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Permits, Standards, and Technology Innovation[1]

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I compare environmental R&D incentives offered by four policy instruments—emission standards, performance standards, tradeable permits, and auctioned permits—in the presence of oligopoly permits and output markets. Because R&D incentives depend on direct and strategic effects, standards can offer greater incentives than do permits. If markets are perfectly competitive, however, tradeable and auctioned permits provide equal incentives that are similar to those offered by emission standards and greater than those offered by performance standards.

Key Words: tradeable permits; standards; technology innovation; oligopoly markets.

1. INTRODUCTION

The extent to which an environmental policy provides firms with incentives to invest in environmental R&D is recognized as an important policy evaluation criterion [8]. Not surprisingly, a substantial theoretical literature has evolved comparing various policy instruments' effect on R&D incentives and concluding that, in general, market-based instruments such as tradeable permits and taxes provide more incentives than do command-and-control instruments such as emission and performance standards [3, 7, 11, 17, 19].[3] For example, Jung *et al.* [7] and Milliman and Prince [11] found that auctioned permits and taxes provide the most incentives and emission standards provide the least.

Because the above authors have either considered a single firm or completely abstracted from the output market, it is not clear how their results would be affected with the introduction of the output market and the possibility of imperfect competition in either the output or the permit market. In a recent paper, Parry [13] introduced a competitive output market and found that R&D incentives under taxes and

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[3]Less consistent with the above findings are the works of Magat [9] and Malueg [10], who showed that relative incentives may vary depending on firm's specific technologies and elements of instrument design.

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tradeable permits do not differ as much as had been predicted.[4] However, he still found that R&D incentives under these two market-based instruments are higher than under (fixed) performance standards. 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. In particular, I explore the effect on R&D of firms' interactions in oligopoly markets.[5]

Since real-world markets are rarely perfectly competitive,[6] 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" in such aspects as capacity, marketing, and cost-reducing R&D [4, 15, 18]. 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 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 develop a model of two firms (1 and 2) that compete à la Cournot in the output market and at the same time are 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: two so-called command-and-control instruments—emission standards and performance standards—and two so-called market-based instruments—grandfathered tradeable permits (hereafter, tradeable 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 [18, 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. In a perfectly competitive setting, this would be the only effect. 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.

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 have found many situations in which standards offer greater R&D incentives

[4]Requate [14] also introduced a competitive output market to compare innovation incentives under tradeable permits and taxes with mixing results. His work, however, did not consider imperfect competition in either market or command-and-control instruments.

[5]Note that Biglaiser and Horowitz [1] have already considered firms' interactions in the market for the discovery of new pollution-control technologies, but under the assumption of perfect competition in the output market. Their focus was on the optimal design of a technology standard coupled with a tax, while in this paper I compare individual instruments.

[6]See Hahn [6] for a discussion of the impact of market power on tradeable permit systems.

than do permits. The reason is that, while direct effects are always positive by definition, strategic effects may be either positive or negative. In this Cournot game, they are always positive under standards because a firm's R&D investment is always a cost-reducing innovation that allows the firm to increase output and profits. Under permits, however, strategic effects from the output market are negative as the firm's R&D investment "spills over" through the permit market (permit auction) reducing its rival's costs and, consequently, increasing its rival's output.[7] Strategic effects from the permits market, on the other hand, can be either positive or negative. Because the equilibrium price of permits falls with R&D, this strategic effect is positive (negative) for a buyer (seller) of permits. Since in a permits auction all firms are buyers of permits, incentives under auctioned permits are greater (or at least equal) than incentives under tradeable permits, which is consistent with the literature (e.g., [11]).

This paper also presents results for different market conditions. If permits and output markets are perfectly competitive, tradeable permits and auctioned permits provide equal R&D incentives, because incentives are independent of the number of grandfathered permits received. Further, if firms are symmetric and standards uniformly allocated, total R&D (sum of individual R&D investments) under emission standards is also equal to total R&D under permits. If standards are not uniformly allocated, total R&D under emission standards can be greater or lower than total R&D under permits, depending on abatement costs and R&D production functions.

