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## **MARKET STRUCTURE AND ENVIRONMENTAL INNOVATION**

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This paper studies firms' incentives to invest in environmental R&D under different market structures (Cournot and Bertrand) and environmental policy instruments (emission standards, taxes, tradable permits and auctioned permits). Because of market strategic effects, R&D incentives vary widely across market structures and instruments. For example, when firms' products are strategic substitutes (i.e., Cournot), either emission standards, taxes or auctioned permits can provide the most incentives. But when firms' products are strategic complements, either taxes or auctioned permits provide the most incentives. If markets are perfectly competitive, however, permits and emission standards offer similar incentives that are lower than those offered by taxes.

JEL classification codes: L13, L50, Q28

Key words: environment, regulation, market structure, innovation

### **I. Introduction**

The relationship between market structure and technical progress has attracted significant attention from economists over the last decades. Motivated by the notion that technical progress is perhaps the main vehicle to solve

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environmental problems in the long-run (Kneese and Schultze, 1978), economists have also focused on the extent to which different environmental policy instruments provide firms with incentives to invest in environmental R&D. This latter work has been carried out under the assumption of perfect competition, abstracting from market structure considerations (Tietenberg, 1985; Millman and Prince, 1989; Jung et al., 1996; Requate, 1998; and Parry, 1999).<sup>1</sup> In general, authors have found that market-based regulatory instruments such as taxes, tradable permits and auctioned permits provide more R&D incentives than command-and-control instruments such as emission standards.<sup>2</sup>

In this paper, I extend the study of firms' incentives to invest in environmental R&D by considering the possibility of imperfect competition in output and permit markets. Since real-world markets are rarely perfectly competitive, extending the environmental innovation literature to allow for imperfect competition can have important policy implications. In fact, the industrial organization literature has shown that strategic or market interactions in oligopoly markets can significantly affect "investment decisions," including cost-reducing R&D (Brander and Spencer, 1983; Spence, 1984; Fudenberg and Tirole, 1984; and Bulow et al., 1985). Depending on the market structure, some firms may have incentives to overinvest while others may have incentives to underinvest. While it is likely that these strategic interactions also affect

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<sup>1</sup> One exception is Biglaiser and Horotiwz (1995) that consider firms interaction in the market for the discovery of new pollution-control technologies and assume perfect competition in the output market. While they focus on the optimal design of a technology standard coupled with a tax, in this paper I focus on the comparison among individual instruments.

<sup>2</sup> Less consistent with the above findings are the works of Magat (1978) and Malueg (1989), who showed that relative incentives may vary depending on firm's specific technologies and elements of instrument design. Laffont and Tirole (1996) have also shown that plain tradable permits may offer little R&D incentives, but the introduction of advance permits and options can restore these incentives. However, they did not compare permits with other instruments.

firms' incentives to invest in environmental R&D, it remains to be seen whether the changes in incentives significantly affect the "environmental R&D rankings" found by previous studies. It may well be that incentives under market-based instruments are still greater (although different in magnitude from the earlier findings) than they are under command-and-control instruments.

To study the effect of imperfect competition on environmental R&D, I extend the model of Montero (2002) and have two firms (1 and 2) competing in either quantities (i.e., Cournot competition) or prices (i.e., Bertrand competition) in the output market and at the same time being subject to an environmental regulation. The regulatory goal is to limit emissions at some predetermined level by means of one of the following four regulatory instruments: emission standards, taxes, (grandfathered) tradable permits and auctioned permits. Firms can reduce their compliance costs and improve their position in the output market by investing in environmental R&D.

As explained by Tirole (1988, pp. 323-336), in such a market-regulatory setting, firm 1's incentive to invest in R&D results from two effects. The direct or cost-minimizing effect accounts for that fraction of firm 1's cost savings (or profit increase) that does not affect firm 2's choice of output. In other words, this effect would exist even if firm 1's R&D investment were not observed by firm 2 before the latter determined its output. The strategic effect, on the other hand, results from the influence of firm 1's R&D investment on firm 2's choice of output. For example, firm 2 may increase its output as an optimal response to firm 1's R&D investment adversely affecting firm 1's profits. Hence, it may be optimal for firm 1 to invest less in R&D in order to avoid an aggressive response by firm 2 in the output market. The sign of this strategic effect may be positive or negative depending on the market-regulatory structure. Not surprisingly, after accounting for direct and strategic effects, the results of this paper indicate that the "R&D rankings" of instruments differ in many ways from earlier findings. In fact, I find situations in which standards offer greater R&D incentives than the other three instruments.

The rest of the paper proceeds as follows. In Section II, I develop the

basic model and explain how to estimate firms' incentives to invest in environmental R&D. In Section III, I assume that firms compete à la Cournot in the output market and estimate R&D incentives under the four aforementioned regulatory instruments. In Section IV, I repeat the analysis of Section III but now assuming that firms compete à la Bertrand. In Section V, I develop some numerical examples to illustrate and complement some of the analytical results of the previous sections using the social optimum solution as a benchmark. In Section VI, I discuss R&D under perfect competition and provide concluding remarks.

## II. The Model

Consider two profit-maximizing firms (denoted by  $i$  and  $j$ ) competing under different market and regulatory structures. When firms compete à la Cournot in the output market (i.e., firms' outputs are strategic substitutes), the inverse demand function is  $P = P(Q)$ , where  $P$  is the output market price and  $Q = q_i + q_j$  is industry output. When firms compete à la Bertrand (i.e., firms' outputs are strategic complements), the demand curve faced by firm  $i$  is  $q_i = D_i(p_i, p_j)$ , where  $p_i$  is the price chosen by firm  $i$ .

Without loss of generality, firm  $i$  produces  $q_i$  at no cost, and in the absence of any regulation, production leads also to  $q_i$  units of emission. Emissions can be reduced at a total cost of  $C(r_i)$ , where  $r_i$  is the amount of emissions reduced, and, as usual,  $C'_i > 0$  and  $C''_i > 0$ . It is convenient to re-write the abatement function as  $C_i(q_i - e_i)$ , where  $q_i - e_i \dots r_i$  and  $e_i$  is firm  $i$ 's emissions after abatement. Thus, if the firm does not abate any pollution  $e_i = q_i$ .

The environmental regulatory structure consists of a goal and instrument. I assume that the regulatory goal is to limit aggregate emissions at some level  $\bar{E} = e_i + e_j$  by means of one of the following four regulatory instruments: emission standards, taxes, (grandfathered) tradable permits and auctioned permits. Under emission standards, firms' emissions are limited to  $\bar{e}_i$  and  $\bar{e}_j$  respectively, such that  $\bar{e}_i + \bar{e}_j = \bar{E}$ . Under tax regulation, firms pay  $\mathcal{T}$  dollars for each unit of emissions. The tax level  $\mathcal{T}$  is set based on the production

technology, output demand, and current abatement technology (i.e., before R&D) to yield  $\bar{E}$ . Under permits regulation, a total number of  $\bar{E}$  permits are either distributed freely or auctioned off. I assume that each instrument design remains unchanged regardless the amount of R&D undertaken afterwards. Alternatively, one could assume that the regulator is unable to observe R&D investments or that observes them after a long time.

