of prices (σ_t, p_{it}), the regulator's objective is to

$$\underset{q_{it},e_{it}}{\text{Max}} \sum_t \left[\sum_{i=1}^{n} p_{it}q_{it} - c_{it}(e_{it}, q_{it}) - \sigma_t \left(\sum_{i=1}^{n} e_{it} - \overline{E_t} \right) \right] \tag{3}$$

where σ_t is the exogenous permit price determined by the (international) demand and supply of permits in the open market and $\overline{E_t}$ is the domestic emissions cap at time t. For each firm i and each of it's rival $-i = \{1, \ldots, i-1, i+1, \ldots, n\}$, the socially optimal conditions are as follows:[6]

$$p_{it} = \frac{\partial c_{it}}{\partial q_{it}} \tag{4}$$

$$-\frac{\partial c_{it}}{\partial e_{it}} = -\frac{\partial c_{jt}}{\partial e_{jt}} (= \sigma_t) \tag{5}$$

for all $i, j \neq i, t$. That is, at period t all firms will simultaneously equate their marginal production costs to their firm-specific product price (4). Also, in the equilibrium, firms' marginal abatement costs will be equalized (5), and will be equal to the (exogenously determined) common permit price.

In contrast, in a *closed* emissions trading system, a single regulator distributes the total supply of permits, and thus ensures that the aggregate emissions are capped: $\sum_i e_{it} = \overline{E}_t$. The emissions permit price is endogenously determined by the (domestic) demand and supply in the closed market. The regulators objective function is thus:

$$\underset{q_{it},e_{it}}{\text{Max}} \sum_t \left[\sum_{i=1}^{n} p_{it}q_{it} - c_{it}(e_{it}, q_{it}) \right] \text{ subject to } \sum_{i=1}^{n} e_{it} = \overline{E_t} \tag{6}$$

The socially optimal conditions are identical to the conditions (4–5), except that firms' marginal abatement costs will be equal to the shadow price of abatement.

2.3 Firm optimisation

We first extended the allocation model of Böhringer and Lange (2005) by allowing for evaluations based on an independent external factor such as population size, socially responsible activities, emissions of other pollutants, lottery draw, and so on. We now focus our attention on the firm-specific problem. Given the profile of other firms' actions, the set of prices (σ_t, p_{it}), and its permit allocation A_{it} for the target pollutant, a firm i will choose a level of emissions, output and an external factor, $(q^*_{it,}, e^*_{it,}, z^*_{it})$ to maximise its total stream of profits:

$$\underset{q_{it},e_{it},z_{it}}{Max} \sum_{t=1} [p_{it}q_{it} - c_{it}(e_{it}, q_{it}) - v_{it}(z_{it})] - \sigma_t(e_{it} - A_{it})$$

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[6] We follow the language of Böhringer and Lange (2005) and refer to the least-cost outcome and corresponding conditions as socially optimal.

Thus, when a relative performance mechanism (2) is used to allocate pollution permits, firm i's objective function is:

$$\begin{aligned}\underset{q_{it},e_{it},z_{it}}{\text{Max}} \sum_{t=1} \Big(& [p_{it}q_{it} - c_{it}(e_{it}, q_{it}) - v_{it}(z_{it})] - \sigma_t e_{it} \\ & + \sigma_t[\lambda_{q,it}^{t-1} h(q_{i(t-1)}, q_{-i(t-1)}) + \lambda_{e,it}^{t-1} g(e_{i(t-1)}, e_{-i(t-1)}) \\ & + \lambda_{z,it}^{t-1} f(z_{i(t-1)}, z_{-i(t-1)})]] \Big)\end{aligned}$$

For each firm i and its rivals $-i = \{1, \ldots, i-1, i+1, \ldots, n\}$, the optimal choices are determined by the first order conditions as follows:

$$p_{it} + \sigma_{t+1}\lambda_{q,i(t+1)}^{t} h_i(q_{it}, q_{-it}) = \frac{\partial c}{\partial q_{it}} \tag{7}$$

$$\sigma_t - \sigma_{t+1}\lambda_{e,i(t+1)}^{t} g_i(e_{it}, e_{-it}) = -\frac{\partial c}{\partial e_{it}} \tag{8}$$

$$\sigma_{t+1}\lambda_{z,i(t+1)}^{t} f_i(z_{it}, z_{-it}) = \frac{dv}{dz_{it}} \tag{9}$$

Similarly to the absolute performance allocation mechanism of Böhringer and Lange (2005), when a firm's current output and emissions determine its *future* allocation of permits (and thus its profits), each firm will take this intertemporal effect into account.[7] Thus, relative to the socially optimal conditions (4) and (5), a mechanism which uses past performance in output and emissions will generate an intertemporal distortion of firms' incentives.

