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Allocation of emission allowances: impacts on technology investments

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Abstract

Allocation of allowances in an emission trading system (ETS) may affect firms' investments in new technologies. In this paper we investigate how the incentives to invest depend on the regulator's expected response to these investments, assuming that allowances are allocated in proportion to output ("output-based allocation" - OBA). If the regulator has commited to the allocation factor, OBA tends to stimulate investments in cleaner technologies, due to higher output and increased price of allowances. On the other hand, if each firm expects the regulator to tighten the allocation factor after observing its clean technology investment, the firms' incentives to invest are moderated. If strong, this last negative effect may dominate the former positive effect on investments. Finally, if allowances are given only to a subset of firms or sectors, then other firms regulated by the ETS will increase their technology investments if and only if their total emission payments increase.

JEL classification: H21, Q58.

Keywords: Emissions trading; Allocation of allowances; Technology investments.

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1 Introduction

One of the most important questions with regards to emission trading systems (ETS) is how to allocate the emission quotas or allowances. Should allowances be auctioned, or allocated freely to emitting firms? Although economists often argue in favour of auctioning,[1] most ETSs to date, such as the SO_2 trading program in the U.S. and the EU ETS for greenhouse gas emissions, have mostly relied on free allocation. What is then the best allocation mechanism of free allowances? The answer to this question is not straightforward, and depends crucially on the purpose of allocation.

[1] One important argument is that auction revenues can be used to reduce distorting taxes (see, e.g., Goulder, 1995; Hoel, 1998; or Goulder et al., 1999).

In this paper we are concerned with the following question: How do different allocation mechanisms affect investments in clean technologies, i.e., technologies that reduce the emission intensities of firms regulated by the ETS. Our reference is an ETS based on either auctioning or lump sum allocation of allowances, such as (unconditional) grandfathering.[2] As shown by Montgomery (1972), such an ETS will be cost-effective if the emission trading market is not distorted by e.g. market power, incomplete participation or distortionary taxes. We compare this reference ETS with a system where allowances are allocated in proportion to firms' production levels. That is, all firms producing the same product receive the same number of allowances for every unit of production (we refer to this as an allocation factor). Such an allocation mechanism is often referred to as benchmarking or output-based allocation (OBA), see e.g. Edwards and Hutton (2001) and Fischer and Fox (2007), and has become increasingly popular in recent years (see below).

Why do we focus on investments in clean technologies? Technological improvements have been essential in handling environmental problems such as acid rain and depletion of the ozone layer, and may be even more important in dealing with the climate change problem. Reaching ambitious climate goals, such as the two degrees target agreed upon in the Copenhagen Accord in 2009,[3] will be immensely costly without substantial technologi-

[2]In the literature, the term grandfathering usually refers to a system where allowances are allocated in a lump sum manner to existing installations, based on emissions before the start of the system. We will follow that terminology, even though most current ETSs typically include conditions to grandfathered allocations (e.g., to continue operation).

[3]See http://unfccc.int/home/items/5262.php.

cal progress over the next few decades. Naturally, incentives to do R&D in climate-friendly technologies are to a large degree driven by the prospects for selling such technologies (see, e.g., Griliches, 1957; or Ruttan, 2001). Given that there are positive externalities from R&D that are not sufficiently internalized, the impacts on clean technology investments of different kinds of regulation should therefore be of interest. Gillingham and Sweeney (2012) point to several barriers specific to the implementation of low-carbon technologies. Moreover, in view of the increasing popularity of OBA (see below), it is important to evaluate its properties with regard to technology investment. This is not to say, however, that one allocation mechanism is better than another simply because it leads to more investments in clean technologies.[4]

Using a simple analytical model, we show that OBA tends to increase the incentives to invest in clean technologies under ex ante regulation, that is, if the allocation factor is not adjusted as a result of firms' investment levels. The intuition is that OBA, acting as an implicit output subsidy, increases production and hence the demand for emissions allowances. This leads to a higher price of allowances and increased incentives to invest in clean technologies.

Under ex post regulation, the regulator may respond to the firms' investments, noticing that their emission intensities have come down, by reducing

[4] Obviously, if technology externalities are already internalized, increased investments should not be considered positively. Moreover, technology externalities should at least in principle be handled with more targeted measures than OBA.

the number of allowances per unit of output. If so, the anticipated loss of free allowances may reduce the firms' incentives to invest in cleaner technologies. Obviously, this depends on whether the individual firm considers its own action to be of importance for the regulator's decision about the allocation factor, which is more likely if the allocation factor only applies to a small number of firms. If this so-called ratcheting effect (Downing and White, 1986) is sufficiently strong, it may outweigh the positive effects on investments, leading to less investments than under auctioning or grandfathering. In general, however, the effects on clean technology investments are ambiguous under ex post regulation. Due to the potential ratcheting effect, the time inconsistency problem detected by Kydland and Prescott (1977) may be relevant here.

We also examine the case with heterogeneous sectors, and consider how different types of sectors may be affected differently with respect to technology investments by OBA.

The development of the EU ETS,[5] which is by far the most important ETS in the world today, illustrates how OBA has gained momentum lately. The allocation mechanism in the EU ETS will shift substantially when entering the third phase (2013-2020).[6] In the first two phases (2005-2012), allocation was mainly based on historic emission levels, setting aside allocation reserves for new installations. In the third phase, allocation will as a general rule be

[5] http://ec.europa.eu/clima/policies/ets/index_en.htm.

[6] http://ec.europa.eu/clima/policies/ets/benchmarking/index_en.htm

based on production in the years 2007-2008 (power producers will in general no longer receive free allowances). For each product, the EU establishes an allocation factor, determining how many allowances installations will receive per unit produced. The allocation factors are based on emission intensities for the ten percent least emission-intensive installations producing this product in 2007-2008. New installations and installations that substantially change their capacity will receive special treatment, meaning that their allocation will be adjusted according to actual production capacity.

Because the benchmark parameters are fixed up to 2020, the firms need not be concerned about ratcheting in the third phase of the EU ETS. After 2020, however, it seems reasonable to expect the benchmark parameters to be adjusted in line with technological developments. The importance of the ratcheting effect would then depend on the number of firms in the EU ETS that produce the same product (and therefore have the same benchmark parameter). As discussed in Section 3, this number varies a lot across products in the EU ETS. Further, if the allocation factor continues to be determined based on the best available technologies, firms that utilize technology with relatively low emission intensities may have significant impact on future benchmark parameters. For this reason, those firms could be more reluctant to invest in best-available technologies.

In the cap-and-trade system passed by the U.S. House of Representatives in 2009,[7] OBA also plays an important role, especially for energy-intensive

[7] http://energycommerce.house.gov/Press_111/20090701/hr2454_house.pdf

and trade-exposed industries. However, this bill has not passed the Senate, and the future of U.S. cap-and-trade is currently highly uncertain.

