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Incentives for Green R&D in a Dirty Industry under Price Competition

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Abstract

In an oligopolistic framework with price competition, we examine the effect of abatement taxes, as well as emission caps on the incentives for adopting a green technology. We identify two new strategic effects, namely the relative efficiency effect, and the competition softening effect, that affect the incentive for green R&D. Under an abatement tax, R&D incentives increase whenever the new technology is non-drastic, and the demand function is either approximately linear, or not too elastic. Another sufficient condition is that the market size be sufficiently large. With emission caps, the result depends on how green the new technology is.

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1. Introduction

We examine the effect of environmental regulations on the incentives for adopting green, i.e. less polluting technology. To this end we consider a dirty industry with two firms who first compete over R&D, and then over prices. The firms can either choose an existing technology, or a new technology which is not only more efficient, but less polluting compared to the existing one. We examine the impact of two classes of environmental regulations, abatement taxes and emission caps, on the incentive for R&D, characterizing conditions under which innovation incentives may, or may not increase.

We begin by considering the case where the government imposes an abatement tax. We find that innovation incentives increase whenever the new technology is non-drastic, and the demand function is either approximately linear, or not too elastic. Another sufficient condition, independent of curvature conditions, is that the market size be sufficiently large.

These results arise because of the *relative efficiency* effect identified here. Under a non-drastic technology an increase in the abatement tax makes an innovating firm relatively more efficient vis-a-vis a non-innovating firm (in the sense that the gap between the two marginal costs increases), though it becomes less efficient in an absolute sense. If the relative efficiency effect dominates, then an increase in the abatement tax increases the incentive for R&D. However, when this effect is small (or even absent, as with a drastic technology), then the innovation incentives are reduced.

We then consider the case of emission caps. Interestingly, emission caps increase innovation incentives if the new technology is not too green. The intuition follows from the fact that with an emission cap there is a *competition softening* effect, so that profit levels increase. The impact this competition softening effect has on R&D incentives however depends on how green the new technology is. If the new technology is as polluting as the old one, then profits under R&D increases at a faster rate, so that innovation incentives increase. Whereas if the new technology is a green one, then an emission cap increases the payoff from not doing R&D, so that the R&D incentive decreases.

We then briefly relate our paper to the literature. Palmer *et al.* (1995) show that in a monopoly context, environmental regulations necessarily reduce the incentives for green innovation in the sense that if a new green technology is not worth investing in before, then it will not be worth investing in after environmental regulations are imposed.[1] One strand of the subsequent literature argues that environmental regulation serves to reduce intra-firm inefficiencies, see e.g. Gabel and Sinclair-Desgagne (1997), while Simpson and Bradford (1996), for example, show that environmental taxes can lead to a reduction in R&D by foreign firms, thus increasing domestic profits. Xepapadeas and de Zeeuw (1999) demonstrate that by phasing out inefficient capital - the modernization effect, environmental regulation can lead to an increase in average productivity. Further, the modernization effect, along with a downsizing effect whereby there is a reduction of total capital stock, can mitigate, though not overturn, the increased costs of environmental regulation. Mohr (2002) uses a general equilibrium framework to address this question. Another paper that relies on external economies is Osang and Nandy (2003), who show that with large spill-over effects,

[1] Roy Chowdhury and Das (2006) however argues that it is possible that for a low level of environmental regulation a monopoly firm chooses the existing technology, whereas for a higher level of regulation the firm chooses the new green technology.

emission caps may increase innovation incentives.

The present paper differs from the literature in several respects, most significantly because it is based on strategic effects not explored so far. These effects differ from the ideas discussed above, namely X-efficiency, first mover advantages, changing the composition of capital and external economies.

The rest of the paper is organized as follows. The next section examines the case of abatement taxes. Whereas section 3 examines the case where stricter government regulation takes the form of emission caps. Finally, section 4 concludes.

2. Abatement Tax

The model comprises two firms 1 and 2, both producing the same homogeneous good with demand function $D(p)$, where $D(p)$ is twice differentiable and negatively sloped for all p such that $D(p) > 0$.