The rest of the paper is organized as follows. In the next section, I develop the basic model and explain how to estimate and compare R&D incentives. In Section 3, I estimate and compare R&D incentives for the four instruments under imperfect permits and output markets. In Section 4, I develop a numerical exercise to illustrate some analytical results of Section 3. The next three sections extend the model in different directions. In Section 5, I compare instruments for an imperfect permits market and a perfectly competitive output market. In Section 6, I consider the opposite case in which only the permits market is perfectly competitive. In Section 7, I let both permits and output markets to be perfectly competitive. Section 8 offers concluding remarks.

2. THE MODEL

Consider two profit-maximizing firms subject to an environmental regulation. Without loss of generality, firm i produces q_i at no cost, and the inverse demand function is $P = P(Q)$, where P is the output market price and $Q = q_1 + q_2$ is industry output. (Here I denote firms by 1 and 2, but I will often use i and j to refer to them). In the absence of any environmental regulation, production leads to q_i units of emission, which can be abated at a cost of $C_i(q_i - e_i)$, where e_i are firm i's final emissions after abatement. As usual, $C' > 0$ and $C'' > 0$.

Firm i can improve its abatement technology by investing in environmental R&D. If it invests K_i, abatement costs are expected to be reduced from $C_i(q_i - e_i)$ to $k_i C_i(q_i - e_i)$ according to the R&D production function

$$k_i = f_i(K_i), \tag{1}$$

[7] Note that in a Bertrand game, strategic effects from the output market are negative under both standards and permits making the R&D rankings more favorable toward permits [12].

where $f(0) = 1$, $f(\infty) > 0$, $f' < 0$, $f'' > 0$, and $f''' \leq 0$. The cost of environmental R&D is $v_i K_i$.

The objective of the environmental regulator is to cap aggregate emissions at $\overline{E} = e_1 + e_2$ either by establishing standards for firms or by issuing (tradeable) permits to be distributed gratis or auctioned off. Each instrument's design exactly yields $\overline{E}$ before any R&D and remains invariant thereafter. Alternatively, I could assume that the regulator is unable to observe R&D investments or that he or she observes them with a significant lag that does not affect firms' R&D decisions.

Depending on the regulatory instrument, the solution of the model involves either a two-period or a three-period equilibrium. In the case of standards, there are two periods. First, the two firms choose environmental R&D investments K_i and K_j, which are known to all firms; then, output levels q_i and q_j, price P, and emission levels e_i and e_j are simultaneously determined. In the case of permits, there are three periods. First, the two firms choose R&D investments; then, emission levels e_i and e_j (specified by the number of permits withheld) and permits price σ are determined; and finally, output levels q_i and q_j, and price P are resolved.[8]

To decide upon the amount of environmental R&D to undertake, firms must have some expectation about how the permits and output markets' equilibria will be resolved. I assume, as in Brander and Spencer [2], for example, that for any given level of R&D, firms have complete information and therefore correctly anticipate the Nash output equilibrium, which is resolved as a Cournot game. When the environmental regulation takes the form of tradeable or auctioned permits, I assume that for any given level of R&D and expected output, firms Nash bargain over the permits price σ (for total quantity of permits fixed at $\overline{E}$). Since information is complete and there are no income effects, the Nash bargaining solution leads to the efficient level of emissions for any given K and q, regardless of the initial distribution of tradeable permits [16].

The optimal amount of R&D investment under each policy instrument could be obtained by maximizing $\pi_i(K_i) - v_i K_i$, where $\pi_i(K_i)$ represents firm i's profits resulting from the (subgame perfect) Nash equilibrium in the permits and output markets when R&D investment is K_i. The solution K_i^* must satisfy $d\pi_i(K_i)/dK_i = v_i$, where $d\pi_i(K_i)/dK_i$ is the total derivative of $\pi_i(K_i)$ with respect to K_i.

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

$$\frac{d\pi_i}{dK_i} = \frac{d\pi_i}{dk_i} f'(K_i) = v_i \tag{2}$$

and $f' < 0$ and $f'' > 0$, it is immediate that K^* increases with the absolute value of $d\pi_i/dk_i$, that is $|d\pi_i/dk_i|$.[9] Thus, if $|d\pi_i^A/dk_i|$ and $|d\pi_i^B/dk_i|$ are the total derivatives under instruments A and B, respectively, we would have that instrument A leads to greater R&D than instrument 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, depending on the values of v and f, A may lead to more, equal, or less R&D

[8] Since permits can be considered an input to the production process, it is reasonable to think that the permits market clears before the output market does.