Why is OBA getting this momentum? The rationale is clearly spelled out by the EU Commission. All sectors except the power sector have been divided into two groups according to their exposure to carbon leakage, i.e., increased emissions outside the EU as a result of emission reductions within the EU. Sectors that are highly exposed to leakage will receive more allowances than other sectors. OBA targets leakage through product markets by indirectly subsidizing output in exposed industries, reducing foreign firms' incentives to enhance their production and thus emissions.[8] Therefore, although OBA is not a cost-effective way of reducing emissions (cf. e.g. Böhringer and Lange, 2005a),[9] it may face less political opposition than e.g. auctioning and be a reasonable approach in a world of open economies and sub-global environmental policies (Fischer and Fox, 2007; Böhringer et al., 2010).

There exist some studies that examine the effects of OBA on, e.g., economic welfare, competitiveness and leakage. For instance, using a CGE model for the Danish economy, Jensen and Rasmussen (2000) show that OBA dampens sectoral adjustment, but causes larger welfare losses than lump-sum allocation. Haites (2003) finds that OBA in an ETS for Alberta (Canada) encourages greater production but lower firm profits, relative to

[8] Carbon leakage may also arise through international fossil fuel markets (Böhringer et al., 2010). OBA is not well suited to target this kind of leakage.

[9] OBA involves subsidizing domestic production in order to ameliorate loss of competitiveness caused by the ETS. This has a negative by-effect, as it causes marginal production costs to exceed the consumer price (see also equation 3 below)

lump-sum allocation. Fischer and Fox (2007) finds that OBA with sectoral distributions based on value added performs close to auctioning with revenue recycling in terms of overall economic indicators. On the other hand, OBA with sectoral distributions based on historical emissions is more effective at counteracting carbon leakage, but at higher welfare costs. Bernard et al. (2007) find that, in order to mitigate leakage, it is better to tax production in a competing unregulated sector than to rebate environmental levies to the regulated firms. If this is not possible, rebating is only justified when the goods of the sectors are close substitutes with similar emissions profiles.[10]

Output-based refunding of emissions taxes (OBR) is examined by Gersbach and Requate (2004). They show that a first-best self-financing OBR scheme exists if the marginal damage from pollution exceeds the marginal distortion in an imperfectly competitive output market with symmetric firms. Sterner and Isaksson (2006) use the Swedish NO_x charge as an example and find that incentives for abatement are approximately equal to that of an emissions tax, while output reduction is smaller. Fischer and Fox (2009) use an optimal tax framework to solve for the optimal OBR scheme, given leakage and distorting labor taxes. They find that the optimal rebate is larger for goods with high substitutability with unregulated goods, and for goods that are strong complements with employment. Fischer (2011) finds that OBR can alleviate output underprovision induced by imperfect competition, but

[10] Analytical studies of allocation of emission allowances are also found in Böhringer and Lange (2005b), Sterner and Muller (2008), Rosendahl (2008), Harstad and Eskeland (2010) and Rosendahl and Storrøsten (2011).

also reduce abatement incentives when market shares are significant as less emissions mean less tax payments and thus less refunds. Hagem et al. (2012) compare OBR with expenditure based refunding, providing also numerical illustrations based on the Norwegain NO_x fund.

There are, as far as we know, no previous studies that have analyzed how OBA affects firms' investments in clean technologies. The papers by Gersbach and Requate (2004) and Fischer (2011) take technology investments into account in their analysis of OBR and a fixed emission price. As will be clear in the present analysis, however, an endogenous allowance price plays a crucial role in determining firms' investment decisions under OBA, both in terms of the investment decisions of firms subject to OBA regulation, and in terms of sector spillovers (e.g., when only some sectors regulated by the ETS receive free allowances).[11] Moreover, Gersbach and Requate (2004) and Fischer (2011) focus on market power in the output market, while we focus on the regulator's potential ex-post adjustments of OBA-rates in response to firms' technology investments.

Finally, there exists a well developed literature on R&D and incentives to invest in abatement technology under emissions trading (with auctioned or grandfathered allowances) and other policy instruments, see, e.g., Denicolo (1999), Montero (2002), Requate and Unold (2003) and Jaffe (2012).

[11] For example, in the third phase of the EU ETS, sectors exposed to carbon leakage receive free allowances, whereas the power sector does not. The analysis in the present paper allows us to examine how technology investments in the power sector are affected by OBA to the other sectors in the EU ETS.

In Section 2 we set up and solve the analytical model. Section 3 provides an extension featuring heterogeneous sectors and Section 4 concludes.

2 Theoretical analysis

We consider an ETS that covers m sectors, denoted $j \in M = \{1, 2, ..., m\}$, each producing a homogenous product q^j to the world market with market price p^j. We assume that the area regulated by the ETS constitutes a sufficiently small part of the world market to leave the price on q exogenous.[12] In sector j there are n^j firms, denoted $i \in N^j = \{1, 2, ..., n^j\}$, which we (in this section) assume have identical cost functions and hence equal activity levels in equilibrium. Let q^j and e^j denote production and emissions for each firm in sector j, respectively, while k^j are technology parameters.[13] The production technology for firms in sector j is summarized by the cost function $c^j(q^j, k^j e^j)$, with $c_1^j > 0$; $c_2^j \leq 0$; c_{11}^j, $c_{22}^j, -c_{12}^j \geq 0$; $c_{11}^j c_{22}^j - (c_{12}^j)^2 > 0$; and $c_1^j(0,0) < p^j$.[14] Except for the presence of the technology parameter k^j, these are standard assumptions (cf., e.g., Böhringer and Lange, 2005b). We notice that a higher k^j goes along with lower emissions for a given combination of production and cost. In other words: Let $e^j(q^j, k^j)$ denote unabated emissions, i.e., the level of emissions that minimizes costs for given production

[12] Our results easily generalize to the case with an endogenous price and price-taking firms, e.g., $p^j(Q^j)$, with $Q^j = n^j q^j$ and derivative $p_1^j \leq 0$.

[13] We omit the firm specific i, because firms are identical within each sector.

[14] We use the shorthand notation f_x to denote the derivative of the function $f(\cdot)$ with respect to its x'th argument.

and technology levels. Then a higher k^j implies that $e^j(q^j, k^j)$ is reduced for any level of q^j. Moreover, marginal costs of abatement are reduced for any combination of q^j and e^j when k^j is increased.

We further assume that both the product markets and the ETS market are competitive.[15] The product markets may consist of firms outside the ETS in addition to the firms within the ETS. This could be the case if the ETS is a subglobal trading system that (also) regulates trade-exposed industries (the EU ETS is a prominent example).

The regulator commits to a binding aggregate emissions cap E. The emissions allowances are partly allocated for free to individual firms proportional to their production level (i.e., OBA), and partly auctioned. Let γ^j denote the allocation factor, i.e., the number of allowances received per unit output, and g the number of auctioned allowances. We then have the following equilibrium condition:

$$\sum_{j \in M} n^j e^j = E = \sum_{j \in M} \gamma^j n^j q^j + g \tag{1}$$

These two equations state that both aggregate emissions (LHS) and the total amount of allowances (RHS) must equal the emissions cap E. The first condition puts a price σ on emissions allowances. As seen below, however, σ also depends on how the allowances are allocated. The second condition shows that the regulator has a certain freedom with respect to allocation of

[15] Results by Joskow et al. (1998) and Convery and Redmond (2007) indicate respectively that the US market for SO_2 emissions and the EU ETS are competitive.

allowances, through the parameters γ^j and g. Below we will consider the effects of changing γ^j, while at the same time keeping E unchanged. We then assume that the regulator adjusts g so that (1) is always fulfilled.[16]

The model is divided into two stages: First, in the beginning of stage 1, the regulator announces the emissions cap and the allocation factors for stage 2. Based on these announcements, all firms choose their technology levels as captured by k^j in stage 1. Technology investment costs are determined by the functions $\kappa(k^j)$, with $\kappa_1 > 0$ and $\kappa_{11} \geq 0$.