We then describe the technology. To begin with both firms have identical production costs. Further, the production cost is linear,[2] i.e. cq. By spending an amount F on R&D, however, both the firms can access a *new* technology. The newer technology is more efficient, with production costs $c'q$, where $c > c' \geq 0$.

Moreover, while both the technologies are dirty, the new technology is less polluting compared to the existing technology. We formalize this by assuming that under the existing technology, every unit of production generates one unit of pollution, whereas under the new technology, one unit of output generates α unit of pollution, where $\alpha \in [0, 1]$. Thus for any $\alpha < 1$, the new technology is greener compared to the old one. This formulation is in line with observations by Xepapadeas and de Zeeuw (1999) who find that new vintages of capital are often less polluting than the earlier vintages.

In this section we focus on an abatement tax which is formalized as Ae, where e denotes the level of emission.[3] Thus for an output level of q, the abatement tax is Aq under the old technology, and αAq under the new technology.

In order to focus on the case of interest we have

Assumption 1 (i) $D(c + A) > 0$.
(ii) $\min\{D(c + A)[c - c' + A(1 - \alpha)], \frac{D(c)}{2}(c - c')\} > F$.

Note that A1(i) states that the abatement tax A is not so large that the existing technology becomes infeasible, whereas A1(ii) states that R&D costs, i.e. F, is not too high.

We consider a two stage dynamic game where, given the abatement tax parameter, the firms first decide on their R&D levels, followed by prices. For simplicity we assume that there is no discounting, though nothing in the analysis hinges on this assumption.

Stage 1. The firms simultaneously decide on whether to do R&D, or not.

Stage 2. The firms play a Bertrand game where they simultaneously decide on their prices.

[2]The linearity assumption allows us to bypass the existence problem associated with convex cost functions under price competition, i.e. the Edgeworth paradox.

[3]Note that the abatement cost parameter used here is a linear version of that used by Barrett (1994). Osang and Nandy (2003) also adopt a similar formulation.

Let (p_1, p_2) denote the price vector announced in stage 2. The share of demand going to firm i, $i \neq j$, is

$$D_i(p_1, p_2) = \begin{cases} D(p_i), & \text{if } p_i < p_j, \\ \frac{D(p_i)}{2}, & \text{if } p_i = p_j, \\ 0, & \text{if } p_i > p_j, \end{cases} \tag{1}$$

Thus the profit function of firm i in stage 2 is given by

$$\pi_i(p_1, p_2, c_i) = D_i(p_1, p_2)(p_i - c_i), \tag{2}$$

where c_i is firm i's per unit production *plus* abatement costs. Let $p^m(\tilde{c})$ (respectively $\pi^m(\tilde{c})$) denote the equilibrium price (respectively profit) of a monopolistic firm with cost $\tilde{c}$.

We examine the subgame perfect Nash equilibrium of this game, so that we start by solving the stage 2 game first.

Stage 2. Depending on the pattern of R&D in stage 1, there are four possible outcomes. First, in case neither firm does R&D, both have the same effective marginal cost $(c + A)$, where note that this includes *both* production costs, as well as the abatement tax. Thus the equilibrium involves both firms charging the same price $(c + A)$, and having a profit of zero. Whereas if both firms do R&D then both firms charge the price $c' + \alpha A$ with a gross profit of zero, and a net profit of $-F$.

Finally, firm i (say), does R&D, whereas firm j does not, so that firm i has an effective marginal cost of $c' + \alpha A$, and firm j has a marginal cost of $c + A$. The equilibrium depends on whether firm i's technological advantage vis-a-vis firm j is *drastic*, or not.

Case (i). Suppose $c' + \alpha A$ is drastic compared to $c + A$, so that $p^m(c' + \alpha A) < c + A$. Then firm i charges its monopoly price and has a monopoly profit of $\pi^m(c' + \alpha A)$.