[9] Because $d\pi/dk < 0$ (to have an interior solution), $|d\pi/dk| = -d\pi/dk$.

than B. The latter will be an indication, for example, that one instrument can more effectively force drastic innovations (big reductions in k) than the other instrument.

By letting firms optimally choose K, and hence k, this modeling approach has the advantage of endogenizing the abatement cost curve shift from $C(\cdot)$ to $kC(\cdot)$, which is typically exogenous in the literature (e.g., [7], [11], and [13]). Yet the results of the paper are fully comparable to this literature. Let us consider two instruments, A and B, and an exogenous shift of the abatement cost curve from C to $\tilde{k}C$, where $\tilde{k} < 1$. Denoting by $\Delta\pi_i^A(\tilde{k})$ and $\Delta\pi_i^B(\tilde{k})$ firm i's cost savings (or, more generally, its increase in profits) from developing (or adopting) the new technology $\tilde{k}$, earlier studies would rank instrument A as providing more R&D incentives than instrument B if $\Delta\pi_i^A(\tilde{k}) > \Delta\pi_i^B(\tilde{k})$.

Since the approach of this paper would rank A as providing more R&D incentives than B if $|d\pi_i^A/dk_i| > |d\pi_i^B/dk_i|$ for all k, it remains to be shown that if $|d\pi_i^A/dk_i| > |d\pi_i^B/dk_i|$ for all k, then $\Delta\pi_i^A(\tilde{k}) > \Delta\pi_i^B(\tilde{k})$. Using (2), $\Delta\pi_i^l(\tilde{k})$ can be written as ($l = A$ or B; subscript i is omitted)

$$\Delta\pi^l(\tilde{k}) = \int_0^{K(\tilde{k})} (d\pi^l/dK)dK = \int_{\tilde{k}}^1 |d\pi^l/dk| f'(K(k))dk. \tag{3}$$

Therefore, if $|d\pi_i^A/dk_i| > |d\pi_i^B/dk_i|$ for all k, it is immediate that $\Delta\pi_i^A(\tilde{k}) > \Delta\pi_i^B(\tilde{k})$.

3. R&D INCENTIVES IN IMPERFECT MARKETS

In this section, I solve the model and estimate the value of $|d\pi/dk|$ for each of the four policy instruments. To facilitate the exposition, I assume, whenever necessary, that firms are symmetric in all respects, including their allocations of standards and tradeable permits.[10]

3.1. *Emission Standards*

Under emission standards regulation, for any given level of k_i, firm i maximizes profits

$$\pi_i(k_i) = P(Q)q_i - k_iC(q_i - e_i), \tag{4}$$

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

$$P(Q) + P'(Q)q_i - k_iC_i'(q_i - \bar{e}_i) = 0. \tag{5}$$

The third term of (5) indicates that the environmental regulation raises marginal production costs by an amount equal to the marginal abatement cost at $e_i = \bar{e}_i$, which depends on the amount of R&D undertaken.

[10]Later, I explore the effect of non-uniform allocations of standards and permits on total R&D.

The incentives to invest in environmental R&D are obtained from the absolute value of the total derivative of (4) with respect to k_i at the optimum level of output and emissions. Using the envelope theorem, this derivative is equal to

$$\left|\frac{d\pi_i}{dk_i}\right| = C(q_i - \bar{e}_i) - P'(Q)q_i\frac{dq_j}{dk_i}. \qquad (6)$$

The first term on the right-hand side (RHS) of (6) 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 effect. In a market with a large number of agents, the direct effect would be the only effect that firm i would consider in determining the optimal amount of R&D.

The second term on the RHS of (6) is the strategic effect. This effect results from the influence of R&D investment on firm j's second-period actions. Since $P' < 0$, its sign depends on the sign of dq_j/dk_i. In this emission-standards–Cournot game, where environmental R&D can be interpreted as pure cost-reducing innovation, it is immediate that $dq_j/dk_i > 0$. The implication is that a lower k_i, which means lower marginal abatement costs k_iC_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 incentives than would occur otherwise.

