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Output-based allocation and investment in clean technologies

Abstract:
Allocation of emission allowances may affect firms' incentives to invest in clean technologies. In this paper we show that so-called output-based allocation tends to stimulate such investments as long as individual firms do not assume the regulator to tighten the allocation rule as a consequence of their investments. The explanation is that output-based allocation 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 rule 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.

Keywords: Emissions trading, allocation of quotas, abatement technology.

JEL classification: H21, Q58

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Sammendrag

Tildeling av gratis utslippskvoter kan påvirke bedrifters insentiver til å investere i ren produksjonsteknologi. I denne artikkelen undersøker vi effektene av gratis tildeling proporsjonalt med produksjon. Det innebærer at bedriftene mottar flere gratis utslippskvoter dersom de øker produksjonen sin. Vi viser at slik tildeling kan stimulere til renere teknologi, så lenge bedriftene ikke forventer en tilstramming i tildelingsregelen som følge av sine investeringer. Forklaringen er at gratiskvotene utgjør en subsidie til bedriftenes produksjon. Den enkelte bedrift vil derfor ønske å produsere mer, og dermed øke sine utslipp. Dette gir økt kvotepris, som igjen gir sterkere insentiver til å investere i ren teknologi. Dersom bedriftene forventer en tilstramming i tildelingsregelen som følge av sine investeringer vil imidlertid disse insentivene svekkes. Denne svekkelsen kan være så sterk at investeringer i ren teknologi faller.

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? The answer to this question is not straightforward, and depends crucially on the purpose of allocation.

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 installations 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

[1] An important argument for auctioning of permits is that the revenues can be used to reduce other distorting taxes in the economy, the so-called double dividend (e.g., see Goulder, 1995; Hoel, 1998; or Goulder et al., 1999).

[2] In the literature, the term grandfathering has mostly been used to describe uncondi-

already by Montgomery (1972), such an ETS will be cost-effective, given that the emission trading market is not distorted by e.g. market power, incomplete participation or distortive 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. Such an allocation mechanism is often referred to as benchmarking or output-based allocation (e.g., see Edwards and Hutton, 2001; Fischer and Fox, 2007), and has become increasingly popular in recent years as a way of reducing emissions leakage and loss in competitiveness (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 technological progress

tional allocation based on historic activity levels such as emissions. We will follow that terminology, even though most current ETSs, such as the EU ETS, typically includes conditions to grandfathered allocations (e.g., the condition to not close the installation).

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

over the next few decades. Naturally, incentives to do R&D in climate-friendly technologies are to a large degree driven by the prospects to sell 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. This is not to say, however, that one allocation mechanism is better than another simply because it leads to more investments in clean technologies. Obviously, other crucial aspects like cost-efficiency and distributional effects matter as well.

Using a simple analytical model, we show that output-based allocation tends to increase the incentives to invest in clean technologies under ex ante regulation, that is, if the allocation rule is not adjusted as a result of the firms' investment levels. Consider a sector consisting of homogenous firms, with a sector-specific benchmark parameter determining the number of allowances allocated per unit of production. If the benchmark parameter is increased for only this sector, keeping the total emissions cap fixed, we find that clean technology investments in this sector will unambiguously rise under ex ante regulation. The explanation is that output-based allocation, acting as an implicit output subsidy, drives up production and hence emissions in this sector. This further leads to a higher price of allowances and increased incentives to invest in clean technologies. The effects on investments in other sectors regulated by the same ETS are ambiguous, as lower emissions in these sectors and higher allowance price pull in different directions.

Under ex post regulation, the regulator may respond to the firms' investments, noticing that the emission intensities of the firms have come down, by reducing the number of allowances allocated per unit of output. If so, the anticipated future 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, which is more likely if the benchmark parameter referred to above 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 described above, leading to less investments than under auctioning or grandfathering. In general, however, the effects on clean technology investments are ambiguous under ex post regulation.

We also examine the case with heterogeneous firms within a sector, and consider how different types of sectors may be affected differently with respect to technology investments by output-based allocation. In addition, in a brief extension we analyze output-based refunding of emissions payments, i.e., an emissions tax with refunding based on production.