We consider two possible game profiles in stage 2: The ex ante regulation game and the ex post regulation game. Under ex ante regulation, the regulator credibly commits in the beginning of stage 1 to some fixed allocation factors γ^j for stage 2. We then derive the firms' profits and activity levels in stage 2 conditioned on their investments in stage 1 as well as the fixed emissions cap and the allocation factors.

In contrast, under ex post regulation the regulator does not commit to any allocation factors until after stage 1. Instead, the regulator announces at the start of stage 1 how the allocation factors in stage 2 will be based on firms' observed technology choices in stage 1. An alternative interpretation is that the regulator is not able to commit to the announced allocation factors, and the firms correctly expect how the factors will be updated, based on the

[16] As the RHS of (1) depends on firms' current output, it may be difficult for the regulator to determine a set of parameters that ensures that the second equation is fulfilled. Thus, the regulator may alternatively allocate allowances in proportion to firms' output in the previous year. Such an adjustment would not affect our qualitative results.

firms' investments, before the start of stage 2. We notice that there may be an element of imperfect information in the ex post game, e.g., with respect to the regulator's knowledge about firms' technology choices.

We solve the model backwards to find the subgame perfect equilibrium. Note that the allocation factors are given when the firms choose their production and emissions levels in stage 2. Hence, the analyses of ex ante regulation and ex post regulation are merged in Subsection 2.1 below.

2.1 The production and abatement decisions

In stage 2 firm $i \in N^j$ in sector $j \in M$ maximizes profits with respect to production q^j and emissions e^j, given technology k^j:

$$\pi^j \equiv \max_{q^j, e^j} \left[p^j q^j - c^j(q^j, k^j e^j) - \sigma \cdot (e^j - \gamma^j q^j) \right] \tag{2}$$

Note that prices p^j and σ are exogenous to the competitive firm, which is also the case for the allocation factor γ^j in this stage. The strict convexity of the cost function ensures that π^j is strictly concave in q^j and e^j. The corresponding first order conditions are:

$$p^j + \sigma\gamma^j = c_1^j(q^j, k^j e^j) \tag{3}$$

$$\sigma = -k^j c_2^j(q^j, k^j e^j) \tag{4}$$

which are equal across all firms within sector j for a given technology parameter k^j. Here, q^j and e^j refer to the optimal production and emissions of firm $i \in N^j$. We observe that marginal costs of production are equal across all firms within a sector as long as the sector-specific allocation factor is identical for all these firms. This would remain true without the assumption about identical firms within sectors. By totally differentiating the first order conditions (3) and (4) with respect to the allowance price σ and the allocation factor γ^j, we get (see the appendix):

$$\begin{pmatrix} \frac{dq^j}{d\gamma^j} & \frac{dq^j}{d\sigma} \\ \frac{de^j}{d\gamma^j} & \frac{de^j}{d\sigma} \end{pmatrix} = \frac{1}{X^j} \begin{pmatrix} \left(k^j\right)^2 \sigma c_{22}^j + \left(\left(k^j\right)^2 \gamma^j c_{22}^j + k^j c_{12}^j\right) \frac{d\sigma}{d\gamma^j} & \left(k^j\right)^2 \gamma^j c_{22}^j + k^j c_{12}^j \\ -\sigma k^j c_{12}^j - \left(\gamma^j k^j c_{12}^j + c_{11}^j\right) \frac{d\sigma}{d\gamma^j} & -\gamma^j k^j c_{12}^j - c_{11}^j \end{pmatrix}, \tag{5}$$

where $X^j = (k^j)^2 \left[c_{11}^j c_{22}^j - (c_{12}^j)^2\right] > 0$. The matrix on the LHS is the substitution matrix. It describes how the firms' control variables q^j and e^j are affected by the allocation factor γ^j and the allowance price σ.

We are now ready to state the following lemma, which holds for any given technology k^j as long as $\frac{de^j}{d\sigma} < 0$:[17]

Lemma 1 *Increasing the allocation factor γ^j in sector $j \in M$ leads to (for fixed levels of k^j):*

i) Higher price of allowances ($\frac{d\sigma}{d\gamma^j} > 0$)

[17] This assumption is fullfilled unless γ^j is too large (cf. 5). Moreover, if there exists an equilibrium where emissions increase when the price of emissions increases, it can be shown that there also exists an equilibrium with lower production such that emissions decrease when the price increases.

ii) Increased emissions and production in sector j *(*$\frac{de^j}{d\gamma^j} > 0$ *and* $\frac{dq^j}{d\gamma^j} > 0$*)*

iii) Decreased emissions and production in other sectors $l \neq j$ *(*$\frac{de^l}{d\gamma^j} < 0$ *and* $\frac{dq^l}{d\gamma^j} < 0$*,* $\forall l \in M \setminus \{j\}$*)*

Proof. See the appendix. ■

Intuitively, increased allocation of allowances to sector j works as a subsidy to production and stimulates output from this sector. Because of the binding cap on aggregate emissions, the firms in sector j must then either decrease their emissions intensity or increase their share of the overall emissions cap. Under our assumption of differentiable functional forms, it is cost effective to do both. Hence, the allowance price is bid up, which leads to lower emissions and production from other sectors $l \neq j$.

In particular, we notice from Lemma 1 that when introducing OBA, i.e., increasing γ^j from zero, the price of allowances will increase. This holds whether OBA is introduced for one or more sectors. If OBA is introduced for all sectors simultaneously, the effects on emissions in one particular sector is ambiguous, but we know that total emissions will have to remain unchanged. The effects on production in a single sector is also ambiguous, but production must rise in sectors with unchanged or higher emissions (cf. equation 4). Therefore, production will increase in all sectors if the allocation factors are increased in such a way that sector emissions remain unchanged. Finally, we notice from the lemma that there is a burden-shifting from sectors with OBA to the other sectors regulated by the ETS.

2.2 The investment decision

At the beginning of stage 1, firms maximize profits with respect to technology k^j, given their knowledge of the equilibria in stage 2:

$$\Pi^j \equiv \max_{k^j} \left[\pi^j - \kappa(k^j)\right] \tag{6}$$

with π^j defined by equation (2). As the firms foresee the tightening of the allocation factor under ex post regulation, and know that the regulator's commitment is credible under ex ante regulation, the first order conditions to this maximization problem differ under the two regulatory regimes. We analyze ex ante and ex post regulation in subsections 2.2.1 and 2.2.2, respectively.