Importantly, this holds both for the absolute performance mechanism (1) but also for the relative performance mechanism (2). To see that, compare equations (7) to (4), as well as (8) to (5). Given that g_i and h_i are both positive, such a mechanism creates an implicit incentive to increase production and emissions beyond socially optimal levels.[8] Because the external factor z is outside the interests or jurisdiction of the social planner, it does not distort incentives when either a relative or absolute performance mechanism is used (9). For a given profile of other firms' actions, firm i chooses external factor z_{it}^*, optimally, so that the marginal cost of obtaining the factor equals the marginal future benefit obtained from the permit allocation. In summary, we have the following generalization of the intuition of Böhringer and Lange (2005):

Remark 2 When firms' permit allocations are at least partially determined by output and emissions, all permit allocation mechanisms of the general form (2) create distortionary incentives in the product and permit markets.

As we noted above, the absolute performance mechanism (1) is a special case of the relative performance mechanism (2). Thus, any mechanism that allocates permits based on historical output and/or emissions will distort firm's incentives to produce output and emissions optimally. Not only would the distortions occur when the adjustable cap grandfathering scheme (which is an APM) is used, but also any other scheme which utilizes firms' relative performance with respect to each other in output and/or emissions.

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[7] Moreover, the longer historical period over which firm's historical relative performance in output and emissions is taken into account by the scheme designers, the more important is the effect of each current choice on future allocations. Because we assume that only one previous period affects current allocation, we do not explicitly address this point here.

[8] Similarly, if either or both g_i and h_i are negative, there would be an incentive to decrease either production or emissions or both to a suboptimal level.

This problem, of increased output and emissions, is associated with the "ratchet effect"—using current performance to determine future targets and future initial allocations (Weitzman 1980; Freixas et al. 1985; Bergland et al. 2002). If a firm decided not to increase emissions (output) then their permit allocation would be "ratcheted" down, as their emissions (output) would be *relatively* lower than all other firms. If such a system was implemented, firms that actively lowered emissions (output) would be implicitly punished. Therefore, each firm has an incentive to increase its *relative* emissions (output) to stop their future permit allocation from being lowered. Thus, both RPMs and APMs will create distortions in the output and permits market when the criteria used to allocate permits is based on historical output and/or emissions information.

However, RPMs possess an additional important feature that APMs do not, namely, that a RPM results in a game among participating firms. This is because when each firm is evaluated relatively to other firms, firms' actions become interdependent. In the Nash equilibrium of this game, each firm chooses a profile $(q_{it}^*, e_{it}^*, z_{it}^*)$ according to Equats. 7–9 given the equilibrium beliefs about other firms' choices.

3 Socially optimal allocation mechanisms

In the last section we examined the inefficiencies caused by a generalised relative performance mechanism where the criteria used to allocate permits were based on historical output, emissions, and an external factor. In this section we will extend the argument of Böhringer and Lange (2005) against the use of historical outputs in generalized relative performance mechanisms. Moreover, when the system is open, so that the permit price is determined exogenously, the external factor should be the sole determinant of the firm's allocations. When the closed system is used, where the permit price can endogenously adjust to the aggregate supply of emissions, there is a possibility of using a linear performance scheme in emissions.