Firms engage in output competition taking into account R&D investments that can reduce their environmental compliance costs, and hence, their ability to compete in the market. Following Spence (1984), I assume that if firm  $i$  and firm  $j$  invest in environmental R&D, abatement costs reduce from  $C_i(q_i - e_i)$  to  $k_i C_i(q_i - e_i)$ , where  $k_i$  is a R&D production function of the form,<sup>3</sup>

$$k_i = f_i(K_i + \theta K_j) \quad (1)$$

where  $K_i$  is firm's  $i$  R&D effort with a total cost of  $v_i K_i$ ,<sup>4</sup>  $f(0) = 1$ ,  $f'(x) > 0$ ,  $f' < 0$ ,  $f'' > 0$ , and  $0 \leq \theta \leq 1$  is a parameter intended to capture possible spillovers. If  $\theta = 0$  there are no spillovers, while if  $\theta = 1$  the benefits of each firm's R&D efforts are fully shared.

Depending on the regulatory instrument, the solution of the model involves either a two-period or three-period equilibrium. In the case of emission standards and taxes there are two periods. First, the two firms choose R&D levels  $K_i$  and  $K_j$  respectively, which are known to both firms, and then, actions  $a_i$  and  $a_j$  (which can be either quantities or prices), and emission levels  $e_i$  and  $e_j$  are simultaneously determined. In the case of permits, there are three periods.

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<sup>3</sup>This way of modeling innovation applies more naturally to production process innovation at the firm. For example, under Title IV of the 1990 Clean Air Act Amendments electric utilities have been making “R&D efforts” to retrofit their boilers to burn different type of coals and hence reduce their compliance costs.

<sup>4</sup>Although one could simply treat  $K_i$  as dollars invested in R&D, this formulation facilitates the numerical resolution of the model. Still, I will often use the words “R&D investment” to refer to  $K$ .

First, the two firms choose R&D investments  $K_i$  and  $K_j$ , then, emission levels  $e_i$  and  $e_j$  (by the amount of permits withheld) and permits price  $F$  are determined, and finally, actions  $a_i$  and  $a_j$  are resolved.<sup>5</sup>

To decide upon the amount of R&D to undertake, firms must have some expectation about how the permits and output markets' equilibria will be resolved. I assume, that for any given level of R&D, firms have complete information, and therefore, correctly anticipate the Nash equilibrium afterwards, which is resolved either as a Cournot game or as a Bertrand game with differentiated products. When the environmental regulation takes the form of tradable or auctioned permits, I assume that for any given level of R&D and expected output, firms Nash bargain over the permits price  $F$  (total quantity is fixed at  $\bar{E}$ ). Since information is complete and there are no income effects, the Nash bargaining solution leads to the efficient level of emissions for any given level of investment ( $K_i$  and  $K_j$ ) and expected actions ( $a_i$  and  $a_j$ ), regardless the initial distribution of the tradable permits (Spulber, 1989).

The optimal amount of R&D to undertake by firm  $i$  under different market and regulatory structures could be obtained from maximizing  $\pi_i(K_i, K_j) - vK_i$ , where  $\pi_i(K_i, K_j)$  represents firm  $i$ 's profits resulting from the subgame perfect Nash equilibrium in the permits (if it is the case) and output markets after observing R&D levels  $K_i$  and  $K_j$ . The solution  $K_i^*$  must satisfy  $d\pi_i(K_i, K_j)/dK_i = v_i$ , where  $d\pi_i(K_i, K_j)/dK_i$  is the total derivative of  $\pi_i$  with respect to  $K_i$ .

Rather than estimating  $K_i^*$  directly, however, in this paper I compare R&D incentives from the total derivative of  $\pi_i(K_i, K_j)$  with respect to  $k_i$ , that is  $d\pi_i/dk_i$ . Because  $K_i^*$  solves

$$\frac{d\pi_i}{dK_i} = \frac{d\pi_i}{dk_i} f'(K_i + \theta K_j) = v_i \quad (2)$$

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<sup>5</sup> Since permits can be considered as another input into the production process, it is natural to think that the permits market clears before the output market.

$f' < 0$  and  $f'' > 0$ , it is immediate that  $K^*$  increases with  $-dB_i/dk_i$ , regardless the level of spillovers  $\mathcal{Z}$ .<sup>6</sup>

Thus, if  $-d\pi_i^A/dk_i$  and  $-d\pi_i^B/dk_i$  are the total derivatives corresponding to regulatory instruments  $A$  and  $B$ , respectively, we would have that  $A$  leads to greater R&D than  $B$  does if  $-d\pi_i^A/dk_i > -d\pi_i^B/dk_i$  for all  $k_i$ . If  $-d\pi_i^A/dk_i > -d\pi_i^B/dk_i$  for only some values of  $k_i$ , however, we would have that instrument  $A$  may lead to more, equal or less R&D than instrument  $B$  depending on the value of market, regulatory, and R&D parameters. In this situation, for example, one instrument can more effectively force drastic innovations (big reductions in  $k$ ) than the other instrument.

### III. R&D under Cournot Competition

In this section, I solve the model and estimate the value of  $-dB_i/dk_i$  for each regulatory instrument when firms compete à la Cournot. I assume that firms are symmetric in all respects, including their allocation of emission standards and tradable permits.

#### A. Emission Standards

Under emission standards regulation and Cournot competition, for any given a level of  $k_i$  and  $k_j$  (or  $K_i$  and  $K_j$ ), firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = P(Q) q_i - k_i C_i(q_i - e_i) \quad (3)$$

subject to  $e_i \leq \bar{e}_i$ , where  $e_i$  is the emission standard established for firm  $i$  and  $Q = q_i + q_j$ . Setting  $e_i = \bar{e}_i$ , the second-period equilibrium is given by the following first-order condition (FOC) for  $q_i$

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<sup>6</sup> Since  $k = f((1+\mathcal{Z})K)$ , eq. (2) can be entirely written as a function of  $k$  as  $dB/dk = v/f'(f^1(k))$ , which solution  $K^*$  will be unique and independent of  $\mathcal{Z}$ . Note, however, that  $K^*$  is a decreasing function of  $\mathcal{Z}$ .

$$P(Q) + P'(Q) q_i - k_i C'_i (q_i - e_i) = 0 \quad (4)$$

The third term of (4) indicates that the environmental regulation rises marginal production costs by an amount equal to marginal abatement cost at  $e_i = \bar{e}_i$ , which depends on the amount of R&D undertaken.

The incentives to invest in R&D are obtained from the (negative) value of the total derivative of (3) with respect to  $k_i$  at the optimum level of output and emissions. Using the envelope theorem, this derivative is equal to

$$-\frac{d\pi_i}{dk_i} = C_i(q_i - \bar{e}_i) - P'(Q) q_i \frac{dq_j}{dk_i} \quad (5)$$

The first term on the right-hand side (RHS) of (5) is the direct effect, which is always positive and increasing with the amount of abatement  $q_i - e_i$ . Hence, the tighter the standard (i.e., the lower  $\bar{e}$  becomes) the higher the direct incentives.