2.2.1 Ex ante regulation

Under ex ante regulation, the first order condition to the maximization problem (6) is given by (see the appendix):

$$\kappa_1(k^j) = \frac{\sigma e^j}{k^j} \tag{7}$$

We are now ready to examine the effects on technology level k^j of increasing the allocation factor γ^j. From Lemma 1 we know that increasing γ^j in one or more sectors will increase the allowance price σ. Thus, for a given level of k^j, the RHS of equation (7) will increase for sectors with unchanged or higher emissions. As $\kappa_{11}(k^j) \geq 0$, and the RHS is decreasing in k^j, it follows that the technology parameter k^j will increase for these sectors. In particular, if the allocation factor is increased for a single sector, it follows from Lemma 1 that it is optimal for firms in this sector to increase their technology investments. For sectors with reduced emissions, we see that the effects on technology investments depend on whether or not the emissions reduction is bigger than the allowance price increase. Finally, if the allocation factors are increased so as to keep sectoral emissions unchanged, the increased allowance price will induce more technology investment in all sectors.

We summarize our results in the following proposition:

Proposition 1 *Assume interior solutions, perfect competition in all markets, and ex ante regulation. We then have:*

i) Increasing the allocation factor in sector $j \in M$ leads to higher technology investments in this sector. Technology investments in sector $l \in M \setminus \{j\}$ increase if and only if σe^l increases.

ii) Increasing the allocation factor in all sectors, so that sectoral emissions remain unchanged, leads to higher technology investments in all sectors.

Proof. The proposition follows from the discussion above. ■

In Section 3, we introduce heterogeneity between sectors and firms in order to investigate how the ambiguity in part (i) may be resolved, and how the results then depend on the functional forms.

Note in particular that the proposition is relevant when going from an ETS with auctioning or lump sum (grandfathered) allocation to OBA. If the regulator has credibly committed to a fixed allocation factor, OBA will tend to induce employment of less emission-intensive technologies than auctioning or grandfathered allowances.[18]

2.2.2 Ex post regulation

Under ex post regulation, we let the allocation factor in sector j be a function of the technology levels chosen by the firms in stage 1. To simplify the exposition, we assume the following specification: $\gamma^j = \varsigma^j f(\frac{1}{n^j}\sum_{i\in N^j} k^i)$, with $\frac{df}{dk^i} < 0$. That is, the endogenous allocation factor is assumed to be a function of the average technology levels among all firms.[19] We return to the implications of alternative assumptions below.

The allocation factor now consists of two elements, a constant ς^j and a function $f(\cdot)$. The interpretation here is that a higher sector specific constant $\varsigma^j > 0$, henceforth referred to as the "allocation parameter", implies more free allowances per unit of production. It is straightforward to show that the results derived for the allocation factor γ^j in Lemma 1 also applies to the allocation parameter ς^j. Further, $f(\cdot)$ captures the regulator's response to the firms' technology investments, which we may refer to as the ratcheting effect (see, e.g., Downing and White, 1986). A higher k^j reduces the firms' (unabated) emissions per unit of production. Thus, under ex post regulation we assume that the regulator will choose a lower allocation factor the higher

[18] This conclusion could change if revenues from auctioning are used to subsidize less emission-intensive technologies, either directly or through R&D support.

[19] Note that all the qualitative results carry over with more general assumptions about the function $f(\cdot)$, as long as $\frac{df}{dk^i} < 0$.

k^j is (e.g., because less free allowances are perceived necessary to avoid loss in competitiveness).

The first order condition to the maximization problem (6) is then given by (see the appendix):

$$\kappa_1(k^j) = \sigma \frac{e^j}{k^j} + \sigma q^j \frac{\varsigma^j}{n^j} \frac{df}{dk^j} \tag{8}$$

We will now discuss the effects on k^j of increasing the allocation parameter ς^j. The first term on the RHS corresponds to the RHS of equation (7) and, hence, tends to increase the firms' investments as the regulator increases ς^j. The second term on the RHS of (8) is the ratcheting effect. We first notice that this is negative whenever $\varsigma^j > 0$. Thus, it follows directly that the second term decreases when OBA is first introduced (i.e., ς^j is increased from zero). Furthermore, we know from Lemma 1 that both σ and q^j increase in ς^j. Thus, the second term of the RHS will become more negative as ς^j is increased, for a given k^j. Consequently, the ratcheting effect will moderate the incentives to invest in cleaner technologies.[20]

It follows that investments under ex post regulation will be lower than under ex ante regulation, given that the ex post allocation factor does not exceed the ex ante factor.[21] Intuitively, the firms' incentives to implement

[20] The change in the RHS also depends on the change in $\frac{df}{dk^j}$. If $f(\cdot)$ is very convex, we cannot rule out the possibility that k^j increases even if the RHS is negative for a given k^j. However, this seems rather unlikely, and is irrelevant if the initial level of ς^j is zero.

[21] Assume that k^j is identical under ex ante and ex post regulation. As γ^j is at least as high under ex ante as under ex post, the first term in the RHS of (8) is also at least as high under ex ante. As the second term is zero under ex ante and negative under ex

advanced technology is reduced if the investment triggers a lower allocation factor, and thereby less free allowances in stage 2.

Since an increase in the allocation parameter ς^j has one positive and one negative effect on the firms' investment level k^j, the total effect of a larger ς^j is in general ambiguous. On the one hand, if the allocation factor is (perceived to be) approximately insensitive to the firms' choice of technology (i.e., $\frac{df}{dk^i} \approx 0$), we obtain the same conclusions as in Proposition 1. One the other hand, if $\frac{df}{dk^i}$ is sufficiently big, the RHS will decrease when ς^j is increased (e.g., from zero). Related to this, we observe from equation (8) that the strength of the ratcheting effect declines in the number of firms n^j. Note that this observation follows from our formulation of the allocation factor $\gamma^j = \varsigma^j f(\frac{1}{n^j}\sum_{i \in N^j} k^i)$ under ex post regulation, and may not hold under alternative specifications.

We sum up our findings in the following proposition:

Proposition 2 *Assume interior solutions, perfect competition in all markets, and ex post regulation. We then have the following effects of increasing ς^j, i.e., increasing the amount of free allowances per unit of production in sector $j \in M$:*

i) Technology investments in any sector $l \in M$ may either increase or decrease (i.e., $\frac{dk^l}{d\varsigma^j} \lesseqgtr 0$). If the regulator's response $f(\cdot)$ is sufficiently (in)sensitive to a single firm's investments, investments in sector j will decrease (in-

post, the RHS must be highest under ex ante. This is inconsistent with identical k^j, which implies identical LHS. A similar argument can be made with k^j highest under ex post.

crease).

ii) Technology investments in sector j will be lower than under ex ante regulation, given that the ex post allocation factor does not exceed the ex ante allocation factor.

