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Halvor Briseid Storrøsten

Incentives to invest in abatement technology
A tax versus emissions trading under imperfect competition

Abstract:
In the longer run, effects on R&D and the implementation of advanced abatement technology may be at least as important as short-run cost effectiveness when we evaluate public environmental policy. In this paper, we show that the number of firms that adopt advanced abatement technology could be higher with emissions trading than with a tax if there is imperfect competition in the permits market. Under perfect competition, the number would always be higher with a tax, given that the regulator is myopic. If we allow for environmental policy response, the ranking is still ambiguous under imperfect competition, while the regimes become equal with perfect competition.

Keywords: Auctioned permits, Emissions taxes, technology adoption, Cournot competition

JEL classification: H23, Q55, Q58

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Address: Halvor Briseid Storrøsten, Statistics Norway, Research Department.
E-mail: halvor.storrosten@ssb.no

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1 Introduction

In the longer run, the cumulative effect of research and development (R&D) may greatly reduce the costs necessary to achieve a given environmental policy target. Furthermore, it may expand the opportunity set of environmental policy itself. As such, long-run effects on R&D and the implementation of advanced abatement technology may be at least as important as short-run cost effectiveness when we evaluate public environmental policy.[1]

This paper examines and ranks the market-based policy instruments, i.e., emissions trading and taxes, with respect to incentives to invest in advanced abatement technology. The analytical results demonstrate that the potential of market power in the emissions trading market is crucial in the ranking of the environmental policy instruments. More specifically, we find that the number of firms that implement advanced abatement technology may be higher with emissions trading than with a tax if there is imperfect competition in the permits market.

There has been some interest in the ranking of incentives to adopt new abatement technology with different environmental policy instruments.[2] In this respect, both Milliman and Prince (1989) and Jung et al. (1996) conclude that auctioned permits induce stronger incentives to invest than a tax under ex ante regulation.[3] The main driver behind this result is the downward shift in the aggregate abatement cost function as firms adopt new technology. This leads to a lower permit price and, correspondingly, additional cost savings in the emissions trading regime. Requate and Unold (2003) challenge this result. They observe that the above-mentioned ranking relies upon the calculation of the aggregate cost savings achieved by an industry-wide adoption of new technology. Comparison of these aggregate cost savings ignores the fact that firms may free ride on the lower permit price, and, hence, it exaggerates their incentives to adopt new technology in equilibrium. Considering the decline in the permit price as firms invest, Requate and Unold (2003) find that more firms implement the new technology with a tax than under emissions trading with perfect competition.

The present paper emphasizes three mechanisms that may be present with emissions trading, but not with a tax. We begin with the mechanism noted by Requate and Unold (2003): a negative shift in the aggregate abatement cost function as other firms implement new technology induces a lower permit price. This mechanism reduces the firms' willingness to pay for new

[1] See, for instance, Kneese and Schultze (1975) or Orr (1976) for an early presentation of this view. Jaffe and Stavins (1995) offer an empirical approach.

[2] For a thorough discussion of the literature we refer to Jaffe et al. (2002), Löschel (2002) or Requate (2005a).

[3] Ex ante regulation means that the regulator moves first and credibly commits to the policy, i.e., the tax or cap on aggregate emissions is constant.

technology (WTP). It is present under both perfect and imperfect competition. Second, investment in new technology by some firm with market power does not only reduce that particular firm's emissions and abatement cost, but also the permit price. The reduction in quota payment corresponding to the lower price on all inframarginal permits purchased increases the WTP of that particular firm. This is analogue to the effect noted by Milliman and Prince (1989) and Jung et al. (1996) above. A major difference is that we find it only if firms have market power. Third, emissions are strategic substitutes under emissions trading and market power.[4] Hence the increase in abatement induced by technology adoption is met by higher emissions from the other firms. This counteracts the ability of firms to influence the permit price.

The first mechanism, which has a negative effect on technology adoption, is present with both perfect and imperfect competition, whereas the second and third mechanisms only apply to firms with market power. Hence, we find that an emissions tax would yield more investing firms in equilibrium under perfect competition, while the ranking may be opposite otherwise. The latter happens if (*i*) there is imperfect competition; (*ii*) the total effect on the firm's WTP from market power is positive; and (*iii*) this positive effect dominates the negative contribution because of the option to free ride.

To our knowledge, incentives to invest in advanced abatement technology with market power in the emissions trading market has not been extensively analyzed in the literature. Montero (2002b) studies a setting where two symmetric firms engage in Cournot competition in the emissions and output markets. He finds that standards can offer greater incentives to commit to R&D than tradable permits with Cournot competition in both markets under ex ante regulation. With a very similar model, Montero (2002a) finds the ranking of R&D incentives to vary widely across market structures and instruments. Most closely related to the present paper, he finds that firms may exercise more, equal or less firm-specific R&D under auctioned permits than under either emission standards or taxes. The model in the present paper differs from Montero (2002a) in several aspects. Perhaps most important, the present paper features a Nash investment equilibrium where n firms make choices of whether or not to purchase new technology that induces a discrete shift in their abatement cost function. Moreover, we assume a supply/demand-determined price (as opposed to Nash bargaining) and a separate R&D sector.[5] Still, our results under ex ante regulation are in agreement with, and, hence, corroborate, the results in Montero (2002a).

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[4] The reaction functions slope downwards, i.e., firm i increases (decreases) its emissions if some other firm j decreases (increases) its emissions.

[5] Empirical results by Lanjouw and Mody (1996) indicate that it is important to make such a distinction.