The second term on the RHS of (5) is the strategic effect. This effect results from the influence of R&D investment on firm  $j$ 's second period action. Since  $P' < 0$ , its sign depends on the sign of  $dq_j/dk_i$ . In this emission-standards-Cournot game, environmental R&D can be interpreted as pure cost-reducing innovation, and therefore we should expect that  $dq_j/dk_i > 0$ . The implication is that a lower  $k_i$ , which means lower marginal abatement costs  $k_i C'_i$ , raises firm  $j$ 's relative costs reducing its output. This interaction in the output market results in a positive strategic effect, leading to more R&D than otherwise.

Obtaining an expression for  $dq_j/dk_i$  (see Appendix A), eq. (5) becomes

$$-\frac{d\pi}{dk} = C(q - \bar{e}) - P'q \frac{C'(P' + P''q)}{(k C' - P') (3P' + 2P''q - k C'')} \quad (6)$$

Assuming that  $P' + P''q < 0$  to insure the existence of a unique pure-strategy Nash equilibrium in output (Gaudet and Salant, 1991), the fraction  $dq_j/dk_i$  of the second term in (6) is indeed positive and so is the strategic effect. Using

Fudenberg and Tirole's (1984) taxonomy, under these market and regulatory structures where products are strategic substitutes, firm's optimal strategy is to behave as a "top dog" and overinvest in R&D.<sup>7</sup>

### B. Taxes

Under tax regulation and Cournot competition, for any given level of  $k_i$  and  $k_j$ , firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = P(Q)q_i - k_i C_i(q_i - e_i) - \tau e_i \quad (7)$$

where  $\tau$  is a fixed tax that firm  $i$  must pay for each unit of emission. The second-period equilibrium is given by the FOCs for  $e_i$  and  $q_i$

$$k_i C'_i(q_i - e_i) - \tau = 0 \quad (8)$$

$$P(Q) + P'(Q) q_i - k_i C'_i(q_i - e_i) = P(Q) + P'(Q) q_i - \tau = 0 \quad (9)$$

Equation (8) indicates that at the optimum, marginal abatement costs are equal to the tax level  $\tau$ , which implies that the oligopoly structure of the industry does not affect the cost-effectiveness property of taxes. Eq. (9) shows that the environmental regulation rises the marginal cost of production by  $\tau$ , which is independent of the amount of R&D. The latter is because the firm simultaneously adjusts  $q_i$  and  $e_i$  for (8) to always hold.

According to (9) then the optimal  $q_i$  is independent of  $k_i$  and  $k_j$ , which in turn implies that  $q_j$  will be independent of  $k_i$  and  $k_j$  as well. The reason is that the marginal cost of production (which here reduces to environmental compliance only) for both firms is constant at  $\tau$ .<sup>8</sup> Therefore,  $dq_j/dk_i = 0$  and

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<sup>7</sup> Note that we are in a case of accommodation of entry rather than entry deterrence.

<sup>8</sup> Note that if we let the production cost be  $c$  the total marginal production cost will still be constant and equal to  $c + \tau$ .

the (negative) value of the total derivative of (7) with respect to  $k_i$  at the optimum is, from the envelope theorem, equal to

$$-\frac{d\pi}{dk} = C(q - e) \quad (10)$$

Under tax regulation there is no strategic effect because firm  $i$ 's R&D investments do not affect its marginal production costs (they do affect total costs), and consequently, its output.

Let us now compare incentives under taxes and under emission standards. Equation (10) differs from (6) in some important ways. First, before any investment in R&D is undertaken (i.e.,  $k_i = 1$ ), (4) and (9) indicate that output levels are the same by regulatory design (tax level  $\tau$  leads to emissions  $\bar{e}_i$  before R&D). This implies that the direct effect  $C_i'(q_i - e_i)$  is the same for both emission standards and taxes. However, under emission standards regulation there is a positive strategic effect that increases R&D incentives, which is measured by the second term of (6). Thus, if the R&D function  $f(\cdot)$  is such that only mild innovations take place (optimal  $k$  close to 1), R&D is likely to be higher under emission standards.

Second, at positive levels of R&D (i.e.,  $k_i < 1$ ), the direct effect is greater under taxes because the corresponding abatement level is larger. Re-writing the output FOCs

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - \bar{e}_i) \quad (11)$$

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - e_i) = \tau \quad (12)$$

we can observe that under tax regulation  $q_i$  is independent of  $k_i$ , while under emission standards  $q_i$  must increase if  $k_i$  drops for eq. (11) to continue holding given that  $\bar{e}_i$  is fixed and  $P' + P''q < 0$  by assumption. From the latter, we also have that an increase in  $q_i$  reduces the LHS of (11) below the LHS of (12). This implies that the amount of abatement under emission standards,  $q_i - \bar{e}_i$ , is lower than under taxes and so is the direct effect.

The importance of the strategic effect of emission standards relative to the direct effect of either taxes or standards depends on the demand curve  $P(Q)$  and the emissions goal  $\bar{E}$ . To see this in a very simple way, consider the following change to the market-regulatory situation: a positive parallel shift of a linear demand curve from  $P$  to  $\alpha P$  ( $\alpha > 1$ ), with  $P' < 0$  and  $P'' = 0$  unchanged, and the same tax level  $\mathcal{T}$ , which necessarily implies a higher emissions goal  $\bar{E}$  and emission standards  $\bar{e}_i$ . Under tax regulation, this new situation leads to higher output  $q_i$  (see eq. (9)), same abatement  $q_i - e_i$  (see eq. (8)), and hence, higher emissions. Now, the direct effect of either instrument at any  $k_i$  remains unchanged because the optimal amount of abatement is not affected by  $\alpha$ .<sup>9</sup>

And from (6) and  $P'' = 0$ , we can see that the strategic effect increases with  $q$ . Thus, by increasing  $\alpha$  (and adjusting  $\bar{E}$  accordingly) we can let the strategic effect of emission standards to be as large as we like without affecting the direct effect under either instrument. We can summarize the comparison between taxes and emission standards in the following proposition:

**Proposition 1:** *Under Cournot competition in the output market, taxes can provide more, less, or the same R&D incentives than emission standards.*

The R&D ranking between taxes and emission standards will ultimately depend on the relative importance of the regulatory goal, output demand and R&D production function  $f(\cdot)$ . Emission standards are likely to offer greater R&D incentives when the  $f(\cdot)$  and  $v$  are such that only minor innovations take place, and when output demand is large and/or more inelastic for the strategic effects to be more important. On the other hand, taxes are likely to provide more incentives at stricter regulatory levels (higher  $\mathcal{T}$  and lower  $\bar{e}$ ) because

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<sup>9</sup> In the case of taxes is immediate since  $\mathcal{T}$  has not changed. In the case of emission standards note, first, that abatement  $q_i - \bar{e}_i$  at  $k = 1$  is independent of  $\alpha$  and, from (4), that  $\frac{dq_i}{dk_i} = \frac{-C'_i}{2P' + P'' - k_i C''_i}$  is independent of  $\alpha$ .

direct effects become relatively more important. We shall illustrate these results with the aid of numerical examples.