Proof. The proposition follows from the discussion above. ■

From (8) we further notice that if both the emissions price and the emissions level in sector j are quite insensitive to the allocation factor, technology investments will tend to decline under ex post regulation if $\frac{df}{dk^i} << 0$. This could be the case if sector j's emissions constitute a small share of the overall cap, and if emissions and output levels are not too tightly connected. We state this in the following corollary:

Corollary 1 *Technology investments in sector $j \in M$ will decrease as a response to a higher ς^j if $d(\sigma e^j) \approx 0$ and $\frac{df}{dk^i} << 0$.*

Proof. The corollary follows from the discussion above. ■

The intuition behind the Proposition is straightforward. First, more free allowances per unit produced increases the firms' production. Therefore, for any given emissions cap and technology, the firms operate at higher costs because their emissions intensity must be lower. The equilibrium allowance price increases. These results follow from Lemma 1. The higher allowance price then increases the firms' incentives to invest in advanced abatement technology, as stated in Proposition 1. Second, the regulator may adjust the allocation factor γ^j in response to this investment. If so, investment in technology will involve less free allowances. This ratcheting effect imposes an additional cost of investment that reduces the firms' incentives to invest in technology.

The impacts of ratcheting obviously depend on how the regulator updates the allocation factor. For instance, in the EU ETS the allocation factor depends on the average of the 10% most efficient installations. With this rule, the ratcheting effect only concerns firms that consider being in the front with respect to low emission intensity. For firms considering to invest in more standard technologies, the ratcheting effect is not relevant. Hence, a consequence of such a rule might be less differences in emissions intensities among installations.

Should firms regulated by the EU ETS be concerned about the ratcheting effect, or is ex ante regulation a better description of this system? During the third phase, from 2013 to 2020, there will be no ratcheting – the benchmark parameters are fixed up to 2020. After 2020, however, the answer to this question is not clear, but it seems reasonable to believe that the benchmark parameters may be adjusted in line with technological developments. Should individual firms be concerned about their own influence on future benchmark parameters? If we look at the number of firms that produce the same product, having its own benchmark parameter, the number varies a lot. For some products, the number is so large that an individual firm has limited influence unless it is really in the front and the allocation factor continues to be determined based on best available technologies. For other products, the number of firms is well below ten, and thus individual firms may have significant impact on future benchmark parameters.

The chemical industry may be an illustrative example. This sector produces several products with separate benchmark parameters. On the one hand, there were 115 plants covered by the EU ETS in 2006 that produced nitric acid, accounting for 41 Mt CO_2-equivalents.[22] Even though several of these plants are operated by the same company, each company's influence on the allocation factor is likely to be modest unless it is in the front. On the other hand, there were only five plants owned by four companies that produced adipic acid in the EU ETS in 2006, and 16 plants owned by five companies that produced sodium carbonate. Together, these plants accounted for 23 Mt CO_2-equivalents. These firms may expect investment in abatement equipment today to induce less free allowances per unit produced after 2020.

There are also other elements, not captured by the model, that can affect the importance of the ratcheting effect. For example, if there is a time delay before the regulator updates the allocation factor, the ratcheting effect would decrease in this delay and the firms' discount rate. Another important aspect is information; i.e., the regulator needs information about the firms' emission intensities in order to update the allocation factor.

[22] Facts on the chemical sector in the EU ETS in this paragraph are taken from Ecofys (2009). See also http://ec.europa.eu/clima/policies/ets/index_en.htm for more details.

2.3 Numerical illustration

In this subsection we briefly illustrate the results above within a simple numerical model. We consider n identical, competitive firms with cost function $c(q, ke) = \frac{\alpha}{2}q^2 + \frac{\delta}{2}(\beta q - ke)^2$,[23] where β/k is the emissions intensity prior to any regulation (BaU).[24] Further, we assume a quadratic investment cost function: $\kappa(k) = \frac{\widehat{\kappa}}{2}\left(k - k^{BaU}\right)^2$. We can easily normalize $p = q^{BaU} = e^{BaU} = k^{BaU} = 1$, so that $\alpha = \beta = 1$. In Appendix B we explain how we calibrate δ and $\widehat{\kappa}$, and solve the model given these functional forms. We consider three policy scenarios: no OBA ($\varsigma = 0$, i.e., only auctioning), OBA ex ante ($\varsigma > 0$ and constant), and OBA ex post. Under ex post regulation we let the allocation factor be proportional to the geometric mean of all firms' emission intensities β/k, i.e.:[25]

$$\gamma = \varsigma \left(\prod_{i \in N^j} k^i \right)^{-\frac{1}{n}}$$

Note that the number of free allowances per unit of production is reduced under ex post compared to ex ante policy, as $k > 1$ when firms invest in new technologies. For instance, if k is doubled, the emissions intensity is halved, and thus the allocation per unit output is halved. Moreover, the degree of ratcheting (as seen for the individual firm) decreases in the number of firms

[23] As explained before, firms trade in a world market at a fixed output price. Thus, even if n is low, we can disregard market power in the product market. We also disregard market power in the ETS. This can formally be done by assuming m sectors with identical cost structure and allocation rules, and m sufficiently large. To simplify derivations, however, we only consider one sector here - the results are the same.

[24] We omit firm subscripts i in this section.

[25] The geometric mean allows simpler calculations than the arithmetic mean.

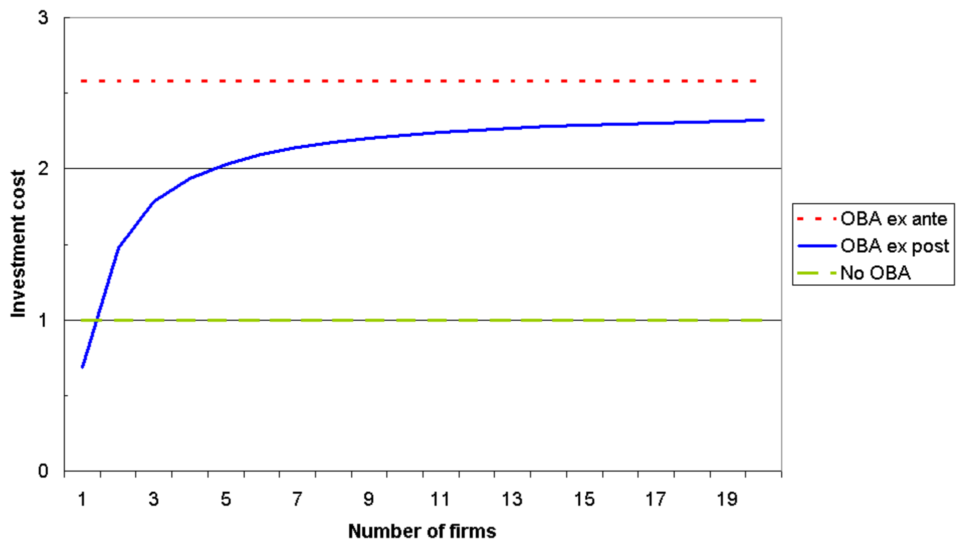

Figure 1: Investment in clean technology. Numerical example

n. We consider a 20% emissions reduction (i.e. $E = 0.8n$) and $\varsigma = 0.5$, i.e., firms receive 50% of the allowances they need under BaU.

Figure 1 shows investment costs ($\kappa(k)$) under the three policy scenarios. For ease of comparison we have normalized investment costs under no OBA to 1 .