The above-mentioned papers focus on the case where the regulator has made a credible commitment to the present policy, i.e., the tax and emissions target are unaffected by the presence of new technology (ex ante or myopic regulation).[6] A problem with this kind of analysis is that it leads to differences in both prices and quantities after technology implementation. As such, it arguably runs into the danger of comparing incommensurable entities. We come back to this in the conclusions. In contrast, ex post analysis allows the regulator to respond to the actions of the participants. Hence, it allows for, for example, equal price or equal quantities after implementation of the new technology. Denicolo (1999) examines ex post regulation under the assumption of perfect competition. He finds that the two regimes are equivalent under optimal policy, because the tax rate and the permit price become equal. The present paper shows that this equivalence disappears if we slacken the assumption of perfect competition in the emissions trading market. Intuitively, firms exercise market power exactly by manipulating the permit price. Therefore, the result of an equal tax rate and permit price is no longer true if firms have market power, and the equivalence of regulatory regimes breaks down. For ease of exposition, the present paper initially focuses on the case of myopic regulation. However, we believe our most interesting results are found in the ex post policy analysis in Subsection 4.2.

The model is solved backwards and follows a timeline that we organize in three periods. First, in period 1, the regulator sets an emissions target or emissions tax. This is such that aggregate emissions are equal in the two regimes with the currently used technology. In period 2, the firms choose whether or not to implement the new technology. Then, in period 3, we derive the firms' abatement and emissions costs contingent on their technology decisions in period 2. Note that the firms' investment decisions are modeled as a two-stage game: the costs derived in period 3 determine the payoffs in the investment game in period 2. This is done in Sections 2 and 3. We show that the investment game has a Nash equilibrium, which is unique up to the number of investing firms, and derive sufficient characteristics to answer the questions addressed in this paper. In Section 4, we compare the regimes in the cases of ex ante and ex post regulation. Section 5 concludes.

Last, the reader may find it convenient to think of emissions of CO_2 and the challenges related to climate change when reading this paper. However, the theory applies equally well to all occurrences where both tradable quantities (e.g., emissions trading) and price-based regulation (e.g., a tax) may be appropriate.

[6] Requate and Unold (2003) also show that the regimes become equal with ex post optimal policy under perfect competition.

2 The abatement decision

We begin with period 3, where the firms minimize abatement and tax or permit cost given their technology. Let the emissions-trading market consist of *n* identical Cournot competitors and a competitive fringe aggregate.[7] Each firm's abatement technology is summarized by the abatement cost function $c^{vi}\left(a^i\right)$, with a^i denoting firm *i*'s abatement and $v \in \{o, \eta\}$ referring to old (o) and new (η) technology. We assume that the cost function is increasing and convex, that is: $c_a^v > 0$ and $c_{aa}^v > 0$. Moreover, we assume that the new technology is unsuited for the fringe.[8] Each firm's emissions are equal to $e^i = \varepsilon - a^i$, where ε denotes the firm's business-as-usual emissions. The prices of one unit of emissions are given by p and τ in the cases of emissions trading and a tax, respectively. There is a binding cap on aggregate emissions given by $\bar{E} = \sum_{i \in N} e^i + E$ in the emissions trading regime, where E denotes the emissions from the fringe aggregate and $N = \{1, 2, ..., n\}$. Last, we assume interior solutions in the emissions trading market.

The Cournot equilibrium is best interpreted as a subgame perfect equilibrium in a two-stage game. First, the Cournot firms simultaneously and credibly commit to their abatement levels.[9] Then the permits are auctioned off, with the market-clearing price determined by the fringe's abatement cost.[10] Solving the game backwards, the minimization problem of the competitive fringe aggregate is:

$$Min_{a^\varphi}\left[c^\varphi\left(a^\varphi\right) + p \cdot \left(\varepsilon^\varphi - a^\varphi\right)\right],$$

where φ refers to the fringe. The solution is:

$$c_a^\varphi\left(a^\varphi\right) = p\,. \tag{1}$$

This first-order condition states the standard result that marginal abatement cost is equal to the permit price. Equation (1) implicitly defines the fringe's emissions as a convex and decreasing function of the permit price. The Cournot competitors therefore face the inverse permit demand function $p(E)$, with

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[7] Our main results easily generalize to the case with heterogeneous firms.

[8] As will be clear later in the analysis, this assumption tends to increase the aggregate WTP with emissions trading relative to that of a tax (because the fringe is competitive). This assumption is made in order to simplify the analysis, but may be motivated by a difference between the Cournot firms and the fringe. For example, the firms in the fringe may be small and the new technology expensive, or they may be operating in different product markets.

[9] We could interpret *a* as abatement capacity in order to achieve a credible commitment.

[10] We assume that the firms state how many permits they want to purchase, and what price they are willing to pay. The auctioneer then constructs a demand curve that, together with the fixed supply, yields an equilibrium price. He then gives priority to the firms with highest willingness to pay, and they pay the equilibrium price.

$E = \overline{E} - n\varepsilon + \sum_{i \in N} a^i$. Define $A^{-i} = \sum_{j \in N \setminus \{i\}} a^j$ for any firm $i \in N$, i.e., the aggregate abatement of all Cournot firms except some representative firm *i*. We note that A^{-i} will depend on the other firms' technology. Then, the permit price can be expressed as a function $p\left(a^i + A^{-i}\right)$. Because the fringe's abatement cost function is increasing and convex we have $p_a = p_A < 0$.[11] The ability of firms to change the price turns infinitesimal as the number of firms increases, and we make the usual assumption that the firms take the price as given under perfect competition.