Thus, for symmetric firms, (6) becomes (see Appendix A for a derivation of dq_j/dk_i)

$$\left|\frac{d\pi}{dk}\right| = C(q - \bar{e}) - P'q\frac{C' \cdot (P' + P''q)}{(P' - kC'')(-3P' - 2P''q + kC'')}. \qquad (7)$$

Assuming that $P' + P''q < 0$ to insure the existence of a unique, pure-strategy Nash equilibrium in output (with k_i and e_i given) [5], the value of dq_j/dk_i in the second term on the RHS of (7) is indeed positive, and so is the strategic effect.[11]

3.2. *Performance Standards*

Under performance-standards regulation, for any given level of k_i, firm i maximizes profits

$$\pi_i(k_i) = P(Q)q_i - k_iC(q_i - e_i), \qquad (8)$$

subject to $e_i/q_i \leq \bar{h}_i$, where $\bar{h}_i < 1$ is the performance standard established for firm i. Setting $e_i = \bar{h}_iq_i$, the second-period equilibrium is given by the FOC

$$P(Q) + P'(Q)q_i - k_iC_i'(q_i - \bar{h}_iq_i) = 0. \qquad (9)$$

The third term on the RHS of (9) indicates that the environmental regulation raises marginal production costs by an amount equal to the marginal abatement cost at $e_i = \bar{h}_iq_i$, which depends on the amount of R&D undertaken because q_i depends on k_i.

Using the envelope theorem, the absolute value of the total derivative of (8) with respect to k_i at the optimum levels of output and emissions is equal to

$$\left|\frac{d\pi_i}{dk_i}\right| = C(q_i - \bar{h}_iq_i) - P'(Q)q_i\frac{dq_j}{dk_i}. \qquad (10)$$

[11] Note that the strategic effect is clearly positive for a linear demand curve ($P'' = 0$).

The direct effect—the first term on the RHS of (10)—is positive, while the strategic effect—the second term—is positive as long as $dq_j/dk_i > 0$. As before, in this performance-standards–Cournot game, environmental R&D can also be interpreted as pure cost-reducing innovation; hence, it is not difficult to show that $dq_j/dk_i > 0$. Again, this interaction in the output market results in a positive strategic effect leading to more R&D incentives than would occur otherwise.

Developing (10) we have (see Appendix B for a derivation of dq_j/dk_i)

$$\left|\frac{d\pi}{dk}\right| = C(q - \bar{h}q) - P'q\frac{C' \cdot (P' + P''q)}{(P' - (1-\bar{h})kC'')(-3P' - 2P''q + (1-\bar{h})kC'')}. \quad (11)$$

Equation (11) differs from (7) because $0 < \bar{h} < 1$, which suggests that incentives under emission and performance standards need not be the same. Let us first consider direct effects. Before any investment in R&D is undertaken (i.e., $k_i = 1$), direct effects $C_i(q_i - e_i)$ are the same for both instruments. This is because emissions are the same (i.e., $\bar{h}_i q_i = \bar{e}_i$), by assumption, and output levels q are also the same, according to FOCs (5) and (9). At positive levels of R&D (i.e., $k_i < 1$), however, the direct effect $C_i(q_i - e_i)$ under emission standards is greater than the direct effect under performance standards because the corresponding abatement level $q - e$ is greater.

To see the latter, let us re-write output FOCs (5) and (9) as

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - \bar{e}_i) \quad (12)$$

and

$$P(Q) + P'(Q)q_i = k_i C_i'(q_i - \bar{h}_i q_i). \quad (13)$$

As k_i drops, output under either instrument must increase for (12) and (13) to continue holding. But since $\bar{e}_i$ is fixed, output (and hence emissions) increases a bit more under performance standards. And, by the assumption $P' + P''q < 0$, the left-hand side (LHS) of (12) is greater than the LHS of (13), which, in turn, implies that the amount of abatement under emission standards is greater than that under performance standards. The reason for this result is that as output increases, the emission standard becomes less flexible (or more costly to comply with) than the performance standard, and therefore, the (direct) gains from R&D are necessarily larger.