The figure illustrates that technology investments are highest under ex ante regulation, both compared to ex post regulation and no OBA.[26] This is in accordance with Proposition 1 and Proposition 2 (ii). Moreover, technology investments are higher under ex post regulation than under no OBA

[26]Investment costs under ex post regulation have a horizontal asymptote at $\kappa(k) = 2.4$, while $\kappa(k) = 2.6$ under ex ante regulation. Even though each firm does not see any ratcheting effect from its own investment when n is sufficiently large, γ declines under ex post, reducing optimal level of output and hence the optimal level of k.

except when $n = 1$, in which case the ratcheting effect is very strong. This illustrates the ambiguity result in Proposition 2 (i).

The numerical model also suggests that ratcheting has significant effects on production and the allowance price. In particular, the ability of OBA to spur production is considerably reduced when the ratcheting effect is strong, see Figure 2 in Appendix B.

3 Heterogeneity between sectors and firms

So far we have examined the effects of increasing the allocation factor in a single sector with identical firms, or increasing the allocation factors in all sectors so that sector emissions remain unchanged. In this section we investigate how cost structures and demand features affect the impacts of OBA for different types of sectors or firms.

To simplify the analysis we consider the case with two sectors $M = \{j, l\}$, with cost functions $c^j(q^j, k^j e^j)$ and $c^l(q^l, k^l e^l)$ and identical firms within each sector. In order to focus on the effects of heterogeneous cost structures, we assume that the two sectors face the same allocation factor, i.e., $\gamma = \gamma^j = \gamma^l$. Note that we can also interpret this as two types of firms within one sector. Observe that the binding emissions cap implies $n^j de^j + n^l de^l = 0$. Thus, in equilibrium emissions from one sector must decrease if the other sector's emissions increase its emissions, and vice versa. We assume that increasing

γ induces a change in the sectors' emissions (i.e., $de^j, de^l \neq 0$).[27]

We first examine which sector will increase its emissions, and consider equation (5), which must hold for both sectors (with γ^j replaced by γ). We know from the second order condition that the denominator X^j in equation (5) is positive. Thus, the terms inside the parenthesis determine the signs of the four elements in the matrix. Note that γ, σ and $\frac{d\sigma}{d\gamma}$ are equal across the two sectors. We see that $\frac{de^j}{d\gamma}$ tends to decrease in c_{11} and increase in the absolute value of c_{12}. More formally, let $\frac{d\sigma}{d\gamma}\left(c_{11}^j - c_{11}^l\right) < \sigma\left(k^l c_{12}^l - k^j c_{12}^j\right)$. Then $de^j > 0$ and $de^l < 0$.

In words, sectors where unit costs increase rapidly when output expands are less likely to increase emissions compared to sectors where unit costs are relatively fixed. Moreover, sectors where emissions are difficult to reduce without reducing output are more likely to increase emissions compared to sectors where the emissions intensity can be reduced without substantial costs. The explanation for these observations is that a higher allocation factor gives incentives to expand production. Sectors with relatively fixed unit costs will then want to expand more than sectors where unit costs increase fast. Moreover, as the price of allowances goes up (cf. Lemma 1), firms would like to reduce their emissions intensities. This is particularly costly if emissions are tightly connected to output, and hence emissions may increase in line

[27] If $de^j = de^l = 0$ firms in both sectors would increase their investments under ex-ante regulation due to the increase in allowance price (cf. equation 7), while we have ambiguity under ex post regulation (cf. equation 8) (as usual, "d" refers to a small change so that, e.g., "de^l" denotes a small change in e^l).

with higher output.

From the first order condition (5) it follows that production will increase in sector j if $de^j > 0$. The effect on production in sector l is ambiguous, and depends on the cost functions of both sectors, cf. (5) (the effect on the allowance price depends on both sector's cost functions). If emissions are reduced mainly because the sector easily can reduce emissions as a response to higher allowance price (c_{12}^l close to zero), output will most likely expand, cf. equation (5). In this case, output might in fact increase even more than in sector j. On the other hand, if emissions are reduced due to high costs of expanding production, output may instead drop when the allowance price goes up, given that the emissions intensity is costly to reduce.[28]

These results imply together with (7) that $\frac{dk^j}{d\gamma} > 0$ under ex ante regulation. Under ex post regulation the effect on k is ambiguous. Thus, the results for sector j are qualitatively the same as in Propositions 1-2. The sign of $\frac{dk^l}{d\gamma}$ is ambiguous under both ex ante and ex post regulation, cf. (7).

To examine the effect on total technology investments under ex ante regulation, we rearrange (7) to $k^j\kappa_1(k^j) = \sigma e^j$, which holds for both sectors. Adding up the equations for the two sectors, we get $k^l\kappa_1(k^l) + k^j\kappa_1(k^j) = \sigma\left(e^l + e^j\right)$. If the technology investment cost functions $\kappa(k)$ are linear, with identical unit costs, differentiation of this equation yields $\left(\frac{dk^l}{d\gamma} + \frac{dk^j}{d\gamma}\right)\kappa_1 = \frac{d\sigma}{d\gamma}\left(e^l + e^j\right) > 0$. Thus, total investment costs and the aggregate investment

[28] Assume for instance that both sectors have Leontief production functions, so that emissions are a fixed proportion of output (for a given k). Then the sign of dq must equal the sign of de, which has to be negative for one of the sectors.

level $k^j + k^l$ increase in the number of free allowances per unit of production. The reason is that OBA increases the allowance price, which again induces stronger incentives to invest in clean technology. In general, however, whether aggregate investments increase or decrease depends on the investment cost functions $\kappa(k)$ and the levels of k^j and k^l before the change in the allocation factor.

We summarize in the following proposition:

Proposition 3 *Assume ex ante regulation and two sectors* $M = \{j, l\}$, *with* $\frac{d\sigma}{d\gamma}\left(c_{11}^j - c_{11}^l\right) < \sigma\left(k^l c_{12}^l - k^j c_{12}^j\right)$ *and* $\gamma = \gamma^j = \gamma^l$. *Then we have* $\frac{dk^j}{d\gamma} > 0$ *and* $\frac{dk^l}{d\gamma} \lesseqgtr 0$. *Moreover, the aggregate investment level* $k^j + k^l$ *increases in the allocation factor* γ *if* $\kappa_{11}(k) = 0$.

Proof. The proposition follows from the discussion above. ■

Note that a similar result can be established with respect to the steepness of the inverse demand function in the case of an endogenous product price. It is straightforward to show that $\frac{dq}{d\gamma}$ and $\frac{de}{d\gamma}$ will have the following additional terms in (5): $\left(k^j\right)^2 c_{22}^j dp_j$ and $-k^j c_{12}^j dp_j$. Assume that the two sectors are identical in all respects but the demand curve. We then see that if sector j has a steeper inverse demand curve than sector l, there will be reduced emissions in sector j and increased emissions in sector l if the regulator increases the allocation facor γ. Hence, $\frac{dk^j}{d\gamma} > 0$ and $\frac{dk^l}{d\gamma} \lesseqgtr 0$.