The cost of any Cournot firm $i \in N$ given technology *v* is equal to:

$$K_{per}^{vi}\left(A^{-i}\right) = Min_{a^i}\left[c^v\left(a^i\right) + p\left(a^i + A^{-i}\right)\cdot\left(\varepsilon - a^i\right)\right], \tag{2}$$

where subscript *per* refers to the permit regime. The first and last terms in this minimization problem refer to abatement cost and emissions cost, respectively. The corresponding first-order condition yields:

$$c_a^v\left(a^i\right) = p(\cdot) - p_a(\cdot)\cdot\left(\varepsilon - a^i\right). \tag{3}$$

The equation implies that a firm with market power increases its abatement in order to reduce the permit price. This reduces the firm's total abatement and quota costs.[12] Furthermore, equation (3) shows that firms' abatements are strategic substitutes, given $p_a(\cdot) - p_{aa}(\cdot)\left(\varepsilon - a^i\right) < 0$. The second-order condition is:

$$c_{aa}^v\left(a^i\right) + p_{aa}(\cdot)\cdot\left(\varepsilon - a^i\right) - 2p_a(\cdot) \geq 0 .$$

We, henceforth, assume that the second-order condition is fulfilled and that firms' abatements (and emissions) are strategic substitutes. A sufficient condition for both assumptions is that the permit price is convex in emissions available to the fringe, or at least not too concave.[13] Moreover, we follow the standard assumption that the sum of the $n-1$ other firms' changes is less than the initial change in

[11] Equation (1) yields $p = c_a^\varphi\left(a^\varphi\right) = c_a^\varphi\left(\varepsilon^\varphi - E\right) = c_a^\varphi\left(\varepsilon^\varphi - \overline{E} + n\varepsilon - a^i - A^{-i}\right)$. Differentiating with respect to a^i or A^{-i}, we get $p_a = p_A = -c_{aa}^\varphi < 0$.

[12] The ability to influence the permit price endows the firm with an opportunity option. This would not be exercised unless it decreased total costs.

[13] From equation (1) we have $p_{aa} \geq 0$ if $c_{aaa}^\varphi(a^\varphi) \geq 0$.

some firm i's emissions (given technology).[14] For instance, if there is a decline in firm i's emissions, aggregate emissions from the Cournot firms in the new equilibrium fall. This allows more emissions from the competitive fringe and a lower permit price. Note that these assumptions guarantee the existence of a unique Cournot equilibrium (see, e.g., Tirole 1988).

In a tax regime, the cost of any firm $i \in N$ given technology v is:

(4) $$K_{tax}^{vi} = Min_{a^i} \left[c^v \left(a^i \right) + \tau \cdot \left(\varepsilon - a^i \right) \right],$$

where subscript *tax* indicates the tax regime. A similar minimization problem applies to the fringe. The problem in equation (4) is equal to that of the firms in the competitive fringe under emissions trading, with $p = \tau$. Hence, the firms equate their marginal abatement costs with the tax:

(5) $$c_a^{\varphi} \left(a^{\varphi} \right) = c_a^v \left(a^i \right) = \tau .$$

This equation applies to both the fringe and the Cournot firms. Note that the cost minimization problem in the tax regime is independent of the other firms' actions. This contrasts with the permit regime.

3 The willingness to pay for abatement technology

In period 2, each firm faces the choice of whether or not to buy new abatement technology. Investment will give a discrete shift in the firm's abatement cost function from $c^o(a)$ to $c^\eta(a)$, where we assume $c^o(a) > c^\eta(a)$ and $c_a^o(a) > c_a^\eta(a)$ for all $a > 0$.

3.1 Tax regime

Each firm will invest in new abatement technology if and only if:

(6) $$WTP_{tax}^i = K_{tax}^{oi} - K_{tax}^{\eta i} \geq F,$$

where K_{tax}^{vi} is defined by equation (4) and F denotes the technology price. The equation says that a firm will invest if the corresponding reduction in tax and abatement cost is at least as great as the price

[14] In order to achieve a unique equilibrium, we assume that the absolute value of the derivatives of the reaction functions in the relevant range is less than 1. The condition $\left| -c_{aa}^{vi} - p_{aa} \left(\varepsilon - a^j \right) + 2p_a \right| > \left| \sum_{j \in N \setminus \{i\}} \left[-p_{aa} (\varepsilon - a^j) + p_a \right] \right|$ is sufficient (see, e.g., Tirole 1988, p. 226). Note that *E >0* in the new equilibrium in period 3, given our existing equilibrium in period 1 and $c_a^o(a) > c_a^\eta(a)$.

it has to pay for the technology. Note that the firm's investment decision is independent of the other firms' actions. The firm's willingness to pay (WTP) is illustrated with the shaded area in Figure 1a.

3.2 Emissions trading with auctioning

Looking ahead, the firms know that their investment decisions induce a subgame with payoffs determined by the model in Section 2. We assume that the firms correctly anticipate the resulting unique Nash-Cournot equilibrium. Given this knowledge, the firms minimize their costs (including the potential technology cost) in a simultaneous "investment game". Let A^{-oi} and $A^{-\eta i}$ refer to aggregate abatement of all the other firms $j \in N \setminus \{i\}$, given that *i* implements old or new technology, respectively. Note that we have $A^{-oi} \geq A^{-\eta i}$ because firm *i*'s abatement increases with new technology and the firms' abatements are strategic substitutes.[15] We have $A^{-oi} = A^{-\eta i}$ under perfect competition. A firm will invest in the new abatement technology if and only if the cost saving following investment is at least as great as the technology price:

(7) $$WTP_{per}^{i} = K_{per}^{oi}\left(A^{-oi}\right) - K_{per}^{\eta i}\left(A^{-\eta i}\right) \geq F,$$

where $K_{per}^{vi}\left(A^{-vi}\right)$ is defined by equation (2). Assume no ties, i.e., no firm is perfectly indifferent between two outcomes. Then, the investment game induced by the "behavioral rule" in equation (7) has a Nash equilibrium that is unique up to the number of firms that invest.[16]