Let us now consider strategic effects. Before any R&D investment is undertaken (i.e., $k_i = 1$), the strategic effect under performance standards is larger than that under emission standards because at similar levels of abatement and output, dq_j/dk_i is larger, provided that $\bar{h}_i < 1$. At positive levels of R&D (i.e., $k_i < 1$), the strategic effect under performance standards continues to be larger (this is immediate for a linear demand curve) because output increases more rapidly as k drops. The reason for the greater strategic effect is that performance standards place less of a restriction on firms' output than do emission standards. One can say that there are "substitution possibilities" between e and q along $h = e/q$.

Finally, before any R&D investment, the sum of direct and strategic effects under performance standards is larger than under emission standards; at positive R&D levels, however, it is not possible to establish a priori which effect dominates. For example, if we take a very elastic linear demand curve, $P(Q)$ (i.e., $|P'|$ very small and $P'' = 0$), the direct effect dominates. Taking direct and strategic effects into account it is possible to establish the following proposition.

PROPOSITION 1. *Under imperfect (Cournot) output competition, performance standards can provide more, less, or the same R&D incentives than emission standards.*

The explanation for this result is that the "flexibility" associated with performance standards relative to emission standards leads to lower compliance costs, resulting in two effects on R&D. On the one hand, R&D incentives are reduced because the cost savings from innovation are smaller. This is the direct, or cost-minimizing, effect. On the other hand, R&D incentives are increased because in a Cournot game, lower costs allow the firm to increase its market share and profits. This is the strategic effect. Thus, the R&D ranking between emission standards and performance standards is ambiguous and ultimately depends on output demand and R&D costs, v. Performance standards are likely to offer greater R&D incentives when v is sufficiently large (so optimal k is a bit smaller than 1) and when output demand is not too elastic. In such a case direct effects are about the same, but strategic effects are considerably greater under performance standards.

3.3. *Tradeable Permits*

Under tradeable-permits regulation, for any given level of k_i, firm i maximizes profits

$$\pi_i(k_i) = P(Q)q_i - k_i C_i(q_i - e_i) - \sigma \cdot (e_i - \epsilon_i), \tag{14}$$

where ϵ_i is the number of permits received by firm i and σ is the market-clearing price of permits after a total of $\overline{E}$ permits have been distributed gratis by the regulator.

Since the permits 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

$$P(Q) + P' q_i - k_i C_i'(q_i - e_i) = 0. \tag{15}$$

Letting $\hat{q}_i(e_i)$ be the solution to the third-period output equilibrium, during the second period firm i chooses e_i to maximize $P(Q)\hat{q}_i(e_i) - k_i C_i(\hat{q}_i(e_i) - e_i) - \sigma \cdot (e_i - \epsilon_i)$. Using the envelope theorem, the Nash bargaining equilibrium in the permits market is given by the following system of equations [16][12]:

$$k_i C_i'(\hat{q}_i(e_i) - e_i) = \sigma = k_j C_j'(\hat{q}_j(e_j) - e_j) \tag{16}$$

$$e_i + e_j = \overline{E}. \tag{17}$$

Using the envelope theorem again, the absolute value of the total derivative of (14) with respect to k_i at the subgame perfect Nash equilibrium in the permits and output market is

$$\left| \frac{d\pi_i}{dk_i} \right| = C_i(q_i - e_i) - P' q_i \frac{dq_j}{dk_i} + \frac{d\sigma}{dk_i}(e_i - \epsilon_i). \tag{18}$$

[12]Firms bargain over σ until no further exchange of permits is mutually beneficial, while taking into account their correct expectation of future outputs $\hat{q}_i$ and $\hat{q}_j$.

The first term on the RHS of (18) 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 easily 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 can demonstrate that (see Appendix C for a derivation of dq_j/dk_i)

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - kC'')}, \tag{19}$$

which is negative, since $P' + P''q < 0$ by assumption.[13] 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 σ 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 D, the total effect of R&D on the permits price is negative (i.e., $d\sigma/dk_i > 0$), regardless of who invests in R&D; otherwise firms' production would be lower after R&D, provided that marginal production costs are equal to σ (see Eq. (15)). 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 ($e_i > \epsilon_i$), this effect is positive because the firm now buys permits at a lower price.