### C. Permits

Because grandfathered tradable permits and auctioned permits are very closely related, I shall merge their analysis into one but emphasizing their differences as they arise. Thus, under “permits” regulation and Cournot competition, for any given level of  $k_i$  and  $k_j$ , firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = P(Q) q_i - k_i C_i(q_i - e_i) - \sigma(e_i - \varepsilon_i) \quad (13)$$

where  $g_i$  is amount of (tradable) permits received by firm  $i$  and  $F$  is the market clearing price of permits after a total of  $\bar{E}$  permits are distributed gratis by the regulator. If instead, the  $\bar{E}$  permits are auctioned off,  $g_i = 0$  and both firms become buyers of permits. The auction clearing price is the same as in the permits market because there are no income effects.

Since the permits market (or auction market) operates first, we start by solving the third-period output equilibrium. Firm  $i$  takes  $e_i$  as given, which is the number of permits withheld in the second period, and maximizes  $P(Q) q_i - k_i C_i(q_i - e_i)$ . The FOC is

$$P(Q) + P' q_i - k_i C'_i (q_i - e_i) = 0 \quad (14)$$

Letting  $\hat{q}_i(e_i)$  be the solution to the third-period output equilibrium, in the second period firm  $i$  chooses  $e_i$  to maximize  $P(Q) \hat{q}_i(e_i) - k_i C_i(\hat{q}_i(e_i) - e_i) - \sigma(e_i - \varepsilon_i)$ . Using the envelope theorem, the Nash bargaining equilibrium in the permits market is given by (Spulber, 1989),<sup>10</sup>

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<sup>10</sup> Firms bargain over  $F$  until no further exchange of permits is mutually beneficial while taking into account their correct expectation of future outputs  $\hat{q}_i$  and  $\hat{q}_j$ .

$$k_i C'_i(\hat{q}_i(e_i) - e_i) = k_j C'_j(\hat{q}_j(e_j) - e_j) = \sigma \quad (15)$$

$$e_i + e_j = \bar{E} \quad (16)$$

Thus, the (negative) value of the total derivative of (13) with respect to  $k_i$  at the subgame perfect Nash equilibrium in the permits and output markets is

$$-\frac{d\pi_i}{dk_i} = C_i(q_i - e_i) - P' q_i \frac{dq_j}{dk_i} + \frac{d\sigma}{dk_i}(e_i - \varepsilon_i) \quad (17)$$

The first term on the RHS of (17) is the direct effect, the second term is the strategic effect from the output market and the third term is the strategic effect from the permits market. While the sign of the direct effect is clearly positive, the sign of other two effects is not so immediate.

In a permits-Cournot game, environmental R&D cannot readily be interpreted as pure cost-reducing innovation because there is an interaction in the permits market. Hence,  $dq_j/dk_i$  may no longer be positive as it was under standards. In fact, we have that (see Appendix B)

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - k_i C'')} \quad (18)$$

which is negative, since  $P' + P''q < 0$  by assumption. The implication is that a lower  $k_i$ , which means lower marginal abatement costs  $k_i C'_i$ , reduces firm  $j$ 's relative costs, increasing its output. The explanation is that any R&D investment made by firm  $i$  "spills over" through the permits market, lowering the price  $F$  and consequently reducing abatement costs for both firms in the same amount at the margin, which ultimately helps firm  $j$  to increase output.

Investments in R&D also affect the permits market. As formally demonstrated in Appendix B, the total effect of R&D on the permits price is negative (i.e.,  $dF/dk_i > 0$ ), regardless of who invest in R&D; otherwise firms' production would be lower after R&D since marginal production costs are

equal to  $F$  (see (14)). The sign of this strategic effect from the permits market depends on whether the firm  $i$  is a seller or buyer of permits. If the firm is a buyer of permits ( $e_i > g_i$ ), this effect is positive because the firm now buys permits at a lower price.

Thus, the total derivative (17) becomes

$$-\frac{d\pi}{dk} = C(q - e) - \frac{P'C'q - C'(3P' + 2P''q) (e - \varepsilon)}{2 (3P' + 2P''q - k C'')} \quad (19)$$

While the strategic effect from the output market is always negative for either tradable permits or auctioned permits, the strategic effect from the permits market is zero under tradable permits ( $e = g$ ) and positive under auctioned permits ( $g = 0$ ). Therefore, we can establish the following proposition:

**Proposition 2:** *Under Cournot competition in the output market and imperfect competition in the permits market, a buyer of permits has greater R&D incentives than a seller of permits, and consequently, auctioned permits lead to more R&D than grandfathered permits.*

In terms of the Fudenberg and Tirole's (1984) taxonomy, eq. (19) indicates that when products are strategic substitutes and firms are under tradable permits regulation, it is optimal to follow a "lean and hungry look" strategy and underinvest in R&D. If firms are under auctioned permits regulation, it may be optimal to follow a "top dog" strategy and overinvest in R&D.

The comparison between tradable permits and the other two regulatory instruments, emission standards and taxes, is rather straightforward. At any value of  $k$ , direct effects under tradable permits and standards are the same and lower than direct effects under taxes (unless  $k = 1$  in which case are equal). Since strategic effects under tradable permits are always negative, it follows:

**Proposition 3:** *Under Cournot competition in the output market and imperfect*

*competition in the permits market, tradable permits offer less R&D incentives than either emission standards or taxes.*

The comparison between auctioned permits and emission standards and taxes is more involved. At any value of  $k$ , direct effects under auctioned permits and standards are the same and lower than direct effects under taxes (unless  $k = 1$  in which case they are equal). On the other hand, strategic effects from the permits market can be large enough for total effects to be higher than total effects under standards and taxes, as we shall see in the numerical section. Thus, we can establish:

***Proposition 4: Under Cournot competition in the output market and imperfect competition in the permits market, auctioned permits can offer more, less, or the same R&D incentives than either emission standards or taxes.***

Results so far are based on the assumption of firms engaged in quantity competition for the output market. As Fundenberg and Tirole (1984) and Tirole (1988) have already shown, the sign of the strategic effect may change as firms engage in price competition for the output market. As we shall see below, this does not necessarily mean that previous propositions simply revert under price competition. There are regulatory interactions that must be taken into account as well.