Case (ii). If the new technology is non-drastic, i.e. $p^m(c' + \alpha A) \geq c + A$, then optimally firm i undercuts $c + A$ by an arbitrarily small amount and has a profit that is arbitrarily close to $D(c + A)[c - c' + A(1 - \alpha)]$. For ease of exposition we shall take firm i's profit to be exactly $D(c + A)[c - c' + A(1 - \alpha)]$.[4]

Let the profit of firm i (the innovating firm), evaluated at the equilibrium price vector, be denoted by $\pi(c', c, A)$. Thus we have

$$\pi(c', c, A) = \begin{cases} \pi^m(c' + \alpha A), & \text{if } p^m(c' + \alpha A) < c + A, \\ D(c + A)(c + A - c' - \alpha A), & \text{otherwise.} \end{cases} \tag{3}$$

The following lemma will be useful later on.

Lemma 1 *(i) $\pi(c', c, A)$ is decreasing in A whenever either (a) $p^m(c' + \alpha A) < c + A$, or (b) $p^m(c' + \alpha A) \geq c + A$ and $\alpha = 1$.*
(ii) If $p^m(c' + \alpha A) \geq c + A$, but $\alpha < 1$, then $\pi(c', c, A)$ may be increasing in A.

[4] As is well known, there is an open set problem here that can be resolved by allowing for grid pricing, and then taking the grid size to zero. While for ease of exposition we refrain from invoking these technicalities, allowing for these does not affect the results qualitatively.

Proof. For $p^m(c'+\alpha A) < c+A$, from (3) note that $\pi(c',c,A) = \pi^m(c'+\alpha A)$. Thus, from the envelope theorem, it follows that

$$\frac{d\pi(c',c,A)}{dA} = \frac{d\pi^m(c'+\alpha A)}{dA} = \frac{\partial \pi^m(c'+\alpha A)}{\partial A} = -\alpha D(p^m(c'+\alpha A)) \leq 0,$$

with the inequality being strict whenever $\alpha > 0$.

Whereas

$$\frac{D(c+A)(c-c'+A(1-\alpha))}{dA} = D'(c+A)[c-c'+A(1-\alpha)] + (1-\alpha)D(c+A),$$

which is negative for $\alpha = 1$. ■

The following examples show that there do exist parameter values for which $D(c+A)(c+A-c'-\alpha A)$ is, in fact, increasing in A so that Lemma 1(ii) is not vacuous.

Example 1 Let the demand function be linear i.e. $q = a - p$. In this case $p^m(c'+\alpha A) = \frac{a+c'+\alpha A}{2}$. Let $a + c' - 2c > A(2-\alpha)$, so that $p^m(c'+\alpha A) > c+A$. Under this condition $\pi(c',c,A) = (a-c-A)[c-c'+A(1-\alpha)]$, which is increasing in A if and only if $a+c'-2c > A(2-\alpha)+\alpha(a-c-A)$. Given that $p^m(c'+\alpha A) > c+A$, this condition is satisfied whenever the new technology is sufficiently green, i.e. α is small.

Further, for this example it is easy to check that if $p^m(c'+\alpha A) < c+A$ for some A, then $\forall A' > A$ it is the case that $p^m(c'+\alpha A') < c+A'$. Thus, for linear demand functions, the profit function is (possibly) increasing in A for A small. As A increases however, the profit function ultimately becomes decreasing in A, and remains so for all higher values of A.

Example 2 Let the demand function be $(1-\alpha)$-*inelastic* in the sense that $\frac{D'(p)}{D(p)/p} \geq -(1-\alpha)$, $\forall p$ (note that this is consistent with the demand function being elastic). Note that $\frac{-D'(c+A)(c-c'+A(1-\alpha))}{D(c+A)} < \frac{-D'(c+A)(c+A)}{D(c+A)} \leq (1-\alpha)$, where the last inequality follows since $D(p)$ is $(1-\alpha)$-*inelastic*, which implies that $D(c+A)(c-c'+A(1-\alpha))$ is increasing in A.

The intuition for Lemma 1(ii) and the two examples is as follows. Consider a situation where only one of the firms does R&D. Suppose moreover that the new technology is non-drastic, i.e. $p^m(c'+\alpha A) \geq c+A$. In case A increases, then *relative* to its competitor, the firm undertaking R&D becomes more efficient, which is captured by the fact that the gap between the two marginal costs, i.e. $[c-c'+A(1-\alpha)]$, increases.