Thus, for symmetric firms, (18) becomes (the last term on (18) vanishes because in a symmetric initial allocation of permits and standards $\epsilon = e = \bar{e}$)

$$\left|\frac{d\pi}{dk}\right| = C(q - e) - \frac{P'C'q}{2(3P' + 2P''q - kC'')}. \tag{20}$$

The comparison between emission standards and tradeable permits is straightforward. By symmetry, the direct effect is the same under both instruments while the strategic effect is positive under emission standards and negative under permits. Therefore, we can then establish the following.

PROPOSITION 2. *Under imperfect (Cournot) competition in the output market and imperfect competition in the permits market, emission standards provide more R&D incentives than tradeable permits.*

Employing (11) and (20) to compare performance standards and tradeable permits is less straightforward, since the strategic effect is higher under performance standards (under permits, it is negative) while the direct effect is lower, except when $k = 1$, in which case they are equal. Thus, total incentives will be higher under performance standards for $k = 1$. At positive levels of R&D, however, total incentives could be higher under permits if the direct effect dominates the strategic effect, which can be the case for a very elastic linear demand curve $P(Q)$ (i.e., $|P'|$ very small and $P'' = 0$). I Summarize in the following.

[13]It is obviously negative for a linear demand curve where $P' < 0$ and $P'' = 0$.

PROPOSITION 3. *Under imperfect (Cournot) competition in the output market and imperfect competition in the permits market, performance standards can provide more, less, or the same R&D incentives as do tradeable permits.*

3.4. *Auctioned Permits*

Under auctioned permits regulation, for any given level of k_i, firm i maximizes profits ($\epsilon_i = 0$),

$$\pi_i(k_i) = P(Q)q_i - k_i C_i(q_i - e_i) - \sigma e_i, \tag{21}$$

where σ is the auction clearing price of permits.[14] Since the FOCs are identical to those specified in the case of tradeable permits (including Appendices C and D), the value of the total derivative of (21) with respect to k_i is

$$\left|\frac{d\pi}{dk}\right| = C(q-e) - \frac{P'C'q}{2(3P' + 2P''q - kC'')} + \frac{C' \cdot (3P' + 2P''q)e}{2(3P' + 2P''q - kC'')}. \tag{22}$$

As before, the strategic effect—second term on the RHS of (22)—reduces firm i's R&D incentives because any investment made by firm i lowers the price σ and hence, increases firm j's output. However, the permits market effect—the last term—is now positive because all firms are buyers of permits.

Comparing (20) and (22), incentives under tradeable permits and auctioned permits differ only in the number of permits a firm needs to buy to cover its emissions. Because under tradeable permits each firm receives a positive amount of permits ($\epsilon_i > 0$), Proposition 4 then follows.

PROPOSITION 4. *Under imperfect (Cournot) competition in the output market and imperfect competition in the permits market, auctioned permits provide more R&D incentives than tradeable permits.*

Finally, we can extend the comparison between auctioned permits and standards. Because strategic effects vary from case to case, Proposition 5 follows.

PROPOSITION 5. *Under imperfect (Cournot) competition in the output market and imperfect competition in the permits market, standards can provide more, less, or the same R&D incentives than auctioned permits.*

For example, if the demand curve is linear ($P'' = 0$) and $e > q/3$ at the equilibrium, the sum of strategic effects from the output and permits markets is positive, which can be greater than the last term on the RHS of (7) for some values of P' and C''.

[14] Note that this price is equal to the equilibrium price under tradeable permits because there are no income effects.