#### **IV. R&D under Bertrand Competition**

In this section, I repeat the previous analysis but assuming instead that firms compete à la Bertrand with differentiated products. The demand curve faced by firm  $i$  is  $q_i \equiv D_i(p_i, p_j)$ , where (i)  $-\partial D_i / \partial p_i \geq \partial D_i / \partial p_j > 0$  and (ii)  $\partial^2 D_i / \partial p_i \partial p_j > 0$ . Because products are not necessarily homogenous (i) simply indicates that a firm's price change has an equal or larger effect on its own demand than on its rival's. On the other hand, (ii) says that a firm's price increase has a smaller effect on its own demand the larger the price of its

rival. I also assume that  $D_i(p_i, p_j)$  is not too convex in  $p_i$ ; otherwise second order conditions (SOCs) do not hold. To avoid clutter I will sometimes use the following notation:  $D'_1 \equiv \partial D_i / \partial p_i$ ,  $D'_2 \equiv \partial D_i / \partial p_j$ ,  $D'_{11} \equiv \partial^2 D_i / \partial p_i \partial p_i$  and  $D''_{12} = D'_{21} \equiv \partial^2 D_i / \partial p_i \partial p_j$  (the same notation applies if we interchange  $i$  by  $j$ ). Note that even if products are homogenous, i.e.,  $-D'_1 = D'_2$ , the competitive outcome, i.e.,  $p = k C'$ , is not obtained because the emissions cap  $\bar{E}$  acts as a capacity constraint.<sup>11</sup>

### A. Emission Standards

Under emission standards regulation and Bertrand competition, for any given a level of  $k_i$  and  $k_j$ , firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C_i(D_i(p_i, p_j) - \bar{e}_i) \quad (20)$$

so the FOC for  $p_i$  is

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C'_i \frac{\partial D_i}{\partial p_i} = 0 \quad (21)$$

and the (negative) value of total derivative of (20) at the optimum level of prices is

$$-\frac{d\pi_i(k_i, k_j)}{dk_i} = C_i(D_i - e_i) - (p_i - k_i C'_i) \frac{\partial D_i}{\partial p_j} \frac{dp_j}{dk_i} \quad (22)$$

Because  $MD_i/Mp_j > 0$  and  $p_i > k_i C'_i$  (capacity constraints allow firm  $i$  to exercise some market power even if product are homogenous), the sign of the strategic effect depends on  $dp_j/dk_i$  (see Appendix C for its derivation). Plugging  $dp_j/dk_i$  into (22) we obtain for symmetric firms

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<sup>11</sup> See Kreps and Scheinkman (1983).

$$-\frac{d\pi}{dk} = C(q - \bar{e}) - (p - k C') D'_2 \frac{B D'_1 C'}{(B^2 - A^2)} \quad (23)$$

where

$$A = (2 D'_1 - k (D'_1)^2 C'' + (p - k C') D''_{11})$$

and

$$B = (D'_2 - k D'_1 D'_2 C'' + (p - k C') D''_{12})$$

SOCs for a local maximum require that  $A < 0$  and  $A'' - B'' > 0$  (see Appendix C), so, as in the Cournot game,  $dp_j/dk_i > 0$ . Thus, (23) indicates that in this market structure where products are strategic complements, firm's optimal strategy is to behave as a "puppy dog" and underinvest in R&D.

## B. Taxes

Under tax regulation and Bertrand competition, for any given level of  $k_i$  and  $k_j$ , firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C(D_i(p_i, p_j) - e_i) - \tau e_i \quad (24)$$

The FOCs for  $e_i$  and  $p_i$  are, respectively

$$k_i C'_i - \tau = 0 \quad (25)$$

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C'_i \frac{\partial D_i}{\partial p_i} = D_i + p_i \frac{\partial D_i}{\partial p_i} - \tau \frac{\partial D_i}{\partial p_i} = 0 \quad (26)$$

Expression (26) indicates that  $p_i$  and  $p_j$  are not affected by the choice of  $k_i$  and  $k_j$ , so the total derivative of (24) at the equilibrium is given by

$$-\frac{d\pi}{dk} = C(q - e) \quad (27)$$

As before, under tax regulation there is no strategic effect because firm  $i$ 's R&D investments do not affect its marginal production costs, and consequently, its output.

Now, we can compare R&D incentives under taxes and emission standards, given by eqs. (27) and (23) respectively, when firms play a Bertrand game in the output market. Before any investment in R&D is undertaken (i.e.,  $k = 1$ ), (26) and (21) indicate that output levels are the same by regulatory design ( $J$  leads to emissions  $\bar{e}$ ). This implies that the direct effect  $C(q - e)$  is the same for both emission standards and taxes. However, under emission standards regulation there is a negative strategic effect that reduces R&D incentives, which is measured by the second term of (23). Similarly, at positive levels of R&D (i.e.,  $k < 1$ ), the direct effect is greater under taxes because the corresponding abatement level is larger. Since strategic effects continue to be negative for emission standards, it immediately follows the next proposition:

**Proposition 5:** *Under Bertrand competition in the output market, taxes offer more R&D incentives than emission standards.*

### C. Permits

As before, the analysis of grandfathered tradable permits and auctioned permits are merged into one. Under permits regulation and Bertrand competition, for any given level of  $k_i$  and  $k_j$ , firm  $i$  maximizes profits

$$\pi_i(k_i, k_j) = p_i D_i(p_i, p_j) - k_i C_i(D_i(p_i, p_j) - e_i) - \sigma (e_i - \varepsilon_i) \quad (28)$$

where  $g_i$  is the amount of (tradable) permits received by firm  $i$  and  $F$  is the market clearing price of permits after a total of  $\bar{E}$  permits are distributed gratis by the regulator. If instead, the  $\bar{E}$  permits are auctioned off,  $g_i = 0$  and

both firms are buyers of permits. Again, the auction clearing price remains the same as in the permits market because there are no income effects.

Since the permits market (or auction market) operates first, we start by solving the third-period output equilibrium. Firm  $i$  takes  $e_i$  as given, which is the amount of permits withheld in the second-period, and maximizes  $p_i D_i - k_i C_i$  with respect to  $p_i$ . The FOC is

$$D_i + p_i \frac{\partial D_i}{\partial p_i} - k_i C'_i \frac{\partial D_i}{\partial p_i} = 0 \quad (29)$$

Letting  $\hat{p}_i \equiv \hat{p}_i(e_i)$  be the solution to the third-period price equilibrium, in the second period firm  $i$  chooses  $e_i$  to maximize  $\hat{p}_i D_i(\hat{p}_i, \hat{p}_j) - k_i C_i(D_i(\hat{p}_i, \hat{p}_j) - e_i) - \sigma(e_i - \varepsilon_i)$ . Using the envelope theorem, the Nash bargaining equilibrium in the permits market is given by (Spulber, 1989),<sup>12</sup>

$$k_i C'_i(D_i(\hat{p}_i, \hat{p}_j) - e_i) = k_j C'_j(D_j(\hat{p}_i, \hat{p}_j) - e_j) = \sigma \quad (30)$$

$$e_i + e_j = \bar{E} \quad (31)$$

Thus, the (negative) value of the total derivative of (28) with respect to  $k_i$  at the subgame perfect Nash equilibrium in the permits and output market is

$$-\frac{d\pi_i}{dk_i} = C_i(D_i - e_i) - (p_i - k_i C'_i) \frac{\partial D_i}{\partial p_j} \frac{dp_j}{dk_i} + \frac{d\sigma}{dk_i}(e_i - \varepsilon_i) \quad (32)$$

where the second term of the RHS of (32) is the strategic effect from the output market, and the third term is the strategic effect from the permits market.