Of course, in an absolute sense this firm becomes less efficient with an increase in A, which captures the effect discussed by Palmer *et al.* (1995). Whenever this relative efficiency effect dominates the absolute one, an increase in A would lead to an increase in $\pi(c',c,A)$. Note that for the cases described in Lemma 1(i), this relative efficiency effect is absent, so that the absolute effect necessarily dominates. Hence the profit of the efficient firm is decreasing in A.

Stage 1. Given the preceding analysis, in stage 1, the firms essentially play the following matrix game:

	R&D	No R&D
R&D	$-F,\ -F$	$\pi(c',c,A)-F,\ 0$
No R&D	$0,\ \pi(c',c,A)-F$	$0,\ 0$

where the strategies of firm 1 are written vertically and those of firm 2 are written horizontally. For every payoff vector the first and second entry represent, respectively, the net equilibrium payoff of firm 1 and firm 2.

We then solve for the Nash equilibrium of this matrix game. Given Assumption 1(ii), there are two pure strategy asymmetric Nash equilibria, where one of the firms adopts the new technology, and the other one does not. We however focus on the symmetric mixed strategy Nash equilibrium where both firms do R&D with probability $r(A)$. It is straight forward to show that

$$r(A) = 1 - \frac{F}{\pi(c', c, A)}. \tag{4}$$

Given A1(ii), we have that $1 > r(A) > 0$.

Summarizing the above discussion we can now write down our first proposition.

Proposition 1 *There is a symmetric mixed strategy equilibrium, where both firms do R&D with probability* $r(A) = 1 - \frac{F}{\pi(c',c,A)}$.

We next turn to comparative statics. Note that irrespective of whether the new technology is drastic (in the sense that $p^m(c' + \alpha A) < c + A$), or not, we have that $\pi(c', c, A)$ is decreasing in both α, and c'. Thus the equilibrium level of R&D increases if the new technology either becomes less polluting, or greener, which is intuitive.

We then observe that whether the new technology is drastic or not depends on how green the technology is. From the profit-maximizing condition, $p^m(c' + \alpha A)$ is strictly increasing in α. Thus there exists $\tilde{\alpha}$ such that it is the maximum $\alpha \in [0, 1]$ for which $p^m(c' + \alpha A) \leq c + A$. For ease of exposition, we focus on the case where $0 < \tilde{\alpha} < 1$.

Proposition 2 *(i) If either $\alpha < \tilde{\alpha}$, so that the new technology is drastic, or $\alpha = 1$, so that it is non-drastic, but is as polluting as the existing one, then the R&D probability under the symmetric mixed strategy equilibrium, i.e. $r(A)$, decreases with an increase in the abatement tax, A.*

(ii) If $1 > \alpha \geq \tilde{\alpha}$, so that the new technology is non-drastic, as well as less polluting compared to the old one, then the innovation probability $r(A)$ may be increasing in the abatement tax, A. If, in addition, the demand function is either linear, or $(1 - \alpha)$-inelastic, then an increase in A necessarily increases the R&D probability $r(A)$.

(iii) The equilibrium level of R&D, $r(A)$, increases as the new technology becomes less polluting, as well as more efficient.

Proposition 2(ii) demonstrates that whenever the new technology is non-drastic and green compared to the existing technology, innovation incentives increase for appropriate parameter values, in particular if the demand function is approximately linear, or not too elastic. As argued in Lemma 1(ii), the intuition follows from the relative efficiency effect of an increase in A. If this effect is sufficiently strong so that an increase in A increases $D(c + A)(c - c' + A(1 - \alpha))$, then innovation incentives increase. As Proposition 2(i) demonstrates though, whenever this effect is small (or absent, e.g. when the newer technology is drastic vis-a-vis the old one), the relative efficiency effect is dominated by the Palmer *et al.* (1995) effect.