The development of the EU ETS, which is by far the most important ETS in the world today (both in economic and political terms),[4] illustrates how output-based allocation has gained momentum lately. The allocation mechanism in the EU ETS will shift substantially from the first (2005-2007) and the second (2008-2012) phases to the third phase in 2013-2020. In the first two phases, allocation was mainly based on historic emission levels, setting aside allocation reserves for new installations without historic emissions. In the upcoming phase, power producers will no longer receive free allowances (with some exceptions though). Allocation to other sectors will, as a general rule, be based on historic production (in the years 2007-2008). New installations and installations that change their capacity substantially will receive special treatment, meaning that allocation will be adjusted according to actual production capacity. For every subsector, the EU establishes a benchmark parameter, which determines how many allowances each installation in this subsector will receive for every unit produced. The benchmark

[4] See http://ec.europa.eu/clima/policies/ets/index_en.htm. The annual value of allowances in the EU ETS has been estimated to 30 billion Euro (Neuhoff et al., 2006).

parameters are based on the emission intensities in the ten per cent least emission-intensive installations in the respective subsectors in 2007-2008.

In the cap-and-trade system passed by the U.S. House of Representatives in 2009,[5] output-based allocation also plays an important role for some sectors, especially energy-intensive and trade-exposed industries. However, this bill has not been passed by the Senate, and the future of U.S. cap-and-trade is currently highly uncertain.

Why is output-based allocation 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. Output-based allocation targets leakage through product markets by indirectly subsidizing output in exposed industries, reducing foreign firms' incentives to enhance their production and thus emissions.[6] Therefore, although output-based allocation is not a cost-

[5] The American Clean Energy and Security Act (H.R. 2454) (http://energycommerce.house.gov/Press_111/20090701/hr2454_house.pdf)

[6] Carbon leakage may occur through different channels. According to Böhringer et al. (2010), changes in international prices of fossil fuels are more important for the overall

effective way of reducing emissions (cf. e.g. Böhringer and Lange, 2005a), it may be preferable 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 output-based allocation on, e.g., economic welfare, competitiveness and leakage. For instance, using a general equilibrium model for the Danish economy, Jensen and Rasmussen (2000) show that output-based allocation dampens sectoral adjustment, but causes larger welfare losses than lump-sum allocation (grandfathering). Haites (2003) finds that output-based allocation in an ETS for Alberta (Canada) encourages greater production but lower firm profits, relative to lump-sum allocation. Fischer and Fox (2007) finds that output-based allocation is close to full auctioning with revenue recycling in terms of overall economic indicators, and clearly outperforms lump-sum allocation. The reason is that allocation rules that stimulate output, mitigate concerns like emissions leakage and tax interactions. Bernard et al. (2007) find that it is better to tax production in a competing unregulated sector than to rebate environmental levies to firms in the regulated sector to mitigate emissions leakage. If this is not possible, rebating is only justified when the goods of

leakage than leakage through the international markets for energy-intensive products.

the sectors are close substitutes with similar emissions profiles.

Output-based refunding of emissions payments is examined by Sterner and Isaksson (2006), with the Swedish NO_x charge as an example. They find that incentives for abatement are approximately equal to that of an emissions tax, while reduction in output is smaller. Fischer and Fox (2009) use an optimal tax framework to solve for the optimal emissions tax and output rebate, given emissions leakage and distorting labor taxes. By mitigating price increases of covered sector products, rebates reduce both the interaction with pre-existing taxes and the loss of competitiveness that can lead to leakage. Thus, they find that the optimal rebate is larger for goods with high substitutability with other unregulated goods, or goods that are strong complements with employment

As far as we know, no previous studies have looked into how different allocation mechanisms affect investments in clean technologies. However, there exists a well developed literature on R&D and incentives to invest in abatement technology under emissions trading (with auctioned or grandfathered permits) and other policy instruments. We refer to Jaffe et al. (2002), Löschel (2002) or Requate (2005) for surveys of this literature.

In Section 2 we set up and solve the analytical model. Subsection 2.1

derives some short run properties of output-based allocation. These properties are necessary for our analysis of the forward looking firms' investment decisions in Subsection 2.2. Section 3 and Section 4 provides extensions to heterogeneous firms and output-based refunding of an emissions tax, respectively. Section 5 concludes.