Since  $p_i > k_i C'_i$  and  $MD_i/Mp_j > 0$ , the sign of the strategic effect from the output market depends on the sign of  $dp_j/dk_i$ , which is (see Appendix D)

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<sup>12</sup> Firms bargain over  $F$  based on their correct expectation of future prices  $\hat{p}_i$  and  $\hat{p}_j$ .

$$\frac{dp_j}{dk_i} = \frac{dp_i}{dk_i} = \frac{D'_1 C'}{2 (A + B)} \quad (33)$$

where  $A$  and  $B$  are as in section IV.A. Since SOCs require that  $A + B < 0$  (see Appendix C), we also have that  $dp_j/dk_i > 0$ . In this permits-Bertrand game, firm  $i$ 's R&D (i.e., lower  $k$ ) leads firm  $j$  to reduce its action  $p_j$ , and hence increase its profits, not only because of output complementarity but also because any R&D investment “spills over” through the permits market reducing abatement costs for both firms in the same amount at the margin. Because of this latter effect, it is not difficult to show that  $dp_j/dk_i$  under permits is always greater than under emission standards. Formally, this is the case because  $A + B < 0$ .

The sign of the strategic effect in the permits market depends on the sign of  $dF/dk_i$  and on whether the firm  $i$  is a seller or buyer of permits. Since  $dF/dk_i > 0$  (see Appendix D for its derivation),<sup>13</sup> when a firm is a buyer of permits ( $e_i > g_i$ ), the strategic effect from the permits market is positive. Accounting for strategic effects in both permits and output markets, the total derivative (32) becomes

$$\begin{aligned} -\frac{d\pi}{dk} &= C(q - e) - \frac{(p - k C') D'_2 D'_1 C'}{2 (A + B)} \\ &+ \frac{k C'(e - \varepsilon)}{2} \left( \frac{(D'_1 + D'_2) D'_1 C'}{A + B} + \frac{C'}{k C''} \right) \end{aligned} \quad (34)$$

In terms of the Fudenberg and Tirole's (1984) taxonomy, eq. (34) indicates

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<sup>13</sup> The value of  $dF/dk_i$  is unambiguously positive when either products are homogeneous (i.e.,  $D'_1 + D'_2 = 0$ ) or the demand curve is linear (i.e.,  $D'_{11} = D'_{12} = 0$ ). If products are too differentiated (i.e.,  $D'_1 + D'_2 << 0$ ) and the demand curve is very convex (i.e.,  $D''_{11} \gg 0$ ),  $dF/dk_i$  may become negative. However, we do not discuss this possibility further here in the interest of a fair comparison with the Cournot competition that is for homogenous products.

that when products are strategic complements, under tradable permits regulation (i.e.,  $e = g$ ) it is optimal for a firm to follow a “puppy dog” strategy and underinvest in R&D. Under auctioned permits regulation (i.e.,  $g = 0$ ), on the other hand, it may be optimal for a firm to follow a “fat cat” strategy and overinvest in R&D.

We now can proceed to compare permits with emission standards and taxes. Comparing R&D incentives under tradable permits ( $e = g$ ) and emission standards only requires to compare  $dp_j/dk_i$  since direct effects are the same for both instruments at any value of  $k$ . Consequently, we have the following proposition:

***Proposition 6:*** *Under Bertrand competition in the output market and imperfect competition in the permits market, tradable permits offer less R&D incentives than emission standards.*

Comparing auctioned permits and taxes (see eq. (27)) follows directly from the discussion between taxes and emission standards of Section III.B. Before R&D (i.e.,  $k_i = 1$ ), direct effects are the same by regulatory design. At positive levels of R&D (i.e.,  $k_i < 1$ ), however, direct effects are larger under taxes while strategic effects may be positive under auctioned permits. For instance, if we reduce  $D_2'$  sufficiently enough so that the strategic effect from the output market under auctioned permits decreases,  $-dB/dk$  can become greater under auctioned permits than under taxes. On the other hand, if we make the regulatory goal stricter (i.e.,  $e$  is only a small fraction of  $q$ ) so that the direct effect under both instruments increases,  $-dB/dk$  can become greater under taxes than under auctioned permits. Therefore, we can establish the following proposition:

***Proposition 7:*** *Under Bertrand competition in the output market and imperfect competition in the permits market, auctioned permits can offer more, less or the same R&D incentives than taxes.*

## V. Some Numerical Examples

In this section, I develop some numerical examples to illustrate and complement some of the analytical results shown in the previous sections. The examples are not randomly selected, but rather to emphasize differences between direct and strategic effects.

### A. Cournot Examples

Let  $P(Q) = a - bQ$  be the demand curve and  $C(q - e) = (q - e)^2$  be abatement costs before R&D, where  $Q = 2q$ . Let  $k = (1 - \gamma) e^{K_T} + \gamma$  be the R&D production function, where  $0 < \gamma < 1$ ,  $K_T = (1 + \varphi) K$ , and  $K$  is the amount of R&D effort by each firm in the equilibrium.<sup>14</sup> The market and regulatory parameters are chosen to yield a significant amount of emissions abatement. To simplify matters, the regulatory design is such that before R&D, marginal abatement costs are equal to some marginal harm  $h$ .

In the first example, Ex. 1, I use the following parameters:  $a = 16$ ,  $b = 0.2$ ,  $\gamma = 0.4$ ,  $v = 5$  and  $h = 10$ . Results in this and following examples are at the firm level. The first row of Table 1 (“Before R&D”) shows market and regulatory characteristics before R&D takes place. The regulatory design imposes a significant reduction,  $q - e$ , upon firms of 50%, which is achieved by either levying a tax  $J = 10$ , issuing a total number of permits  $\bar{E} = 10$ , which leads to  $F = 10$ , or setting emission standards  $\bar{e} = 5$  for each firm. Note that the reason for the output price  $P(Q)$  to be close to marginal costs is because the large price elasticity ( $-3$  at the market equilibrium), which will make strategic effects to be relatively less important than direct effects. Firm’s optimal R&D efforts,  $K$ , for three levels of R&D spillovers ( $\varphi = 0$ ,  $0.5$ , and  $1$ ) and under each of the regulatory regimes (E. ST., TAX, T. P., and A. P.) are shown in the next 4 rows.<sup>15</sup> R&D investments are larger under taxes (TAX) than

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<sup>14</sup> Optimal  $K$  under each regulatory regime is obtained from (2) and either (6), (10) or (19).

<sup>15</sup> Note that market and environmental outcomes are not affected by  $\varphi$ . This is because optimal  $k$  is independent of  $\varphi$  (see footnote 6).

under emission standards (E. ST.) and auctioned permits (A. P.) because direct effects are more important. The parameters of the example were chosen that it is possible to have no investment under tradable permits (T. P.).