Note, however, that Proposition 2(ii) is conditional on the technology being non-drastic. We then turn to identifying sufficient conditions that ensure both that the technology is non-drastic, and given that, the innovation incentives are increasing in the abatement tax. We develop a condition dependent on market size. In order to capture this idea let us introduce a market size parameter, β, so that for the rest of this section market demand is given by $\beta + D(p)$.

We first argue that for β sufficiently large, the new technology is non-drastic for any given A. Recall that the monopoly price satisfies

$$\beta + D(p) = -D'(p)(p - c' - \alpha A), \tag{5}$$

so that for $D(p)$ concave, the monopoly price, $p^m(c' + \alpha A, \beta)$, is increasing in β. Further, if $D'(p)$ is bounded, then the monopoly price goes to infinity as β increases.

Lemma 2 *Let $D(p)$ be concave and $D'(p)$ be bounded. Then $p^m(c' + \alpha A, \beta)$ is increasing in β and goes to infinity for β large.*

We next argue that for any sufficiently large market size, $\pi(c', c, A)$ is increasing in A whenever the new technology is non-drastic. Note that

$$\frac{d(\beta + D(c + A))[c - c' + A(1 - \alpha)]}{dA} = D'(c + A)(c - c' + A(1 - \alpha)) + [\beta + D(p)](1 - \alpha),$$

which is positive for β sufficiently large.

Putting the two arguments together, we have that, for β sufficiently large the new technology is non-drastic compared to the existing one, so that the innovation incentives are increasing in the abatement tax. Further, for A small, the industry becomes more competitive post R&D, since $c' < c$.

Proposition 3 *Let the market demand be $\beta + D(p)$, with $D(p)$ concave and $D'(p)$ bounded. Then, for any A, there exists a market size $\beta(A)$ such that $\forall \beta \geq \beta(A)$, the innovation incentive $r(A)$ is increasing in the abatement tax. Moreover, for A small, the new technology is more competitive compared to the existing one.*

As an example, let the demand function be linear, i.e. $D(p) = a - p$. It is then straightforward to show that whenever the demand is large enough, so that $a > 2c + c' + A(2 + \alpha)$, the innovation incentive is increasing in A.

3. Emission Caps

In this section we consider the impact of an *emission cap* of e on both firms. This translates into an *output cap* of e on a non-innovating firm, and of $\frac{e}{\alpha}$ in case of an innovating firm. We shall argue that depending on how green the new technology is, emission caps may or may not increase R&D incentives.

In order to focus on the case of interest we assume that in case there is no R&D, the emission cap binds for both firms, i.e. $2e < D(c)$. We assume that the residual demand function is the efficient one.[5] We need a final technical assumption that ensures the existence of a pure strategy equilibrium in the price game.

Assumption 2 *The demand function is elastic, i.e.* $\frac{D'(p)}{D(p)/p} \leq -1$, $\forall p$.

For simplicity we focus on two extreme cases, first when $\alpha = 1$ and second when $\alpha = 0$, showing that the results for the two cases are quite different.

Case (i). $\alpha = 1$**:** In this case the new technology is as polluting as the existing technology. While Proposition 1 shows that an increase in abatement tax does not increase the R&D incentives in this case, the results are different with an emission cap. As usual we solve the game backwards.

Stage 2. Note that the emission cap necessarily binds, irrespective of whether the firms do R&D, or not. It is then straightforward to extend the argument in Tasnadi (1999) to show that for all R&D outcomes, the equilibrium involves both firms charging a price $D^{-1}(2e)$ and supplying e.

Stage 1. We then calculate the incentive for R&D. Clearly the *gross gain* to firm i from doing R&D is $e(c - c')$. Thus R&D is carried out if and only if $e(c - c') \geq F$. Thus for $e(c - c') \geq F$, the firms adopt the technology with probability 1. Note that such an e necessarily exists whenever $\frac{D(c)}{2}(c - c') > F$.

We then consider the case where there are no emission caps (formally an emission cap set at infinity). Note that this is equivalent to the case in the earlier section with an abatement tax of $A = 0$. Thus the probability of doing R&D is the same as in that case, so that $R(\infty) = r(0)$. Finally from (4) it follows that $0 < R(\infty) = r(0) < 1$. Thus under these parameter values R&D increases under environmental regulations.