2 Theoretical analysis

We consider an emission trading system (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 covered by the ETS constitutes a sufficiently small part of the world market to leave the price on the good produced exogenous.[7] In sector j there are n^j firms, denoted $i \in N^j = \{1, 2, ..., n^j\}$, which we assume have identical cost functions and hence activity levels. Let q^j and e^j denote production and emissions for each firm in sector j, respectively, while k^j are technology parameters.[8]

[7] 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 $p_1^j \leq 0$. However, our results will be affected if the product price is not independent across sectors, and the effect will then depend on the specification of the dependency, e.g., if the goods produced are substitutes or compliments.

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

The production technology for firms in sector j is then 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 $c_1^j(0,0) < p^j$.[9] 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 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.[10] 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) covers trade exposed industries (the EU ETS is a prominent example).

The regulator commits to a binding aggregate emissions cap $E = \sum_{j \in M} n^j e^j$.

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

[10] 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.

Further, the regulator allocates permits to individual firms proportional to their production level (i.e., output-based allocation), with γ^j being the allocation factor. As seen below, the permit price σ is affected not only by the emissions cap but also by the allocation factors.

The model is divided into two stages: First, in the beginning of stage 1, the regulator announces the emissions cap and the allocation *rules* 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 and the fixed emissions cap and allocation factors.

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

Under ex post regulation, we let the allocation factor in sector j in stage 2 be given by $\gamma^j = \overline{\gamma}^j f(\frac{1}{n^j}\sum_{i \in N^j} k^i)$, with $\frac{df}{dk^i} < 0$.[11] The interpretation here is that a higher sector specific constant $\overline{\gamma}^j > 0$ implies a more generous allocation rule, and we will thus refer to $\overline{\gamma}^j$ as the generosity parameter. Further, $f(\cdot)$ captures the regulator's possible response to the firms' technology investments (ratcheting). An increase in k^j reduces the firm's (unabated) emissions per unit of production. With ex post regulation, the regulator may respond to this new information by reducing the number of free permits per unit produced in the subsequent stage 2 (e.g., because less free permits is perceived necessary to avoid loss in competitiveness).

Note that there is an element of imperfect information in the ex post game, as the knowledge gained from observations of firms' technology choices in stage 1 is used to decide the allocation factors before the beginning of stage 2. We assume that the firms are able to foresee these allocation factors, based on the announcements made at the start of stage 1, when they choose their

[11] All the main results carry over with more general assumptions about the function $f(\cdot)$.

investment levels in stage 1.

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:

$$\pi^j \equiv \max_{q^j, e^j} \left[p^j q^j - c^j(q^j, k^j e^j) - \sigma(e^j - \gamma^j q^j) \right] \tag{1}$$

Note that prices p^j and σ are exogenous to the 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:

$$p^j + \sigma\gamma^j = c_1^j(q^j, k^j e^j) \tag{2}$$

$$\sigma = -k^j c_2^j(q^j, k^j e^j) \tag{3}$$

which are equal across all firms within sector j for a given and equal 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 if and only if 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 (2) and (3) with respect to the permit price σ and the allocation factor γ^j, we get (see the appendix):

$$\begin{pmatrix} \frac{dq^j}{d\gamma^j} & \frac{dq^j}{d\sigma} \\ \frac{de^j}{d\gamma^j} & \frac{de^j}{d\sigma} \end{pmatrix} = \frac{1}{X^j} \begin{pmatrix} \sigma(k^j)^2 c_{22}^j + (\gamma^j (k^j)^2 c_{22}^j - \sigma) \frac{d\sigma}{d\gamma^j} & \gamma^j (k^j)^2 c_{22}^j - \sigma \\ \sigma^2 + (\sigma\gamma^j - c_{11}^j) \frac{d\sigma}{d\gamma^j} & \sigma\gamma^j - c_{11}^j \end{pmatrix}, \tag{4}$$

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 permit price σ.

Let us first examine the effects of a change in the permit price, which could, e.g., arise from an adjustment of the allocation factor in another sector. These effects are given in the second columns in the matrixes in equation (4). We see that for sufficiently small γ^j we have $\frac{de^j}{d\sigma} < 0$ and $\frac{dq^j}{d\sigma} < 0$. This would of course be the case with full auctioning, in which case the allocation factors are equal to zero. For higher levels of γ^j, however, it is possible that $\frac{dq^j}{d\sigma} > 0$ and even $\frac{de^j}{d\sigma} > 0$. The latter requires the allocation factor and the permit price to be sufficiently big. The reason is that the allocation factor acts as a subsidy to production, and the value of this subsidy increases with the permit price. A higher permit price obviously makes emissions more expensive, too, and the net effects on output and emissions depend on the size of γ^j as well as the production technology. Below we will assume that $\sigma\gamma^j - c_{11}^j < 0$, so that emissions are decreasing in the permit price.[12]