3.1 Open system

Recall that in a (small) open permit trading system, the aggregate supply of permits is determined jointly by the domestic allocation of permits and by the allocations of permits to all other foreign participants. Thus, the permit price is determined exogenously. Following Böhringer and Lange (2005), the market equilibrium outcome (8), can be transformed into the socially optimal outcome (5), by implementing the sufficient condition $\lambda_{e,i(t+1)}^t = 0$ for all i. Similarly, one can ensure that the individually optimal production level (7) corresponds to the socially optimal production level (4), by setting $\lambda_{q,i(t+1)}^t = 0$ for all i. This leads us to the following:

Proposition 1 *In a (small) open trading system, a socially optimal outcome can be achieved by allocating permits based on relative performance in an external factor z_{it} only. That is, an optimal mechanism involves setting $\lambda_{q,it}^{t-1} \equiv \lambda_{e,it}^{t-1} \equiv 0$, for all i, t in the allocation equation (2):*

$$A_{it} = \lambda_{z,it}^{t-1} f(z_{i(t-1)}, z_{-i(t-1)}) \tag{10}$$

That is, in open trading systems, to achieve the socially optimal outcome, a regulator should place a zero weight for historical output and emissions, and design a system that is based solely on firms' performance in an external factor, which is *not* related to the output and emissions choice variables. By restricting allocation to variables that do not affect the permit and product market, the firms' incentives remain undistorted. This occurs because using an external factor breaks the intertemporal link between the permit rent (output subsidy) and the incentive to alter the choice variables. Our results agree with the commonly held view that one can obtain a socially optimal outcome by distributing permits based on an external factor (Goulder et al. 1997; Cramton and Kerr 2002). Because an absolute performance mechanism is a special case of relative performance mechanism, the above result can be reduced to the result of Böhringer and Lange (2005, Proposition 2). That is, if the allocation function for each firm i is independent of rivals' actions, it is socially optimal to use historical external factor to allocate permits.

3.2 Closed system

We now consider an emissions program where the permit price is endogenously determined by the demand and supply in a closed permit market. This includes a conventional closed market system where the sole supply of permits originates from one regulator and where the permit price is determined by the aggregate level of emissions in the emissions program.

Comparing equations (4) with (7) and equations (5) with (8) one can obtain the following socially optimal conditions for output and emissions:

$$\lambda^t_{q,i(t+1)} h_i(q_{it}, q_{-it}) = 0 \tag{11}$$

$$\lambda^t_{e,i(t+1)} g_i(e_{it}, e_{-it}) = \lambda^t_{e,j(t+1)} g_j(e_{jt}, e_{-jt}) \tag{12}$$

$\forall i,\, j \neq i$ and $-i = \{1, \ldots, i-1, i+1, \ldots, n\}$.

Similar to the exogenous case, Eq. 11 suggests that to achieve social optimality, the marginal benefit to firm i from increasing output should be equal to zero. Thus, a sufficient condition for achieving social optimum involves the regulator placing a zero weight on each firm's historical output:

$$\lambda^t_{q,i(t+1)} = 0 \;\forall\, i, t \tag{13}$$

In contrast, Eq. 12 suggests that the marginal permit allocation should be equal across firms. This condition is difficult to ensure for all firms and for all functional forms of g. We could find only one set of sufficient conditions for social optimality in emissions which holds for *all* functional forms of g, which is similar to the sufficient conditions for output:

$$\lambda^t_{e,i(t+1)} = 0 \;\forall\, i, t \tag{14}$$

that is, the regulator should put a zero weight on each firm's historical emissions choices. These conditions not only ensure social optimality for any relative (and thus absolute) performance mechanism, but also requires less problem solving by the regulator and participating firms.

Instead, if a non-zero weight for historical emissions choices is selected then only a narrow class of RPMs satisfy the social optimality condition (12). In other words, only RPMs that create an identical marginal allocation can obtain a socially optimal outcome. An example of such mechanism is a yardstick mechanism that allocates permits to each firm based on how its historical emissions compare to the other firms' average historical emissions e.g. $g(e_{it}, e_{-it}) = \frac{1}{\lambda^t_{e,i(t+1)}} \left(\frac{\bar{E}_{t+1}}{n} + \alpha_t \left(e_{it} - \frac{\sum_{-i} e_{-it}}{n-1} \right) \right)$ for all i and t (as well as its "absolute" counterpart $g(e_{it}) = \frac{\alpha_t}{\lambda^t_{e,i(t+1)}} e_{it}$). Obviously, equating emissions "weights" $\lambda_{e,it}$ across firms makes the problem easier.