4 Conclusion

Allocation of emission allowances may affect firms' incentives to invest in clean technologies. In this paper we have shown that output-based allocation (OBA) tends to stimulate such investments, given that individual firms do not expect that the regulator will reduce the amount of free allowances granted by the allocation factor as a consequence of their investments. The explanation is that OBA creates an implicit subsidy to the firms' output, which increases production, leads to a higher price of allowances, and thus increases the incentives to invest in clean technologies. On the other hand, if the firms expect the regulator to tighten the allocation factor after observing their clean technology investment, the firms' incentives to invest are moderated. If strong, this last effect may outweigh the enhanced investment incentives induced by increased output and higher allowance price. For sectors regulated by the ETS, but with no or unchanged allocation factor, the effects on investments are ambiguous. The reason is that a higher allowance price and lower emissions (due to the higher price) pull in opposite directions with respect to investment incentives. This is especially relevant for the power industry in the EU, which no longer will receive allowances in the upcoming phase of the EU ETS.

The potential ratcheting effect suggests that the argument for policy rules rather than discretion, as pointed out by Kydland and Prescott (1977), may be relevant for OBA. That is, it may be optimal for the regulator to commit to an allocation factor for an appropriate length of time, even if new information on firms' technologies is thereby ignored. We notice, however, that such a policy tends to be time inconsistent (cf. Kydland and Prescott, 1977).

Our analysis featured some assumptions that should be commented on. First, we assumed that product and factor markets are independent across sectors participating in the ETS. Without this assumption, an increase in the allocation factor would have additional spillover effects, dependent on e.g. whether the products are complements or substitutes. Second, the main part of our analysis assumed identical firms within each sector. Without this assumption, our results would be firm dependent and less clear-cut. In general, however, we find that more free allowances per unit of production under ex ante regulation will increase the technology investments of those firms that do not decrease their emissions in the new equilibrium. Finally, we have examined the special cases of respectively no and immediate tightening of the allocation factor in response to firms' investments. It may be more realistic to assume that there is a delayed ratcheting, i.e., that the regulator responds to the firms' investments in a subsequent period. For example, the EU ETS will not revisit its allocation factors before 2020, but may possibly update the allocation factors in the fourth phase (post-2020) based on firms' technologies in the third phase (pre-2020). Our model is easily extended to feature such a delay, which can be seen as a combination of the ex ante and the ex post analysis above. Naturally, the effect of more free allowances per unit of production would then depend on the time delay before the regulatory response, and the corresponding discount factor.

A Appendix

Derivation of equation (5): Differentiating the first order conditions (3) and (4) wrt. γ we get (omitting heading j):

$$\begin{aligned} \sigma + \gamma d\sigma &= c_{11}\frac{dq}{d\gamma} + kc_{12}\frac{de}{d\gamma} \\ d\sigma &= -kc_{12}\frac{dq}{d\gamma} - k^2 c_{22}\frac{de}{d\gamma}, \end{aligned}$$

while differentiation wrt. σ yields:

$$\begin{aligned} \gamma &= c_{11}\frac{dq}{d\sigma} + kc_{12}\frac{de}{d\sigma} \\ 1 &= -kc_{12}\frac{dq}{d\sigma} - k^2 c_{22}\frac{de}{d\sigma}. \end{aligned}$$

Rewriting, using matrix notation, we get.

$$\begin{pmatrix} c_{11} & kc_{12} \\ -kc_{12} & -k^2 c_{22} \end{pmatrix} \begin{pmatrix} \frac{dq}{d\gamma} & \frac{dq}{d\sigma} \\ \frac{de}{d\gamma} & \frac{de}{d\sigma} \end{pmatrix} = \begin{pmatrix} \sigma + \gamma\frac{d\sigma}{d\gamma} & \gamma \\ \frac{d\sigma}{d\gamma} & 1 \end{pmatrix},$$

which may be written $AY = B$ (with the obvious definitions of matrixes). The solution for the substitution matrix Y is then given by $Y = A^{-1}B$, where the inverse is given by:

$$A^{-1} = \frac{1}{k^2\left(c_{11}c_{22} - (c_{21})^2\right)} \begin{pmatrix} k^2 c_{22} & kc_{12} \\ -kc_{12} & -c_{11} \end{pmatrix}.$$

Hence, the solution for Y is given by:

$$\begin{pmatrix} \frac{dq}{d\gamma} & \frac{dq}{d\sigma} \\ \frac{de}{d\gamma} & \frac{de}{d\sigma} \end{pmatrix} = \frac{1}{k^2\left[c_{11}c_{22} - (c_{21})^2\right]} \begin{pmatrix} \sigma k^2 c_{22} + (\gamma k^2 c_{22} + kc_{12})\frac{d\sigma}{d\gamma} & \gamma k^2 c_{22} + kc_{12} \\ -\sigma kc_{12} - (\gamma kc_{12} + c_{11})\frac{d\sigma}{d\gamma} & -\gamma kc_{12} - c_{11} \end{pmatrix},$$

which is equation (5).

Proof of Lemma 1: Beginning with $\frac{de^j}{d\gamma^j}$ in equation (5), and given the assumption that $\frac{de^j}{d\sigma} = -\gamma^j k^j c_{12}^j - c_{11}^j < 0$, we see that the combination $\frac{de^j}{d\gamma^j} < 0$ and $\frac{d\sigma}{d\gamma^j} \leq 0$ is infeasible (remember that $c_{12}^j < 0$). If we assume that $\frac{d\sigma}{d\gamma^j} > 0$, then emissions from firms in other sectors e^l $(l \in M \setminus \{j\})$ must fall under the Lemma's assumption that $\frac{de^l}{d\sigma} < 0$. It then follows that $\frac{de^j}{d\gamma^j} > 0$ in order to fulfill equation (1). If we instead assume that $\frac{d\sigma}{d\gamma^j} < 0$, then emissions in other sectors must increase, and thus $\frac{de^j}{d\gamma^j} < 0$. However, we have just ruled out this combination. $\frac{d\sigma}{d\gamma^j} = 0$ is also infeasible. The reason is that (5) then implies $\frac{de^j}{d\gamma^j} > 0$ and unchanged emissions in other sectors, which together imply that aggregate emissions exceed the binding emissions cap. Hence, we have proved that we must have $\frac{de^j}{d\gamma^j} > 0$ and $\frac{d\sigma}{d\gamma^j} > 0$. Not surprisingly, as OBA acts as a subsidy to production, it then follows from equation (4) that $\frac{dq^j}{d\gamma^j} > 0$.