Next we consider the effects in sector j of a more generous allocation factor γ^j. These effects are given in the first columns in the matrixes in equation (4). Beginning with $\frac{de^j}{d\gamma^j}$, and given the assumption that $\sigma\gamma^j - c_{11}^j < 0$, we see that the combination $\frac{de^j}{d\gamma^j} < 0$ and $\frac{d\sigma}{d\gamma^j} \leq 0$ is infeasible. If we assume that $\frac{d\sigma}{d\gamma^j} > 0$, then we have just established that emissions from firms in other sectors e^l $(l \in M \backslash \{j\})$ must fall. It then follows that $\frac{de^j}{d\gamma^j} > 0$ in order to reach the emissions cap. 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

[12] If the allocation factor is so high that 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.

ruled out this combination. $\frac{d\sigma}{d\gamma^j} = 0$ is also infeasible, as (4) then implies $\frac{de^j}{d\gamma^j} > 0$ and unchanged emissions in other sectors. 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 output-based allocation acts as a subsidy to production, it then follows from equation (3) that $\frac{dq^j}{d\gamma^j} > 0$.

We sum up our findings in the following lemma, which holds as long as $\frac{de^j}{d\sigma} < 0$:

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 permits ($\frac{d\sigma}{d\gamma^j} > 0$)

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 $l \neq j$ for sufficiently low levels of γ^l ($\frac{de^l}{d\gamma^j} < 0$ and $\frac{dq^l}{d\gamma^j} < 0$, $\forall l \in M \setminus \{j\}$)

Proof. The Lemma follows from the discussion above. ■

In particular, we notice that introducing output-based allocation, i.e., increasing γ^j from zero, the price of permits will increase. This holds whether output-based allocation is introduced for one or more sectors. If output-based allocation 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 3). We last note that production will increase in all sectors if the allocation factors are adjusted so as to keep sector emissions unchanged.

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:

$$\Pi^j \equiv \max_{k^j} \left[\pi^j - \kappa(k^j)\right] \tag{5}$$

with $\pi^j(\cdot)$ defined by equation (1). Because the firms foresee the tightening of the allocation rule 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 the next 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 (5) is given by (see the appendix):

$$\kappa_1(k^j) = \frac{\sigma e^j}{k^j} \tag{6}$$

Anticipating the equilibrium in stage 2, equation (6) governs the firms' choice of technology k^j in stage 1. From Lemma 1 we know that increasing (or introducing) γ^j in one or more sectors will increase the permit price σ. Thus, we see that the RHS of equation (6) will increase for sectors with unchanged or higher emissions, and increase or decrease for other sectors when γ^j increases. 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 the former group of sectors, and increase or decrease for the other sectors. In particular, if the allocation factor is increased for a single sector, it is optimal for this sector to increase its technology investments. Moreover, if the allocation factors are increased so as to keep sectoral emissions unchanged, technology investments will increase for all sectors.

We summarize our results in the following proposition:

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

i) Increasing the allocation factor in sector $j \in M$ leads to higher technology investments in this sector. Technology investments in other sectors $l \in M \setminus \{j\}$ may either increase or decrease.

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. ■

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

2.2.2 Ex post regulation

Under ex post regulation, the allocation factor is given by $\gamma^j = \overline{\gamma}^j f(\frac{1}{n^j}\sum_{i \in N^j} k^i)$. Remember that we interpret a higher sector specific constant $\overline{\gamma}^j > 0$ as a generosity parameter, while $f(\cdot)$ captures the regulator's possible response to the firms' technology investments (ratcheting). It is straightforward to show that the results derived for the allocation factor γ^j in Lemma 1 applies to the generosity parameter $\overline{\gamma}^j$ with this specification of the allocation rule. The first order condition to the maximization problem (5), with $\gamma^j = \overline{\gamma}^j f(\frac{1}{n^j}\sum_{i\in N^j} k^i)$, is given by (see the appendix):[13]

$$\kappa_1(k^j) = \sigma\left(\frac{e^j}{k^j} + q^j \frac{\overline{\gamma}^j}{n^j}\frac{df}{dk^j}\right) \tag{7}$$