Thus, any RPM with identical marginal allocations across firms can socially optimally allocate permits based on firms' relative performances with respect to historical emissions and an external factor. Our results agree with Böhringer and Lange (2005) who were able to prove that the optimality result holds for a linear APM. Therefore, RPMs and APMs that have identical marginal allocations across firms can obtain a socially optimal outcome.

Thus, it follows from inspection of equations (11) and (12) that:

Proposition 2 *In closed trading system, a socially optimal outcome can be achieved by allocating permits based on relative performance in an external factor* z_{it} *as well as using suitably chosen relative performance schemes in historical emissions, and ignoring firms' historical outputs, i.e.* $\lambda_{q,it}^{t-1} \equiv 0$*, for all* i, t*. Thus, the allocation equation (2) becomes:*

$$A_{it} = \lambda_{e,it}^{t-1} g\left(e_{i(t-1)}, e_{-i(t-1)}\right) + \lambda_{z,it}^{t-1} f\left(z_{i(t-1)}, z_{-i(t-1)}\right) \tag{15}$$

where functions g are chosen such that condition (12) is satisfied.

Again, because absolute performance mechanisms are a special case of relative performance mechanism, the above result can be reduced to the result of Böhringer and Lange (2005, Proposition 1). Importantly, one can achieve social optimality in the closed system by using the same permit allocation scheme as in the open system:

Corollary 1 *In closed trading system, a socially optimal outcome can be achieved by allocating permits based on relative performance in an external factor* z_{it} *only, i.e.* $\lambda_{q,it}^{t-1} \equiv \lambda_{e,it}^{t-1} \equiv 0$*, for all* i, t*. Thus, the allocation equation (2) becomes:*

$$A_{it} = \lambda_{z,it}^{t-1} f(z_{i(t-1)}, z_{-i(t-1)}) \tag{16}$$

In other words, regardless of the nature trading system, one can implement the socially optimal permit allocation mechanism based on the relative performance in the external factor. Thus, the external factor plays a key role in optimal permit allocation scheme, calling for further issues to be considered by the allocation mechanism designer.

4 The external factor

We argued in the previous section that one can achieve social optimality in the product and target pollutant markets by using firms' relative performance with respect to an external factor to allocate target pollution permits. In this section, we will describe the external factor, possible mechanisms based on relative performance in this external factor, as well as the benefits of this approach.

4.1 Criteria for the choice of an external factor

We define the external factor as anything which has no direct relevance to the product and target pollutant emissions markets, and which is thus beyond the interest or jurisdiction of the regulator. Examples of possible external factor include population size in firm's locality, firm's socially responsible activities, firm's emissions of other pollutants, a random event such a lottery draw, and so on. Since the external factor can take a variety of forms, the regulator faces a choice of a suitable external factor. However, there is number of issues involved in the external factor choice.

Independence: To achieve social optimality, the "production" of the external factor has to be independent of firms' output and emissions of the target pollutant. Obviously, if the external factor is correlated with firm's output and/or emissions, firms' incentives will be distorted, and social optimality will not be achieved.

Ease of use: As the main objective of the regulator is to minimise the aggregate cost of the emissions program, a desirable external factor should be easy for the regulator to observe.

Reward of Effort: The regulator may choose the external factor to reward firms' efforts. When heterogeneity of firms' is substantial, the external factor may take a form of "intensity", or within-firm relative assessment—for example, proportion of firm's community activities relatively to the size of locality.

Equal Opportunity: The regulator may wish to ensure that all firms have equal opportunity to obtain permit allocations, and thus that the external factor can be produced by every participating firm. When the regulated firms believe they are being treated "fairly" in a sense of *equality of opportunity*, then the emissions program may have a higher chance of success.

Political Acceptability of the External Factor: The success of the allocation scheme may depend on political acceptability of the external factor by the regulated firms and regulator (as well as possibly by the general public).

Fair Allocations: As psychologists suggest, judgments of allocative fairness are affected by the *relative* merits of the recipients, thus suggesting that relative performance mechanisms may be perceived to be "fair" as long as the external factor is considered to be meritorious.[9]

Double Dividend: Of particular interest may be those external factors where the marginal benefits will typically exceed the marginal social costs. In other words, the external factor may be chosen so that it confers some additional benefit to the regulator other than the control of emissions. The regulator could define a costly z_{it} in such a way as it would prefer to observe higher (or lower) values.