We observe that A^{-vi} will increase if other firms implement new technology (cf. equation (3) applied to any other firm $j \in N \setminus \{i\}$ and $c_a^o(a) > c_a^\eta(a)$). The permit price then declines because $p_A\left(a^i + A^{-vi}\right) < 0$. This triggers a reduction in both $K_{per}^{oi}\left(A^{-oi}\right)$ and $K_{per}^{\eta i}\left(A^{-\eta i}\right)$. However, as the firm's emissions are higher with old technology, the change in $K_{per}^{oi}\left(A^{-oi}\right)$ dominates and the firm's WTP declines.[17] That is, the firm's WTP declines if it expects other firms to invest because it anticipates a lower equilibrium permit price independent of its own actions. This mechanism, which is

[15] Moreover, as will be clear below, the number of other investing firms is never higher if firm *i* uses new technology than if firm *i* uses old technology.

[16] The game is finite and, hence, has at least one mixed strategy Nash equilibrium. Equation (7) ensures that this is unique up to the expected number of investing firms. In a correlated equilibrium, where some sort of signal "coordinates" which firms that undertake the investment, we can assure that this expected number is realized. If we formulate the game in extensive form without simultaneous moves, we get a unique subgame perfect equilibrium that also realize this expected number of firms, by Kuhn's theorem and the assumption of no ties (see, e.g., Osborne and Rubinstein 1994, p. 33, pp. 44–48 and pp. 99–100).

[17] This is particularly easy to illustrate with perfect competition by lowering τ in Figure 1a (inserting $p = \tau$).

present with both perfect and imperfect competition in the emissions market, allows a firm to free ride on the lower permit price triggered by other firms' investments.

What happens with a firm's WTP if it has market power? We first note that technology adoption will reduce the permit price. This happens because $p_a\left(a^i + A^{-vi}\right) < 0$ and investment increases the firm's abatement (cf. equation 3). The corresponding reduction in quota payment on all inframarginal permits purchased increases the WTP of that particular firm. In terms of equation (7), we get a decrease in $K_{per}^{\eta i}\left(A^{-\eta i}\right)$ that is not present under perfect competition. Secondly, a firm with market power knows that a decision to invest will induce a reduction in the other firms' abatement (i.e., $A^{-oi} > A^{-\eta i}$). This happens through two linkages: (*i*) the lower permit price induced by the firm's investment reduces the other firms' abatements (given their technology); and (*ii*) the number of other investing firms in equilibrium may decline if the firm decides to invest itself. More precisely, suppose the number of investing firms in equilibrium *m* satisfies $0 < m < n$ and *x* firms invest in equilibrium if firm *i* does not invest. Then, $x-1$ firms invest if firm *i* invests. This is a consequence of the unique number of investing firms in the Nash investment equilibrium.[18] Therefore, the isolated effect of the other firms' responses to the firm's decision to invest is a higher permit price. This counteracts (possibly nullifies) the price reduction triggered by the Cournot firm's investment and reduces its WTP. Last, we know that the firm's total cost declines if it has market power. This creates an upper bound on the firm's cost savings by technology adoption (and, hence, its WTP) that is lower than the upper bound under perfect competition. Is it possible that the overall effect of market power on the firm's WTP is negative? The answer is yes, as the following simple example shows. Let the new technology offer zero emissions at zero cost. Then, equation (7) says that the firm's WTP is equal to its total cost before investment, which is less if the firm exercises market power. Hence, the firm's WTP would have been higher if it failed to recognize its market power and behaved as a competitive firm. The Cournot firm's WTP under emissions trading is illustrated with the light-shaded areas minus the dark-shaded area in Figure 1b.

4 Comparison of regimes

The papers mentioned in the introduction focus on the case of ex ante regulation. This approach, which we follow in Subsection 4.1, induces differences in both aggregate emissions and aggregate abatement costs between the regimes after implementation of the new technology. On the other hand,

[18] The latter argument would perhaps be more intuitive if we formulated the game in extensive form, and the firms observed the earlier mover's investment decision. Nevertheless, this must be true in order to achieve a simultaneous Nash investment equilibrium.

with ex post regulation, the policy is adjusted because the aggregate abatement cost function shifts down as firms invest. In Subsection 4.2, we examine ex post regulation featuring equal aggregate emissions across regimes, both before and after implementation of the new technology.

4.1 Ex ante regulation

In this section, we treat both the tax rate (τ) and the aggregate emissions cap ($\bar{E}$) as constants. We assume the following relationship between the tax and the permit price:

$$\tau \geq p\left(a^{oi} + A^{-oi}\right) \geq p\left(a^{\eta i} + A^{-\eta i}\right), \tag{8}$$

where a^{oi} and $a^{\eta i}$ refer to firm *i*'s abatement in equilibrium if it uses old and new technology, respectively. The first weak inequality in equation (8) follows from our assumption of equal aggregate emissions before any firm has implemented the new technology. The second inequality holds because the permit price declines in the Cournot firm's aggregate abatement and $a^{oi} < a^{\eta i}$ and $\left(a^{oi} - a^{\eta i}\right) \geq \left(A^{-oi} - A^{-\eta i}\right)$.[19]

With perfect competition, we have two equalities in equation (8) if no other firms implement the new technology. The first equality must be true in order for the regulator to induce equal emissions in the two regimes before any firm has implemented the new technology, while the second follows because $A^{-oi} = A^{-\eta i}$ and the firm's own increase in abatement is insufficient to alter the permit price. Our model then implies equal abatement and price on emissions in the two regimes (cf. the equations 1, 3 and 5). It is hardly surprising that the firm's WTPs become equal across the regimes in this case. More formally, the minimization problems in equations (2) and (4) become equal, and imply equal WTPs in equations (6) and (7).