**Table 1. R&D under Cournot Competition**

Ex.	Scenario	$\tau, \sigma$	$q$	$P$	$e$	$k$	$K$		
							$\theta = 0$	$\theta = 0.5$	$\theta = 1$
1	Before R&D	10	10	12	5	1	---	---	---
	E. ST.	n.a.	11.35	11.46	5	0.72	0.62	0.41	0.31
	TAX	10	10	12	1.5	0.59	1.16	0.77	0.58
	T. P.	10	10	12	5	1	0	0	0
	A. P.	9.15	11.42	11.43	5	0.71	0.65	0.44	0.33
2	Before R&D	10	20	14	15	1	---	---	---
	E. ST.	n.a.	20.74	13.70	15	0.83	0.33	0.22	0.16
	TAX	10	20	14	12.75	0.69	0.73	0.49	0.37
	T. P.	10	20	14	15	1	0	0	0
	A. P.	8.81	21.99	13.21	15	0.63	0.96	0.64	0.48
3	Before R&D	10	10	60	5	1	---	---	---
	E. ST.	n.a.	10.18	58.16	5	0.70	0.70	0.47	0.35
	TAX	10	10	60	3.18	0.73	0.59	0.39	0.30
	T. P.	10	10	60	5	1	0	0	0
	A. P.	8.79	10.08	59.20	5	0.87	0.25	0.17	0.13

In Ex. 2, I let the demand curve to increase to  $a = 22$ , which significantly reduces the regulatory requirements to 25%. I also increase  $v$  from 5 to 5.6 to ensure that emissions are positive for all values of  $\lambda$ . This drop in the regulatory goal makes direct effect relatively less important, which leads to higher R&D

under auctioned permits than under standards and taxes. Finally, in Ex. 3, I keep the 50% regulatory goal of Ex. 1 and make the demand curve more inelastic setting  $a = 160$  and  $b = 5$ .<sup>16</sup> Strategic effects from the output market are now much more important than direct effects, which leads to higher R&D under standards than under taxes and auctioned permits.

### B. Bertrand Examples

In the following examples, I continue using a linear demand curve and let  $D_i(p_i, p_j) \equiv q_i = a - b p_i + c p_j$ , where  $-D'_1 \equiv b \geq c \equiv D'_2$ .<sup>17</sup> Cost and R&D production functions remain the same. In the first example of Table 2, Ex. 1, I consider homogenous products and use the following parameters:  $a = 10$ ,  $b = 0.5$ ,  $c = 0.5$ ,  $\gamma = 0.4$ ,  $v = 5.6$  and  $h = 10$ . With these parameters, the amount of reduction is significant and equal to 50%, as shown in the first row of Table 2 under “Before R&D.” In this example (negative) strategic effects from the output market are large enough for taxes to lead to more R&D than auctioned permits.

In Ex. 2, I reduce the regulatory goal to 25% and use the following parameters values:  $a = 20$ ,  $b = c = 1$ ,  $\gamma = 0.4$ ,  $v = 5.4$ . Because both direct effects and (negative) strategic effects from the output market decrease with these new values, auctioned permits lead to more R&D than taxes.

## VI. Concluding Remarks

In this paper, I have compared a firm’s incentives to invest in environmental R&D under different market structures and environmental policy instruments. Because of market strategic effects, R&D incentives are found to vary widely

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<sup>16</sup> I also increase  $v$  to 5.7 for the same reasons above.

<sup>17</sup> As before, optimal  $K$  under each regulatory regime is obtained from (2) and either (23), (27) or (34).

**Table 2. R&D under Bertrand Competition**

Ex.	Scenario	$\tau, \sigma$	$q$	$P$	$e$	$k$	$K$		
							$\theta = 0$	$\theta = 0.5$	$\theta = 1$
1	Before R&D	10	10	10	5	1	---	---	---
	E. ST.	n.a.	10	10	5	1	0	0	0
	TAX	10	10	10	2.75	0.69	0.73	0.49	0.37
	T. P.	10	10	10	5	1	0	0	0
	A. P.	7.87	10	12.13	5	0.79	0.44	0.29	0.21
2	Before R&D	10	20	10	15	1	---	---	---
	E. ST.	n.a.	20	10.04	15	1.00	0.01	0.01	0
	TAX	10	20	10	12.21	0.64	0.91	0.61	0.45
	T. P.	9.96	20	10.04	15	1.00	0.01	0	0
	A. P.	6.32	20	13.68	15	0.63	0.95	0.63	0.46

across market structures and instruments. In particular, I found that when firms' products are strategic substitutes (i.e., Cournot), either emission standards, taxes or auctioned permits can provide the most incentives. But when firms' products are strategic complements (i.e., Bertrand), either taxes or auctioned permits can provide the most incentives.

A natural question that remains is how the results of the paper change as markets become more competitive. To answer this question, we can simply extend the model from two to a large number of firms competing à la Cournot. Strategic effects no longer matter, so we need only concentrate on direct effects, or more precisely, on abatement levels levels  $q_i - e_i$ . Before R&D (i.e.,  $k = 1$ ), direct effects are the same for all instruments by regulatory design. By the same arguments laid out in the paper (see Section III.B for example), at positive levels of R&D (i.e.,  $k < 1$ ), however, direct effects are higher under taxes than under permits and emission standards because abatement is higher.

Consequently, under perfect competition, tradable permits, auctioned permits and emission standards lead to the same amount of R&D but lower than taxes.

Additional to the above finding is that under perfect competition R&D incentives are not affected by the way the permits are initially distributed among firms, and that is why incentives under grandfathered permits and auctioned permits are the same. This is in sharp contrast with previous literature (e.g., Millman and Prince, 1989; and Jung et al, 1996), where authors fail to distinguish between cost savings (including permits payments) and innovation incentives. The reason is that for any given output price  $P$  and permits price  $F$ , the effect of a change in  $k$  on the profits  $B$  of a price-taking firm does not depend on the distribution of permits  $g$ . Even output  $q$  is not affected by changes in  $k$ , because at the margin the additional production cost from the regulation continues to be  $F$ .

There are a few extensions to the model that may be worth exploring. One extension would be to consider a different technology innovation process. It could be modeled as a patent race where R&D firms (other than production firms) compete for the invention of a more efficient technology to be sold to producing firms either because lowers production costs or because the regulator imposes firms to adopt the new technology. Note that this has already been done for the case of perfect competition in the output market (Biglaiser and Horowitz, 1995). Another interesting extension would be to consider ex-ante asymmetries among firms. Firms will often have different costs of production and costs to conduct R&D either because of size (economies of scale) or past experience. Firms may also have different costs to adopt new technologies because of previous investments or commitments like long-term contracts.

## Appendix A

Under Cournot competition and emission standards regulation, the first order conditions for firms  $i$  and  $j$  are given by (4). Taking total derivative with respect to  $k_i$  at the Nash equilibrium in both FOCs we obtain

$$P' \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_i}{dk_i} + P'' q_i \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) - C'_i - k_i C''_i \frac{dq_i}{dk_i} = 0 \quad (A1)$$

$$P' \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_j}{dk_i} + P'' q_j \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) - k_j C''_j \frac{dq_j}{dk_i} = 0 \quad (A2)$$

Then, subtracting (A2) from (A1) and rearranging (A2), we obtain the system of equations that by symmetry reduces to

$$(P' - kC'') \frac{dq_i}{dk_i} + (-P' + kC'') \frac{dq_j}{dk_i} - C' = 0 \quad (A3)$$

$$(P' - P'' k) \frac{dq_i}{dk_i} + (2P' + P'' q - k C'') \frac{dq_j}{dk_i} = 0 \quad (A4)$$

which leads to

$$\frac{dq_j}{dk_i} = \frac{C' (P' + P'' q)}{(P' - k C'') (-3P' - 2P'' q + k C'')} \quad (A5)$$

This is the fraction of the last term in (6) in the text.