Derivation of the first order conditions (7) and (8): Let heading ij denote any firm $i \in N^j$ in sector $j \in M$. The maximization problem under ex post regulation is given by:

$$\Pi^{ij} \equiv \max_{k^{ij}} \left[p^j q^{ij} - c^j(q^{ij}, k^{ij} e^{ij}) - \sigma(e^{ij} - \varsigma^j f(\frac{1}{n^j} \sum_{i \in N^j} k^i) q^{ij}) - \kappa^j(k^{ij}) \right],$$

with first order condition:

$$\begin{aligned}
\frac{d\Pi^{ij}}{dk^{ij}} &= \left[p^j - c_1^j(\cdot) + \sigma \frac{\varsigma^j}{n^j} f(\cdot) \right] \frac{dq^{ij}}{dk^{ij}} - \left[\sigma + k^{ij} c_2^j(\cdot) \right] \frac{de^{ij}}{dk^{ij}} - c_2^j(\cdot) e^{ij} + \sigma q^{ij} \frac{\varsigma^j}{n^j} \frac{df}{dk^{ij}} - \kappa_k(k^{ij}) = 0 \\
&\Leftrightarrow \; -c_2^j(\cdot) e^{ij} + \sigma q^{ij} \frac{\varsigma^j}{n^j} \frac{df}{dk^{ij}} - \kappa_k(k^{ij}) = 0 \\
&\Leftrightarrow \; \kappa_k(k^{ij}) = \sigma \left(\frac{e^{ij}}{k^{ij}} + q^{ij} \frac{\varsigma^j}{n^j} \frac{df}{dk^{ij}} \right),
\end{aligned}$$

where we used the first order conditions (3) and (4) in the derivation of the two last equalities. The last equation is identical to (8) when we omit the firm specific notation i (due to the assumption of identical firms). Finally, ex ante regulation implies $\frac{df}{dk^{ij}} = 0$, which yields equation (7).

B Appendix

Consider the numerical model described in subsection 2.3. We then have the clearing condition $e = E/n$ in the allowance market. Each firm solves:[29]

$$\max_{k}\left[\max_{q,e}\left[pq-\left(\frac{1}{2}q^{2}+\frac{\delta}{2}\left(q-ke\right)^{2}\right)-\sigma\left(e-\gamma q\right)\right]-\frac{\widehat{\kappa}}{2}\left(k-1\right)^{2}\right],$$

where γ is as specified in Subsection 2.3. The reduced form solutions for q and σ are:

$$\begin{aligned}
q &= \frac{p+\left(1-k\gamma\right)k\delta\frac{E}{n}}{1+\delta-k\gamma\delta}, \\
\sigma &= \frac{\left(p-k\frac{E}{n}\right)k\delta}{1+\delta\left(1-k\gamma\right)}.
\end{aligned}$$

These equations are valid under all three regimes (with $\gamma = 0$ under no OBA). The first order conditions wrt. k under full auctioning and ex ante regulation yields:

$$E\delta\left(q-k\frac{E}{n}\right)=n\kappa\left(k-1\right)$$

with solution $k = \frac{1}{n\kappa+\delta E^{2}/n}\left(n\kappa+Eq\delta\right)$ (k as function of q). Inserting the solution for q above and solving we get the reduced form solution for k under ex ante policy:

[29] We omit firm subscripts i when possible to keep notation simple.

$$
\begin{aligned}
k &= \frac{1}{2}+\frac{1}{2\gamma}+\frac{1}{2\gamma\delta}+\frac{E^2}{2n^2\kappa\gamma} \\
&\quad -\frac{1}{2n^2\kappa\gamma\delta}\sqrt{n^4\kappa^2\left(\gamma\delta-\delta-1\right)^2+\delta^2E^4+2n^2\kappa\delta E\left(E\left(\delta+\gamma\delta+1\right)-2np\gamma\delta\right)}.
\end{aligned}
$$

By taking the limit of the RHS of this expression as $\gamma \to 0$ we obtain the solution for k under no OBA. This is given by:

$$
k=\frac{\kappa+\kappa\delta+p\delta E/n}{\kappa+\kappa\delta+\delta E^2/n^2}
$$

Under ex post regulation, the first order condition wrt. k implies:

$$
E\delta\left(q-k\frac{E}{n}\right)-\sigma q\frac{\varsigma}{k^2}=n\kappa\left(k-1\right),
$$

which, together with the solution for q above, implicitly yields k.

As mentioned in the main text, we normalize $p=q^{BaU}=e^{BaU}=k^{BaU}=1$, and let the emissions cap be given by $E=0.8n$. Moreover, δ is calibrated so that a 20% decrease in emissions incurs a 20% increase in production costs, given $q=q^{BaU}$ and $k=k^{BaU}$. This gives $\delta=5$. The qualitative results are not very sensitive to the value of δ (the graphs for OBA ex post and no OBA in Figure 1 cross each other between $n=1$ and $n=2$ also when $\delta=1$ and $\delta=10$). To calibrate $\widehat{\kappa}$, notice first that k must increase by 25% in order to satisfy the emissions cap without increasing production costs when $q=q^{BaU}$. We calibrate $\widehat{\kappa}$ so that the corresponding investment

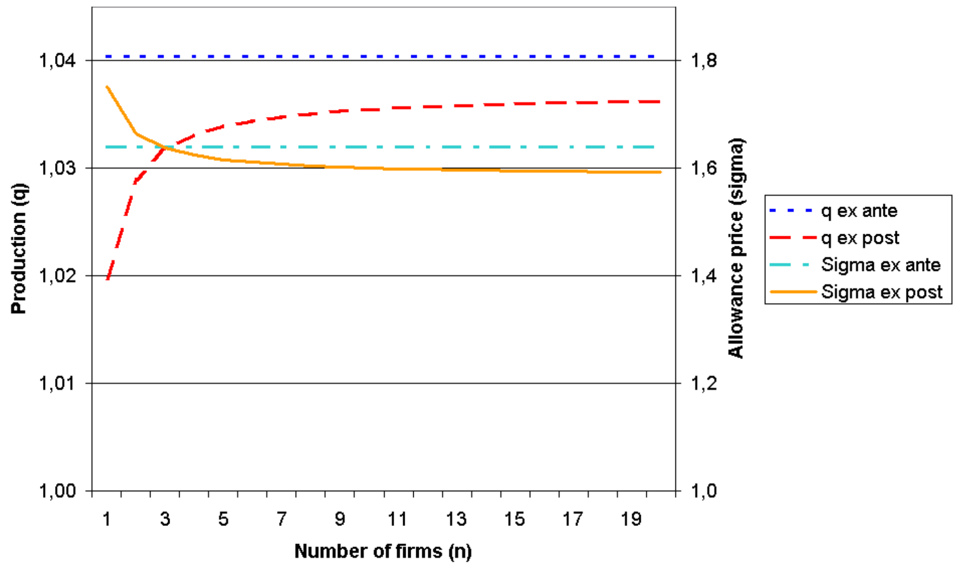

Figure 2: Production and allowance price. Numerical example

costs are equal to the 20% increase in production cost above (for given q and k). This gives $\widehat{\kappa} = 3.2$.

Figure 2 plots production and the allowance price under the regulatory schemes. Both production and the allowance price are normalized to one under no OBA. We see that production and the alllowance price are 4% and 75% higher under ex ante regulation than under full auctioning, respectively. Under ex post regulation, production and the allowance price depends on the strenght of the ratcheting effect, as captured by the number of firms. In particular, the allowance price under ex post is larger than under ex ante when n is small. The reason is that the less effective technology adopted under ex post involves higher abatement costs. For a larger number of firms, however, an opposing effect dominates: production is bigger under ex ante. This requires a stronger abatement effort, and induces the allowance price to be higher under ex ante than under ex post when n is large. Finally, we also note that the output increase from no OBA to OBA (under ex ante) is halved under ex post regulation with only one firm.

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