As the last three of these issues may be of particular interest to mechanism designers, we will discuss them in detail.

4.2 A non-monetary external factor

As it was mentioned above, one of the possible reasons why regulators avoid allocating permits based on firms performance in external "monetary" factor—such as auction bids—is that it is politically unpopular. We thus suggest that perhaps a mechanism that is based on relative performance in a non-monetary external factor, may have a better political acceptability, in particular if they involve a possibility of social betterment. When a non-monetary external factor is chosen as a basis for permit allocations, there are no direct financial transfers. Firms instead are rewarded for the (non-monetary) actions they choose. This reasoning is very similar to the arguments that advocate a grandfathering system rather than an auction (Stavins 1998). However, as we showed above, grandfathering schemes involving historically updated outputs and emissions are distortive. Yet we suggest that a regulator can choose a non-monetary external factor that is agreeable for firms (or at least less controversial than other criteria).

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[9] Note further that, as Mellers (1982, 1986) demonstrated, the allocations (of salaries and taxes) judged to be "fair" by human subjects, depended on the *rank* of each recipient's merit in the merit distribution of the comparison group. In other words, a rank-based contest may be a good candidate for a "fair" relative performance mechanism.

There is a variety of possible non-monetary external factors. Charitable activities such as support of improvements in education and health infrastructure in the local community may be viable. This may prove to be a meritorious allocation process; firms are given the “right” to pollute based on the degree of their social responsibilities within a community. Another set of alternative external factors may be of particular relevance to environmental regulator. These may include reduction of an external “basket” of environmental pollutants or environmental indicators, for example noise pollution, or investments in energy efficiency. That is, firms could be allocated permits for the target pollutant based on their reduction of completely separate and independent pollutants.

However, we have to emphasize again that, to achieve social optimality in output and emissions markets, a potential non-monetary external factor z_{it} has to be independent from the firm’s emissions and output choices. Thus special care has to be taken in regulator’s choice of non-target pollutants as external factors as emissions of some pollutants can be correlated with emissions of the target pollutant, leading to potential inefficiencies in target pollutant emissions market.

4.3 The regulator’s secondary objective

As we mentioned above, there may exist external factors which are irrelevant to the product and target pollutant emissions market, but nevertheless the regulator may be interested in firms engaging in production of this external factor. If this is the case, the regulator may have a primary objective of controlling emissions at lowest social cost, as well as a secondary objective of increasing the aggregate amount of the external factor, or its net benefits.

One obvious example of multiple regulatory objectives is the “double dividend” argument for the use of auctions for permit allocations. As Cramton and Kerr (2002, p. 335) suggest, a permit auction can raise revenue whilst enforcing emissions control. This revenue can be used to reduce distortionary taxes in the economy (e.g. Parry 1997) or reduce the burden on auction participants through a revenue neutral auction (Hahn and Noll 1982; Hahn 1988).

Alternatively, there can be two (non-competing) regulators with different objectives. For example, the energy (electricity) industry may be required to participate in an emissions program whilst simultaneously being overseen by social/public policy regulator to promote firms’ anti-discriminatory personnel policies. The environmental policy regulator aims to control aggregate emissions at the lowest possible cost and is not concerned about the size or cost of the external factor in any way. The second regulator is possibly a social/public policy regulator who’s aim is to maximise the aggregate external factor produced by the participating firms. Another example of a double objective may be the regulation of two environmental targets, with one target being controlled by target pollutant permit market, and another target currently being unregulated—for example, emissions of CO_2 and a basket of other greenhouse gases. In any case, the secondary objective involves maximization of firms’ aggregate activities, expenditures, or efforts (for a similar objective see for example Moldovanu and Sela 2001).