## Appendix B

Under Cournot competition and permits regulation, the equilibrium conditions in the permits and output markets for firms  $i$  and  $j$  are given by (14), (15) and (16). Taking total derivative with respect to  $k_i$  in these FOCs (eq. (14) is used twice for both  $i$  and  $j$ )

$$P' \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_i}{dk_i} + P'' q_i \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) - C'_i \quad (B1)$$

$$-k_i C'_i \left( \frac{dq_i}{dk_i} - \frac{de_i}{dk_i} \right) = 0$$

$$P' \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) + P' \frac{dq_j}{dk_i} + P'' q_j \left( \frac{dq_i}{dk_i} + \frac{dq_j}{dk_i} \right) \quad (B2)$$

$$-k_j C''_j \left( \frac{dq_j}{dk_i} - \frac{de_j}{dk_i} \right) = 0$$

$$C'_i + k_i C''_i \left( \frac{dq_i}{dk_i} - \frac{de_i}{dk_i} \right) = k_j C'_j \left( \frac{dq_j}{dk_i} - \frac{de_j}{dk_i} \right) = \frac{d\sigma}{dk_i} \quad (B3)$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0 \quad (B4)$$

From (B3) and (B4), we obtain

$$\frac{de_i}{dk_i} = \frac{1}{2} \frac{dq_i}{dk_i} - \frac{1}{2} \frac{dq_j}{dk_i} + \frac{C'}{2 k C''} \quad (B5)$$

$$\frac{de_j}{dk_i} = \frac{1}{2} \frac{dq_j}{dk_i} - \frac{1}{2} \frac{dq_i}{dk_i} + \frac{C'}{2 k C''} \quad (B6)$$

and replacing (B5) into (B1) and (B6) into (B2), to become (B1') and (B2'), respectively, and then subtracting (B2') from (B1'), we obtain

$$\frac{dq_i}{dk_i} = \frac{dq_j}{dk_i} \quad (B7)$$

Then, to find  $dq_j/dk_i$ , we replace (B5)-(B7) into either (B1) or (B2) to obtain

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - k C'')} \quad (B8)$$

and to find  $dF/dk_i$ , we replace (B5)-(B8) into (B3) to obtain

$$\frac{d\sigma}{dk_i} = \frac{(3P' + 2P''q) C'}{2 (3P' + 2P''q - k C'')} \quad (B9)$$

## Appendix C

Under Bertrand competition (regardless of whether products are homogeneous or differentiated) and emission standards regulation, the first order conditions for firms  $i$  and  $j$  are given by (21). Taking total derivative with respect to  $k_i$  at the Nash equilibrium in both expressions, rearranging, assuming symmetry and using the simplified notation (see text) gives

$$A \frac{dp}{dk_i} + B \frac{dp_j}{dk_i} - D'_1 C' = 0 \quad (C1)$$

$$B \frac{dp_i}{dk_i} + A \frac{dp_j}{dk_i} = 0 \quad (C2)$$

where,  $A = (2 D'_1 - k (D'_1)^2 C'' + (p - k C') D''_{11})$

and,  $B = (D'_2 - k D'_1 D'_2 C'' + (p - k C') D''_{12})$

Second order conditions (SOCs) for a local maximum require that  $A < 0$  and  $A'' - B'' > 0$ . Since  $B > 0$ , the SOCs also imply that  $A + B < 0$ .

Subtracting (C2) from (C1) and rearranging, we obtain

$$\frac{dp_j}{dk_i} = \frac{-B D'_1 C'}{A^2 - B^2} \quad (C3)$$

which is positive since  $D'_1 < 0$  and  $D'_{12} > 0$ . This is part of the last term in (23) in the text. Note that if the demand curve  $D(p_i, p_j)$  is linear (i.e.,  $D''_{12} = D''_{11} = 0$ ) it is immediate that  $A < 0$ ,  $B > 0$ ,  $A + B < 0$  and  $dp_j/dk_i > 0$ .

## Appendix D

Under Bertrand competition (regardless of whether products are homogeneous or differentiated) and permits regulation, the equilibrium conditions in the permits and output markets for firms  $i$  and  $j$  are given by (29), (30) and (31). Taking total derivative with respect to  $k_i$  in all four expressions (and assuming symmetry)

$$A \frac{dp_i}{dk_i} + B \frac{dp_j}{dk_i} - D'_1 k C'' \frac{de_i}{dk_i} - D'_1 C' = 0 \quad (D1)$$

$$B \frac{dp_i}{dk_i} + A \frac{dp_j}{dk_i} + D'_1 k C'' \frac{de_j}{dk_i} = 0 \quad (D2)$$

$$C' + k C'' \left( D'_1 \frac{dp_i}{dk_i} + D'_2 \frac{dp_j}{dk_i} - \frac{de_i}{dk_i} \right) = \quad (D3)$$

$$= k C'' \left( D'_2 \frac{dp_i}{dk_i} + D'_1 \frac{dp_j}{dk_i} - \frac{de_j}{dk_i} \right) = \frac{d\sigma}{dk_i}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0 \quad (D4)$$

where A and B are as in Appendix C. From (D3) and (D4), we obtain

$$\frac{de_i}{dk_i} = \frac{D'_2 - D'_1}{2} \left( \frac{dp_j}{dk_i} - \frac{dp_i}{dk_i} \right) + \frac{C'}{2 k C''} \quad (D5)$$

$$\frac{de_j}{dk_i} = \frac{D'_2 - D'_1}{2} \left( \frac{dp_i}{dk_i} - \frac{dp_j}{dk_i} \right) + \frac{C'}{2 k C''} \quad (D6)$$

and replacing (D5) into (D1) and (D6) into (D2), to become (D1') and (D2'), respectively, and then subtracting (D2') from (D1'), we obtain

$$\frac{dp_i}{dk_i} = \frac{dp_j}{dk_i} \quad (D7)$$

Then, to find  $dp_j/dk_i$ , we replace (D5) thru (D7) into either (D1) or (D2) to obtain

$$\frac{dp_j}{dk_i} = \frac{D'_1 C'}{2 (A + B)} \quad (D8)$$

which is positive from the second order conditions discussed in Appendix C.

Finally, to find  $d\sigma/dk_i$ , we replace (D5) - (D8) into (D3) to obtain

$$\frac{d\sigma}{dk_i} = \frac{k C''}{2} \left( \frac{(D'_1 + D'_2) D'_1 C'}{A + B} + \frac{C'}{k C''} \right) \quad (D9)$$

It is not difficult to demonstrate that this expression is unambiguously positive when either products are homogeneous (i.e.,  $D'_1 + D'_2 = 0$ ) or the demand curve is linear (i.e.,  $D'_{11} + D'_{12} = 0$ ).

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