The assumption that no other firm invests in equilibrium is untenable and, albeit useful for reference, the above scenario is not very appealing. We, therefore, assume that enough firms implement the new technology to trigger a lower permit price. Then, A^{-vi} increases and the left inequality in equation (8) becomes strict. As argued in Subsection 3.2, the lower permit price reduces WTP^i_{per} because of the free-riding option. As the WTPs were equal across the regimes before the increase in A^{-vi}, and WTP^i_{tax} remains constant, this entails that $WTP^i_{tax} > WTP^i_{per}$ under perfect competition. This is in agreement with Requate and Unold (2003).

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[19] The first inequality is true because firm *i*'s abatement increases with new technology. The second inequality stems from the standard assumption that the sum of the $n-1$ other firms' changes is no greater than the initial change in firm *i*'s emissions.

We know from Subsection 3.2 that implementation of new technology done by some firm with market power reduces the permit price, unless the increased abatement induced by the firm's technology implementation is fully absorbed by the other firms' increases in emissions. The corresponding reduction in quota payment on all inframarginal permits purchased because of the lower permit price increases WTP_{per}^{i}. We now have two strict inequalities in equation (8). We show, in the Appendix, that the aggregate effect on the WTP of the firms from market power (the second inequality in equation 8) may be positive and sufficiently strong to dominate the above-mentioned negative effect from the free ride option (the first inequality in equation 8). If so we have $WTP_{tax}^{i} < WTP_{per}^{i}$.

We have established that the option to free ride reduces the WTP of the firms under both perfect and imperfect competition in the emissions market. This effect is not present with a tax. Furthermore, the ability to influence the permit price may increase the WTP of the firms under emissions trading, but this only applies to firms with market power. Hence, we have the following lemma:

Lemma 1. *Let some firm have the opportunity to invest in advanced abatement technology. Then its WTP may be higher with emissions trading than with a tax if there is imperfect competition in the emissions trading market. If there is perfect competition, its WTP is always higher with a tax.*

Proof. See the Appendix.

The purpose of the present paper is to examine the relative number of firms that implement the new technology in the investment equilibrium under the two regulatory regimes. We, therefore, define $D_{tax}(m)$ and $D_{per}(m)$, which denote the inverse aggregate technology demand functions under a tax and emissions trading, respectively (where *m* refers to the number of firms that invest in equilibrium). These functions yield the maximum technology price (*F*) consistent with the corresponding number of investing firms (*m*). We remember that the WTP of the firms declines in *m* under emissions trading (because of a lower permit price), but is unaffected with a tax (cf. the equations 6 and 7).[20] Last, let the inverse technology supply function be given by $F = S(m)$, with $S_m \geq 0$.[21] We state the following proposition:

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[20] The function $D_{per}(m)$ has a stepped curve characteristic (with *F* declining in *m*), while $D_{tax}(m)$ is horizontal (with *m* along the x-axis).

[21] The inverse technology supply function is only needed in order to establish part (*ii*) of Proposition 1.

Proposition 1. *Let* $m^*_{tax}, m^*_{per} \in [0,n]$ *be the number of Cournot firms that invest in advanced abatement technology in equilibrium under the two regimes. Then, we have one of the following:*

(i) $m^*_{tax} \geq m^*_{per}$ *for any S(m); or*

(ii) $m^*_{tax} \leq m^*_{per}$ $\left(m^*_{tax} \geq m^*_{per}\right)$ *if S(m) corresponds to high (low) supply costs; or*

(iii) $m^*_{tax} \leq m^*_{per}$ *for any S(m).*

Proof. Case (*i*) follows directly from Lemma 1 as we approach perfect competition, or if the market power effect is negative, because $D_{per}(m) < D_{tax}(m)$ for all *m*. On the other hand, we have $D_{per}(m) > D_{tax}(m)$ for low *m* if the change in WTP because of market power is positive and dominates the negative contribution from the option to free ride. We, then, have two possibilities: either $D_{per}(m) > D_{tax}(m)$ for all *m*; or there exists some $m' \in (0,n)$ where $D_{per}(m) > (<) D_{tax}(m)$ for all $m < (>) m'$. In the first case, m^* is always highest with emissions trading (case *iii*). In the latter case, the ranking depends on $S(m)$ (case *ii*). More precisely, $m^*_{tax} \leq m^*_{per}$ $\left(m^*_{tax} \geq m^*_{per}\right)$ if $S(m) = D_{tax}(m)$ for $m \leq (\geq) m'$ (see Figure 2b). Numerical examples are given in the Appendix.

In case *(i),* the demand for technology under emissions trading is equal to or lower than that of a tax if $m = 1$, and declines in *m (*see Figure 2a). For example, this is true under perfect competition (and myopic regulation). Case *(iii)* features a demand curve under emissions trading that starts above the demand under a tax. Furthermore, it does not decline sufficiently in *m* to cross the demand with a tax. This is illustrated in Figure 2c and could be the case if there are few Cournot firms. In between, we have case *(ii)* (see Figure 2b). Here the demand functions cross each other at $m = m'$. We have sketched two potential technology supply functions, where $m^*_{tax} \leq m^*_{per}$ and $m^*_{tax} \geq m^*_{per}$ with $\overline{S}(m)$ and $\underline{S}(m)$, respectively. Therefore, the ranking of regimes depends on the technology supply function in case (*ii*), which contrasts with the cases (*i*) and (*iii*).