As we argued above, one can achieve the socially optimal outcome in product and target pollutant markets by allocating permits using an external factor only. Therefore, using such an approach simultaneously achieves the primary target of socially optimal outcome in the two markets *and* a secondary target of maximisation of the aggregate external factor. Formally, let $\Delta \in (0, 1]$ represent the relative importance of the primary target (emissions control), and let us consider (small) open system (the argument for the closed system will be only slightly different). In this case, the “combined” regulatory objective is:

$$\underset{q_{it},e_{it},z_{it}}{Max} \sum_t \sum_{i=1}^{n} [\Delta(p_{it}q_{it} - c_{it}(e_{it}, q_{it})) - (1-\Delta)z_{it}] \text{ subject to } \sum_{i=1}^{n} e_{it} = \overline{E_t} \quad (17)$$

The first order conditions for emissions and output are identical to the socially optimal equations (4) and (5). Moreover, this combined regulatory objective allows for firms' individually optimal choice of the external factor. It follows from inspection of Eqs. 7–9 and 17 that:

Remark 3 If a RPM is used to allocate permits based on a costly external factor then a secondary (regulatory) target can be achieved whilst still achieving the socially optimal outcome with respect to the target pollutant.

In other words, by allocating target pollutant permits among firms based on their relative performance in a suitably chosen external factor, a regulator can "kill two birds with one stone" by achieving emission control at the lowest social cost in output and permit markets, and maximizing aggregate production of a socially beneficial external factor.

5 Conclusion

The purpose of this paper was to analyse the impact and optimality of implementing a generalised (dynamic) relative performance mechanism for the initial allocation of pollution permits. We extend the results of Böhringer and Lange (2005) to accommodate most of the existing dynamic initial allocation mechanisms, including grandfathering and auctions, as well as novel mechanisms, such as rank-order contests. We show that using firms' historical outputs for allocating permits is never optimal, while using firms' historical emissions is optimal only in closed trading systems and only for a narrow class of allocation mechanisms. Instead, it is possible to achieve social optimality by allocating permits based on an external factor which is independent of output and emissions. We outline sufficient conditions for a socially optimal relative performance mechanism and discuss the issues related to the choice of a suitable mechanism for initial allocation.

Due to these potential benefits, we advocate using a relative performance mechanism with an external factor for the dynamic allocation of permits. The numerous advantages of using a relative performance mechanism include its adaptability to changing economic, technological, and other conditions, as well as a possibility of transferring risk of possible systemic shocks (such as oil price changes) to the regulator. The advantage of using an external factor involves a possibility of achieving secondary regulatory goals, such as revenue maximization, social betterment or reduction in other environmental problems. Moreover, if the secondary goal is political agreeable, the permit trading scheme may also enjoy greater public acceptance.

Allocating permits for a target pollutant based on firms' relative performance in external factor increases firms' flexibility in meeting both regulatory goals by choosing the most cost–effective approach. That is, firm's cost–effective behaviour may depend on whether it has comparative advantage in abatement of the target pollutant, or in the production of the external factor. We think that such potential asymmetries among firms are important for the optimal design of permit allocation schemes, a topic of potential future research.

We also propose a novel allocation mechanism involving a rank-order contest, which is a generalization of an all-pay auction. In an external factor rank-order contest, firms are ranked in the order of their relative production of the external factor, and it is firm's rank, and not the level of the external factor, that determines firm's permit allocation. As the theoretical literature suggests, an allocation scheme with a suitably chosen "prize" structure is expected to achieve the secondary goal of maximizing aggregate production of the external factor—the goal which may not be achievable with other allocation mechanisms. In other words, by allocating target pollutant permits among firms using a rank-order contest in socially desirable activities (including abatement of unregulated greenhouse gases or even charitable activities) a regulator can "kill two birds with one stone" by achieving emission control at the lowest social cost in output and permit markets, and maximizing aggregate amount of a socially beneficial activity.

The external factor rank-order contest has some advantages over the presently used grandfathering scheme. While regulators seem to prefer grandfathering due to its political agreeability among the regulated firms, these schemes can be unpopular with the general public. In contrast, an external factor contest not only has a potential of achieving social optimality, but also it achieves a secondary regulatory goal (which may be perceived as achieving "fairness"), while the grandfathering scheme involving historical output and emissions achieves none of these two goals.

While we have presented arguments in favour of using RPMs based on an external factor in allocating permits, we nevertheless appreciate the potential practical difficulties involving in the choice of a suitable external factor. The success of the trading scheme rests on the regulator's ability to find an external factor that is desirable, politically agreeable, independent from output and emissions, and allows for an adequate comparison between firms. We nevertheless hope that the arguments presented in this paper may be of relevance to the environmental policy makers.

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