We will now discuss the effects on k^j of increasing the generosity parameter $\overline{\gamma}^j$. The first term on the RHS corresponds to the RHS of equation (6) and, hence, tend to increase the firms' investments as the regulator increases the generosity parameter. However, the regulator may tighten the allocation rule before stage 2 in response to the firms' investment. This effect, which reduces the firms incentives to invest, is captured by the term $q^j \frac{\overline{\gamma}^j}{n^j}\frac{df}{dk^j} < 0$ in the second term on the RHS of equation (7). Intuitively, the firms' incentives to implement advanced technology is reduced if the investment triggers a tightening of the allocation factor, and thereby less free permits in stage 2. This is the so-called ratcheting effect, see, e.g., Downing and White (1986). We see from equation (7) that the strength of the ratcheting effect increases

[13] We used $\frac{df}{dk^i} = \frac{df}{dk^j}$ for $i \in N^j$ (firms are identical within any sector $j \in M$).

in the generosity of the allocation rule as given by $\overline{\gamma}^j$.

It follows that an increase in $\overline{\gamma}^j$ has one positive and one negative effect on the firms' investment level k^j, through the first and second term on the RHS of equation (7), respectively. Therefore, the sign of the change in the RHS of (7) induced by a more generous allocation rule is ambiguous (in general). On the other hand, if the allocation factor is (perceived) approximately insensitive to the firms' choice of technology, we obtain the same conclusions as in Proposition 1. In this respect, we observe from equation (7) 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 rule $\gamma^j = \overline{\gamma}^j f(\frac{1}{n^j}\sum_{i\in N^j} k^i)$ 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. Then, increasing the generosity of the allocation rule in sector $j \in M$, as given by $\overline{\gamma}^j$, may either increase or decrease technology investments in any sector $j' \in M$.*

Proof. The proposition follows from the discussion above. ■

The intuition behind the Proposition is straightforward. First, a more generous allocation rule 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 permit price increases. These results follow from Lemma 1. The higher permit price then increases the firms' incentives to invest in advanced abatement technology. Second, the regulator may adjust the benchmarking parameter in response to this investment. If so, investment in technology will involve less free allowances in the future. This ratcheting effect (which increases in the generosity of the allocation rule) imposes an additional cost on investment that reduces the firms' incentives to invest in technology.

Should firms regulated by the EU ETS be concerned about the above-mentioned ratcheting effect, or is ex ante regulation a better description of this system? During the third phase, lasting eight years, 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.[14] Should individual firms be concerned about their

[14]In the EU ETS, the allocation factor will depend on the average of the 10% most

own influence on future benchmark parameters? If we look at the number of firms in each subsector having its own benchmark parameter, the number varies a lot. In some subsectors the number is so large that an individual firm has limited influence unless it is really in the front and the allocation factor is determined based on best available technologies. In other subsectors 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 consists of several subsectors 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.[15] Even though several of these plants are operated by the same company, each company's influence on the allocation rule is likely to be modest. On the other hand, there were only 5 plants (4 companies) that produced apidic acid in the EU ETS in 2006, accounting for 13 Mt CO_2-equivalents. These firms may expect investment in abatement equipment

efficient installations. In our model framework, with identical firms in each sector, and thus equal k^j across all firms in sector j, we are not able to analyze the impacts of different variants of allocation rules.

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

today to induce less free permits per unit produced from 2020 onwards.

3 Sector heterogeneity

In this section we present some simple comparative statics in order to explore the relationship between firms' cost structures and output-based regulation. We limit the analysis to the case with two sectors $M = \{j, l\}$, with cost functions $c^j(q^j, k^j e^j)$ and $c^l(q^l, k^l e^l)$. Because we focus on heterogeneous cost structures, we assume that the two sectors face the same regulation, i.e. $\gamma = \gamma^j = \gamma^l$. Observe that the binding emissions cap implies $n^j de^j + n^l de^l = 0$.[16] Therefore, the equilibrium emissions from the l-sector must decrease if the j-sector increases its emissions and vice versa. We will henceforth assume that the increase in the generosity of the allocation rule induces a change in the firms emissions (i.e., $de^j, de^l \neq 0$)[17]. Which sector will increase its emissions? The denominator X^j in equation (4) is positive. Hence, it affects

[16] Using derivatives here is slightly awkward, because it is limited to very small changes. An alternative would be to use differential notation and assume that the larger changes examined shared sign with the smaller changes examined in previous sections.