Note that a border solution in the investment game is quite probable in the tax regime if the slope of the technology supply function is low (certain if $S_m = 0$ with identical firms). Last, we have $m^*_{tax} = m^*_{per} = n$ $\left(m^*_{tax} = m^*_{per} = 0\right)$ for sufficiently low (high) technology supply costs.

4.2 Ex post regulation

In this section, we assume that the regulator's objective is to keep aggregate emissions constant at $\overline{E}$. For instance, this could refer to the situation where a country is obliged to restrict emissions below a certain level due some international agreement. Such ex post regulation requires that we add a fourth period to our model, where the regulator adjusts the tax rate (τ) after observing the new aggregate abatement cost function (after firms have implemented the new technology). The regulator has no need to act in period 4 with emissions trading. Therefore, this particular type of ex post regulation entails that our previous analysis of incentives of the Cournot firms to invest under emissions trading remains valid. On the other hand, the firms' investment decisions under tax regulation are now indirectly subject to some of the mechanisms we found under emissions trading in Subsection 3.2. This is so because the firms anticipate the policy response. More precisely, (*i*) a firm may free ride on the lower tax induced by other firms implementation of new technology; (*ii*) the firm may induce a lower tax by investing if it is sufficiently big to trigger a regulatory response; and (*iii*) the number of other investing firms in equilibrium may decline if the firm decides to invest itself. These mechanisms were examined in Subsection 3.2. However, we do not allow the firms to induce a lower tax by operating at a marginal abatement cost level that is above the tax rate. We state the following proposition:

Proposition 2. *Assume that the regulator instantaneously responds to the investment of firms by adjusting the tax rate such that emissions remain equal to a constant emissions target. Let the firms correctly anticipate the new tax rate. Then, the regimes are equal if there is perfect competition in the potential permits market. In the case of imperfect competition, the ranking is ambiguous regarding both the WTP of the firms and the number of investing firms.*

Proof. See the Appendix.

The result under perfect competition is observed by Denicolo (1999), but is included for completeness. The two regimes are then identical because the regulator instantaneously reduces the tax rate such that it exactly mimics the permit price. This is analogous to the case with two equalities in equation (8), where we found both abatement and the costs of emissions to be equal in the two regimes. As firms exercise market power exactly by manipulating the permit price, it is not very surprising that this is no longer true under imperfect competition.

In order to build some intuition for Proposition 2, we give two simple examples where the relative WTPs of the firms are higher with a tax and with emissions trading, respectively. Example 1:

We know that a firm with market power will increase its abatement in order to reduce the permit price (cf. equation 3). The potential to exercise this option, which reduces the firm's total abatement and quota costs, is only available to Cournot firms under emissions trading. This creates an upper bound on the firm's cost savings by technology adoption that is lower than the upper bound under tax regulation. Suppose that the new technology offers zero emissions at zero costs. Then, because $K_{tax}^{oi} > K_{per}^{oi}\left(A^{-oi}\right)$ and $K_{tax}^{\eta i} = K_{per}^{\eta i}\left(A^{-\eta i}\right) = 0$, we have $WTP_{tax}^{i} > WTP_{per}^{i}$ by the equations (6) and (7).

Example 2: Suppose there is only one dominating firm and that the old technology is highly inflexible. Further, for the sake of the argument, assume that the cost savings by exercising market power are almost zero because of this technology inflexibility. (A numerical example with less demanding assumptions is given in the proof of Lemma 1.) Then, the costs with old technology are almost equal with a tax and emissions trading. Moreover, if the new technology is more flexible, allowing the firms to manipulate the permit price efficiently, the costs after technology implementation are lower with emissions trading. Hence, we have $WTP_{tax}^{i} < WTP_{per}^{i}$ because $K_{tax}^{oi} \approx K_{per}^{oi}\left(A^{-oi}\right)$ and $K_{tax}^{\eta i} > K_{per}^{\eta i}\left(A^{-\eta i}\right)$ (cf. the equations 6 and 7).

These examples accentuate the importance of our assumption that firms are unable to manipulate the tax rate by operating at a marginal abatement cost level that is above the tax. In this respect, we note that the regulator must adjust the tax rate in such a way that it *exactly* mimics the permit price in order for the Denicolo (1999) result to apply (otherwise the ranking is ambiguous). As the permit price depends upon both the technology of the fringe and the Cournot firms' reaction functions under imperfect competition, this is unlikely (but not impossible).

The literature sometimes examines interim regulation, where the regulator observes the technology innovation and adjusts its emissions target before the firms invest.[22] In this case, we simply redo our previous ex ante analysis with a stricter or equal emissions cap and a lower tax, maintaining our assumptions of equal aggregate emissions in period 1 and no regulatory action in phases 2 to 4. Therefore, our results still remain valid. Last, the previous ex ante analysis applies in the intermediate periods if the regulator's response is delayed.

5 Conclusion

In this paper, we have shown that the number of firms that adopt advanced abatement technology may be higher under emissions trading than under a tax if there is Cournot competition in the permits market. With perfect competition, this number will always be higher with a tax under ex ante

[22] See, for instance, Requate (2005b).

regulation. How can we explain this? One the one hand, the firms may free ride on the lower permit price triggered by the investments of other firms under emissions trading. This reduces the WTP of the firms under both perfect and imperfect competition. On the other hand, a firm's ability to influence the permit price might increase the WTP of firms. Although the first and negative effect is always present, the latter only applies to firms with market power. This explains why the number is higher with a tax if there is perfect competition in the emissions market, while the ranking is ambiguous otherwise. The ambiguity remains if we allow for environmental policy response unless there is perfect competition in the emissions trading market, in which case the regimes become equal.