Intuitively, the emission cap binds both in the presence and the absence of R&D, so that profits increase under both scenarios compared to the case where there is no such cap. The profit under R&D however increases at a greater rate (since marginal costs are lower), so that the incentive to do R&D increases.

Case (ii). $\alpha = 0$**:** In this case the new technology is a green one and leads to zero pollution.

Stage 2. Note that the emission cap never binds for a firm that does R&D. Thus the equilibrium involves both firms charging a price of c' in case both firms do R&D, and a price of $D^{-1}(2e)$ in case neither firm does R&D. Whereas if firm i (say) alone does R&D, then it has a profit of $\pi(c', c, 0) - F$, whereas firm j has a profit of zero.

Stage 1. Given the preceding analysis, in stage 1, the firms essentially play the following matrix game:

	R&D	No R&D
R&D	$-F,\ -F$	$\pi(c', c, 0) - F,\ 0$
No R&D	$0,\ \pi(c', c, 0) - F$	$[D^{-1}(2e) - c]e,\ [D^{-1}(2e) - c]e$

[5] Our analysis however goes through in case the residual demand follows the proportional rule.

Note that in case $\pi(c', c, 0) - F < [D^{-1}(2e) - c]e$, then in equilibrium there is no R&D. So let $\pi(c', c, 0) - F > [D^{-1}(2e) - c]e$. We consider the symmetric mixed strategy equilibrium where both firms do R&D with probability

$$R(e) = 1 - \frac{F}{\pi(c', c, 0) - [D^{-1}(2e) - c]e}. \tag{6}$$

It is clear that the R&D probability in the absence of emission caps is given by $r(0)$. Comparing with (4), we find that, $R(e) < r(0) = R(\infty)$, so that an emission cap reduces the incentive to do R&D. The result is quite intuitive and driven by the fact that in this case the R&D incentives for firm i is unaffected by the emission cap if firm j does R&D (since firm i has zero profits in either case), but it is adversely affected by such a cap in case firm j does R&D. This follows from the competition softening effect since the payoff from not doing R&D increases because of the emission cap.

Proposition 4 *If the new technology is not too green, in particular if $\alpha = 1$, then the R&D probability is higher in the presence of an emission cap. If however the new technology is very green, in particular if $\alpha = 0$, then an emission cap lowers the probability of doing R&D.*

Thus innovation incentives as long as the new technology is not too green. The intuition is as follows. With a quantitative restriction on pollution, there is a qualitative change in the nature of competition itself. In the absence of any such restrictions, there is unfettered price competition, whereas with emission caps there is a competition softening effect (since the firms cannot produce beyond their cap). How this softening of competition affects the R&D incentives is quite subtle though.

4. Conclusion

We examine the incentive effects of environmental regulations in a strategic framework with price competition. Our analysis relies on strategic effects that are likely to be present in many oligopolistic contexts, namely the relative efficiency effect and the competition softening effect. The relative efficiency effect arises since, with an abatement tax, an increase in abatement tax makes a firm opting for a greener technology relatively more efficient compared to the other firm. The competition softening effect arises because an emission caps changes the nature of competition from one of unfettered price competition to a less intense one. Interestingly, depending on how green the new technology is, this effect has an ambiguous effect on the innovation incentives. These two effects are new in this literature, and differs from the existing ideas in the literature, namely X-efficiency, first mover advantages in a strategic trade context, phasing out of old technology and external economies. We identify conditions such that this effect may or may not be sufficient to increase the incentive for R&D.

Further, our analysis throws up the following testable hypotheses:

A. An increase in abatement tax is likely to increase innovations whenever (i) the demand function is either linear, or elastic but not significantly so, or (ii) whenever the market size is sufficiently large.

B. An increase in emission taxes is likely to increase innovations whenever the new technology is not too green.

One possible direction for future research may be to re-examine this question in under horizontal product differentiation. Apart from adding to the realism of the model, this would allow one to compare the results across price, and quantity competition, thus examining the sensitivity of the results to the nature of competition. This is beyond the scope of the present paper though and must await future work.

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