[17] If $de^j = de^l = 0$ firms in both sectors would increase their investments under ex-ante regulation due the increase in permit price (cf. equation 6), while we have ambiguity under ex post regulation (cf. equation 7).

the size of the elements in equation (4), but not the sign. Thus, it is left to the nominator to determine the signs of the elements in the substitution matrix (4). Let us begin with $\frac{de}{d\sigma}$ and $\frac{de}{d\gamma}$. Note that γ and σ in the RHS of equation (4) are equal across the two sectors. Therefore, we must have $\frac{de^j}{d\gamma} > 0$ and $\frac{de^l}{d\gamma} < 0$ if and only if $c_{11}^j < c_{11}^l$ (remember that $\frac{d\sigma}{d\gamma} > 0$ by Lemma 1). Let $c_{11}^j < c_{11}^l$. It then follows from the first order condition (3) that $\frac{dq^j}{d\gamma} > 0$. It is indeterminate whether the $l-$sector increases or decreases its production (cf. equation 3). Thus, we may have $\frac{dq^j}{d\gamma} > 0$ and $\frac{dq^l}{d\gamma} > 0$ even tough aggregate emissions are constant.

Can we say something more about the sign of $\frac{dq^l}{d\gamma}$? Assume, for the sake of the argument, that the firms' production functions are Leontief in q and e. Then the sign of dq is equal to the sign of de for both types of firms, which implies that $\frac{dq^l}{d\gamma} < 0$ when $c_{11}^j < c_{11}^l$. With a more flexible production function we may have $\frac{dq^l}{d\gamma} > 0$, however.

Also, it can be seen from equation (2) that the firms in sector j increase their production more than the firms in sector l, given $c_{11}^j < c_{11}^l$. How? We know that the LHS of this equation are equal for both types of firms. Moreover, we have established that our assumption $c_{11}^j < c_{11}^l$ entails $\frac{de^j}{d\gamma} > 0$ and $\frac{de^l}{d\gamma} < 0$. Therefore, we must have $dq^j > dq^l$ in order to retain the equality in equation (2) (remember that $c_{12} \leq 0$). This increases the demand for emissions from firms in sector j relative to that of the firms in sector l.

Intuitively, $c^j_{11} < c^l_{11}$ implies that the marginal production cost curve of firms in sector j is flatter than the marginal production cost curve of firms in sector l. Therefore, and because the product prices are exogenous, firms in sector j increases production more than firms in sector l in response to a subsidy to production (in the form of free permits per unit produced).

The results in the paragraphs above and equation (6) imply that $\frac{dk^j}{d\gamma} > 0$ under ex ante regulation. Under ex post regulation we have $\frac{dk^j}{d\gamma} > 0$ if each firm perceives the allocation factor to be sufficiently insensitive to its own technology investment, e.g., because the number of firms in the sector is high (cf. equation 7). The sign of $\frac{dk^l}{d\gamma}$ is ambiguous under ex ante (and thereby also ex post) regulation, cf. equation (6). However, rearranging equation (6), we get $k^l \kappa_1(k^l) = \sigma e^l$. A similar equation holds for the firms in sector j. Adding up these two equations, we get $k^l \kappa_1(k^l) + k^j \kappa_1(k^j) = \sigma \left(e^l + e^j\right)$. Under the assumption of linear technology investment cost functions $\kappa(k)$, differentiation of this equation yields $\left(\frac{dk^l}{d\gamma} + \frac{dk^j}{d\gamma}\right) \kappa_1 = \frac{d\sigma}{d\gamma} \left(e^l + e^j\right) > 0$. This implies that total investment costs and the aggregate investment level $k^j + k^l$ increase in the generosity of the allocation rule. The reason is that output-based allocation increases the permit price, which again induces stronger incentives to invest in clean technology. In general, however, the sign of the change in aggregate investment depends on the shape of the investment cost function $\kappa(k)$ and the levels of k^j and k^l before the change in the allocation rule.