As mentioned in the introduction, ex ante policy analysis involves that the regulator set the tax or aggregate emissions cap before the new technology is implemented. This allows the regulator to induce equal emissions with old technology. However, as the aggregate abatement cost function will be affected by the investments of the firms in the new technology, it leads to differences in both prices and quantities after technology implementation. As such, it arguably runs into the danger of comparing incommensurable entities. Moreover, even if we accept that the analysis induces differences in prices and quantities after the technological innovation, the argument still implies that ex ante analysis may be appropriate only if the technological advance is assumed to be a one-time-only event. Why is this true? Assume that there are s technological innovations. Then, the ex ante analysis assumption of equal aggregate emissions before technology implementation would be true for the first innovation, but not for the subsequent $s-1$ innovations (in which case, the prices and quantities differ across the regimes both before and after the technological innovation). Therefore, comparison under the assumption of equal initial price or equal initial quantities across the regimes presumes some sort of regulatory response if there is more than one technological innovation. Given the continuously forward-moving nature of R&D, this constitutes an important shortcoming of ex ante analysis. Last, ex ante analysis involves problems related to time inconsistency on the part of the regulator (see, e.g., Kydland and Prescott 1977). This well-known argument is not repeated here, but we note that it applies even if the advance is assumed a one-time-only event.

The ranking of regimes is an empirical question if there is market power in the potential emissions trading market. Nevertheless, does the theory indicate anything about what to expect? Because emissions are strategic substitutes (under emissions trading), other firms will increase their emissions if some firms choose to invest. This counteracts the efforts of the investing firms to induce a lower permit price. As such, free riding could both heavily deteriorate the gain from technology investment and give significant cost savings to the free riders. Thus, our theoretic framework suggests that it is rather unlikely that more firms implement the new technology under emissions trading than with a tax if the number of firms is reasonably high. On the other hand, more firms may invest with emissions trading if there are few dominant firms, or if the new technology is much more flexible than the old technology. The latter happens because the new technology then allows the firms to exploit their potential for market power more effectively.

Last, the present paper abstracts from the product market and focuses on cost minimization. Montero's papers (2002a, 2002b) show that Cournot competition in both product and emissions markets induce a strategic effect that may be negative under myopic regulation. This is because the investment of the firms reduces the permit price and, hence, the production costs of their rivals. Considerations involving Cournot competition in the product markets are outside the scope of the present paper, but constitute interesting topics for future research.

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Appendix

Proof of Lemma 1: The case of perfect competition is both handled in the text and proved previously by Requate and Unold (2003). We proceed by constructing simple examples that prove both $WTP_{tax} < WTP_{per}$ and $WTP_{tax} > WTP_{per}$ are possible with Cournot competition in the emissions market: Let there be $n = 2$ identical firms and let heading $i = 1,2$ indicate the firm involved. Further, assume $\varepsilon = 1$ and let the technology be characterized by $c^v\left(a^i\right) = \left(a^v/2\right)\left(a^i\right)^2$. Note that total cost is equal to $\psi\left(\varepsilon - a^i\right) + \left(a^v/2\right)\cdot\left(a^i\right)^2$, with φ equal to *p* and τ with emissions trading and a tax, respectively. Let the fringe's emissions and abatement technology be given by $e^\varphi = \varepsilon^\varphi - a^\varphi = 9 - a^\varphi$ and $c^\varphi\left(a^\varphi\right) = \left(1/2\right)\left(a^\varphi\right)^2$, respectively. The emissions cap is given by $\bar{E} = 10$. Then equation (1) entails that $p = a^\varphi = 1 - a^1 - a^2$. With emissions trading Cournot firm *i* solve:

$$Min_{a^i}\left[\left(1 - a^i - a^j\right)\left(1 - a^i\right) + \frac{\alpha^v}{2}\left(a^i\right)^2\right],$$

with solutions $a^i = \left(2 - a^j\right)\big/\left(2 + \alpha^k\right)$ for $i, j = 1,2$ and $i \neq j$ (cf. equation 3). These two solutions and the permit price constitutes a linear equation system with three equations and three unknowns (given *k*). This system determines the firms' WTP under emissions trading. Under a tax regime the firms face:

$$Min_{a^i}\left[\tau\left(1 - a^i\right) + \frac{\alpha^v}{2}\left(a^i\right)^2\right],$$

with solutions $a^i = \tau/\alpha^v$ (cf. equation 5). We also have $a^\varphi = \tau$ by equation (5). Last, in order to ensure equal emissions in the two regimes before the emergence of new technology, we must have $a^1 + a^2 + a^\varphi = 1$. We are left with a linear equation system with four equations and four unknowns. The last equation does not apply when we calculate the new equilibrium (with new technology). However, as the tax rate is assumed to be constant, we then use the remaining three equations to solve for three unknowns (τ is known).

Let the old and new technology be characterized by $\alpha^o = 3$ and $\alpha^\eta = 2$. Starting with emissions trading and using the above equations, we get $a^1 = a^2 = 1/3$ and $p = 1/3$ with old technology. Total cost is then equal to 0.39 for both Cournot firms. Now assume that one firm invests in new technology. This gives a total cost of 0.33 for both the investing and noninvesting firms, which entails a cost saving of 0.06. On the other hand, if both firms invest, the firms' cost savings are equal to 0.11. These payoffs induce the investment game illustrated in Figure 3 (with payoffs multiplied by 100). Assume firm 1 employs old technology. Then the WTP of firm 2 is equal to 0.06 (cf. equation 7). On the other hand, the WTP for firm 2 is only 0.33 – 0.28 = 0.05 if firm 1 chooses to invest because of the free ride option. Solving the four-equation system induced by a tax regime, we find that the WTP of the firms (as given by equation 6) is equal to 0.54 – 0.51 = 0.03. Hence, we have proved that $WTP_{per} > WTP_{tax}$ is possible.