We summarize in the following proposition:

Proposition 3 *Assume ex ante regulation and two sectors $M = \{j, l\}$, with $c_{11}^j < c_{11}^l$ 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 generosity of the allocation factor if $\kappa_{11}(k) = 0$.*

Proof. The proposition follows from the discussion above. ■

Note that a similar result could be established with respect to the steepness of the inverse demand function in the case of an endogenous product price. That is, ceteris paribus, if firms in sector l face a steeper inverse demand function than firms in sector j, and the regulator increases the generosity of the allocation rule, we get higher emissions from sector j and lower emissions from sector l. This implies $\frac{dk^j}{d\gamma} > 0$ and $\frac{dk^l}{d\gamma} \lesseqgtr 0$. We last observe that the analysis above is analogous with analysis of two types of firms operating in one single sector, given that the product prices satisfy $p^j = p^l$ and the firms produce a homogenous good.

4 Output-based refunding of an emissions tax

In this section we extend the previous analysis to output-based refunding of emission payments. The major departure from our previous analysis is that the price of emissions is now fixed, while aggregate emissions become an endogenous variable. Moreover, the firms do not receive free permits based on their production levels, but a monetary payment.

Without a cap on aggregate emissions, the first order conditions (2) and (3) alone governs the firms' actions, with σ now referring to the constant emissions tax. The effects of γ^j on the firms' actions are still given by equation (4), but with $d\sigma = 0$. So, while output based allocation under emissions trading entailed a production subsidy and higher production costs (through the higher permit price), output-based refunding of an emissions tax only features the production subsidy. This yields $\frac{dq^j}{d\gamma^j} > 0$ and $\frac{de^j}{d\gamma^j} > 0$ (cf. equation 4 with $d\sigma = 0$). Also, because the tax is constant, increasing the allocation factor in sector j has no effect on firms in other sectors $l \neq j$ covered by the tax regime. Naturally, this result hinges on our assumption about independency between sectors, both with regard to input and output markets.

The analysis of the firms' investment decisions in stage 1 is analogue to the case with output-based allocation under emissions trading, and the equations (6) and (7) still apply. However, while both σ and e^j was endogenous in the previous analysis, σ is now fixed. Otherwise, the interpretation of these equations are very similar to our previous discussion, and will not be repeated here. We state the following result regarding output-based refunding of emission payments:

Proposition 4 *Assume interior solutions, perfect competition in all markets, and ex ante regulation. Then, increasing the output-based refunding in sector $j \in M$ leads to higher technology investments k^j in this sector. Technology investments in other sectors $l \neq j$ are unaffected.*

Proof. The proposition follows from equation (4) and (6), and the discussion above. ■

As in our analysis of output-based allocation under emissions trading, a more generous refunding rule γ^j increases technology investment k^j in the particular case where the allocation factor is (perceived) insensitive to the firms' choice of technology. As an example, the allocation factor in the Swedish NO_x scheme with output-based refunding of emission payments is given by the tax rate times the fraction of total emissions divided by total production. Hence, the firms' incentives to invest in new equipment would decline due to the ratcheting effect if investment would lead to a substantial decline in this fraction. This is not very likely given the high number of (fairly equally sized) firms.[18]

5 Conclusion

Allocation of emission allowances may affect firms' incentives to invest in clean technologies. In this paper we showed that output-based allocation tends to stimulate such investments in sectors encompassed by the allocation rule, given that individual firms do not assume the regulator to tighten the allocation rule as a consequence of their investments. The explanation is that output-based allocation 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 rule after observing their clean technology investment, the firms' incentives to invest are

[18] 365 units participated in the Swedish NO_x scheme in 2006, with the largest unit having an output share of 2.2%, see Sterner and Isaksson (2006).

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.

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 rule would have additional spillover effects, dependent on e.g. whether the products are complements or substitutes. Second, the firms are allocated free permits proportional to production in the current period in our model. In reality, however, output-based allocation may give firms free permits today based on production (or capacity) in some previous period. Still, the key characteristic of output-based allocation is the implicit output subsidy provided by the allocation rule. Third, the main part of our analysis assumed identical firms within each sector. Without this assumption, our results would be firm dependent (not sector specific) and less clear-cut. In general, however, we find that a more generous allocation rule 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 rules 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 a more generous allocation rule would then depend on the time delay before the regulatory response, and the corresponding discount factor.

A Appendix

Derivation of equation (4): Differentiating the first order conditions (2) and (3) 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.

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

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:

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

Hence, the solution for Y is given by:

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

which is equation (4).

Derivation of the first order conditions (6) and (7): 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:

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

with first order condition

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

where we used the first order conditions (2) and (3) in the derivation of the two last equalities. The last equation is identical to (7) 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 (6).

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