Similar calculations show that $WTP_{per} < WTP_{tax}$ if $\alpha^o = 3$ and $\alpha^\eta = 1/2$. In general, equations (6) and (7) entail that $WTP_{per} < WTP_{tax}$ if α^η is sufficiently small because Cournot firms operate with lower costs. We also remember that $WTP_{per} < WTP_{tax}$ for sufficiently high *n* (as we approach perfect competition). This completes the proof.

Numerical example of Proposition 1: Continuing the examples above, the equations (6) and (7) give that $m_{tax} \leq m_{per}$ if $\alpha^o = 3$ and $\alpha^\eta = 2$, while $m_{tax} \geq m_{per}$ if $\alpha^o = 3$ and $\alpha^\eta = 1/2$ (depending on *S*(*m*)). Note that these examples refer to cases (*i*) and (*iii*), respectively.

Proof of Proposition 2: With perfect competition, the regulator repeatedly and instantaneously adjusts the tax rate such that it mimics the permit price. This is the case with three equalities in equation (8), which we found to imply that $WTP_{tax} = WTP_{per}$ in the text. Another proof is available in Denicolo (1999). We again prove the ambiguity with Cournot competition simply by constructing examples of both possibilities. The calculations are similar to the ones above, except that we keep the equation $a^1 + a^2 + a^\varphi = 1$ and adjust the tax rate after technology adoption in the tax regime. The reader may verify that the individual firm's WTP with a tax are then equal to 0.07 and 0.06 if one or both firms invest, respectively, given the technologies characterized by $\alpha^o = 3$ and $\alpha^\eta = 2$. We found above that 0.06 and 0.05 give these costs if one or both firms invest under emissions trading. Hence, $WTP_{per} < WTP_{tax}$ and $m_{tax} \geq m_{per}$ (depending on *S(m)*). It is straightforward to show that the technologies characterized by $\alpha^o = 10$ and $\alpha^\eta = 8$ give $WTP_{per} > WTP_{tax}$ and $m_{tax} \leq m_{per}$. This completes the proof.

Figures

Figure 1. The willingness to pay for advanced abatement technology with a tax (a) and emissions trading (b)

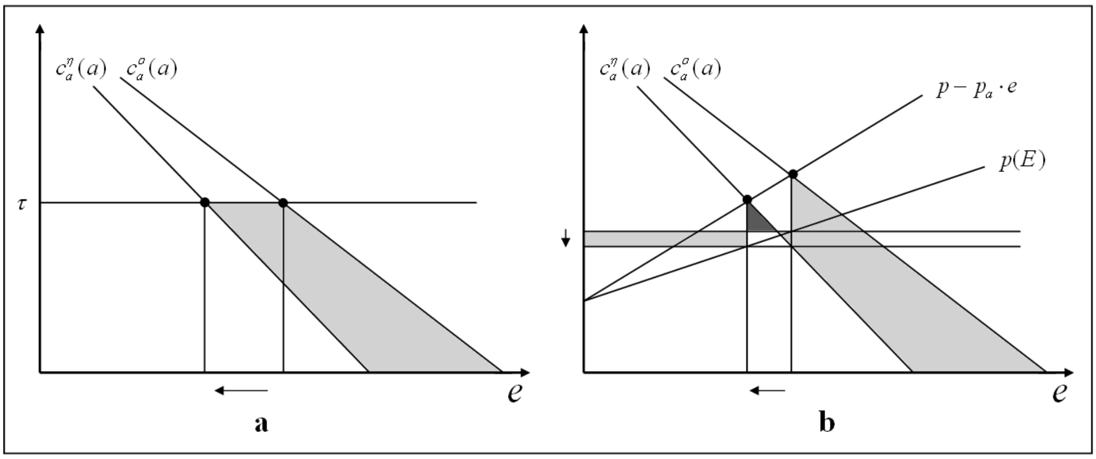

Figure 2. Illustration of Proposition 1. The number of investing firms (*m*) is always higher with a tax (permits) in a (c), while the ranking depends in *S(m)* in b

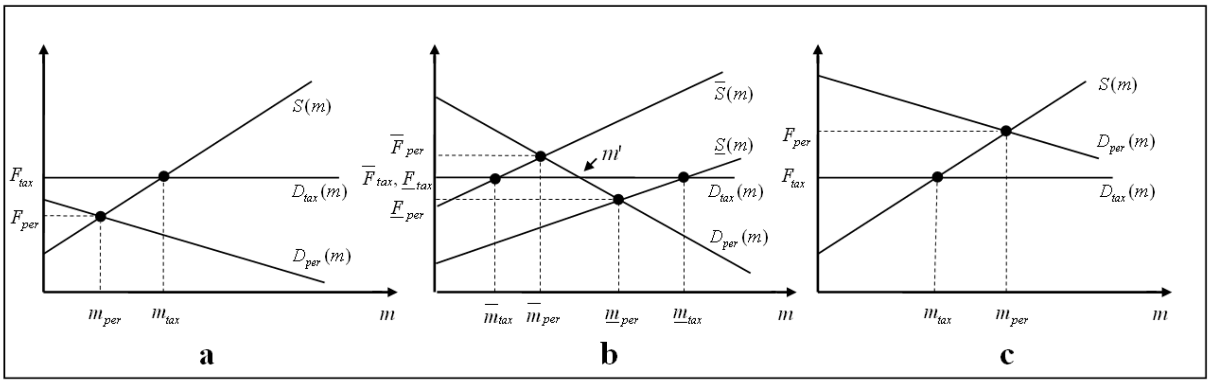

Figure 3. A numerical example of the investment game with two identical firms