TABLE I
Comparing R&D Incentives for Different Values of k and Regular Demand

Instrument	a	b	k	σ	e	q	$P(Q)$	Effect Direct	Effect Strategic	Effect Total
E.ST.	10	2	1	n.a.	1	1.50	4.00	0.25	0.19	0.44
P.ST.[a]	10	2	1	n.a.	1	1.50	4.00	0.25	0.34	0.59
T.P.	10	2	1	1.00	1	1.50	4.00	0.25	−0.15	0.10
A.P.	10	2	1	1.00	1	1.50	4.00	0.25	0.15	0.40
E.ST.	10	2	0.75	n.a.	1	1.53	3.87	0.28	0.25	0.53
P.ST.	10	2	0.75	n.a.	1.03	1.54	3.85	0.26	0.39	0.65
T.P.	10	2	0.75	0.80	1	1.53	3.87	0.28	−0.18	0.10
A.P.	10	2	0.75	0.80	1	1.53	3.87	0.28	0.17	0.46
E.ST.	10	2	0.5	n.a.	1	1.57	3.71	0.33	0.34	0.67
P.ST.	10	2	0.5	n.a.	1.05	1.58	3.68	0.28	0.45	0.73
T.P.	10	2	0.5	0.57	1	1.57	3.71	0.33	−0.22	0.11
A.P.	10	2	0.5	0.57	1	1.57	3.71	0.33	0.20	0.53

[a] The performance standard is $h = e/q = 2/3$.

4. A NUMERICAL EXERCISE

In this section, I develop a simple numerical exercise to illustrate some of the analytical results just shown. Let $P(Q) = a - bQ$ be the demand curve and $C(q - e) = k \cdot (q - e)^2$ be abatement costs after R&D investment K, where $k = f(K)$. Tables I and II present incentives (i.e., $|d\pi/dk|$) at three different levels of R&D ($k = 1, 0.75$, and 0.5) for two demand curves (regular and elastic).

The "regular demand" case ($b = 2$) is displayed in Table I. As shown in the first four rows, aggregate emissions (e) are capped at 2 units, which, by symmetry, is equivalent to a unit of emission per firm before any R&D investment (i.e., $k = 1$). The performance standard (h) required to achieve such an emissions level is 2/3 ($e/q = 1/1.5$). The equilibrium prices (σ) in both the tradeable permits (T.P.) and the auctioned permits (A.P.) cases are also equal to 1. Output (q) and output price ($P(Q)$) are equal across all instruments.

The incentives to invest in R&D are presented in the last three columns of Table I. The parameters were chosen to have direct and strategic effects of similar magnitude. As discussed earlier, the direct effect is always positive, while the strategic effect (including output and permit markets) is positive for emission standards (E.ST.), performance standards (P.ST.) and auctioned permits and negative for tradeable permits. In this particular example, standards always provide more incentives than do permits.

The "elastic demand" case ($b = 0.05$) is displayed in Table II. As shown in the first four rows, aggregate emissions are now capped at 16 units, equivalent to 8 units per firm. A more elastic demand curve reduces firms' market power; therefore, direct effects become much more important than strategic effects. As a result, incentives under standards and tradeable permits do not differ much, but they are always lower than incentives under auctioned permits.

We now turn to the comparison of R&D incentives under different market conditions. We start with a case in which the output market is perfectly competitive.

TABLE II
Comparing R&D Incentives for Different Values of k and Elastic Demand

								Effect		
Instrument	a	b	k	σ	e	q	$P(Q)$	Direct	Strategic	Total
E.ST.	10	0.05	1	n.a.	8	12.09	8.79	16.75	0.06	16.81
P.ST.[a]	10	0.05	1	n.a.	8	12.09	8.79	16.75	0.41	17.16
T.P.	10	0.05	1	8.19	8	12.09	8.79	16.75	−0.60	16.16
A.P.	10	0.05	1	8.19	8	12.09	8.79	16.75	0.59	17.34
E.ST.	10	0.05	0.75	n.a.	8	13.33	8.67	28.44	0.14	28.58
P.ST.	10	0.05	0.75	n.a.	10.06	15.21	8.48	26.48	1.07	27.55
T.P.	10	0.05	0.75	8.00	8	13.33	8.67	28.44	−1.13	27.32
A.P.	10	0.05	0.75	8.00	8	13.33	8.67	28.44	0.90	29.35
E.ST.	10	0.05	0.5	n.a.	8	15.65	8.43	58.56	0.50	59.05
P.ST.	10	0.05	0.5	n.a.	13.54	20.47	7.95	48.01	3.74	51.75
T.P.	10	0.05	0.5	7.65	8	15.65	8.43	58.56	−2.79	55.77
A.P.	10	0.05	0.5	7.65	8	15.65	8.43	58.56	1.49	60.04

[a] The performance standard is $h = e/q = 0.662$.

5. COMPETITIVE OUTPUT MARKET

The analysis in Section 3 can be easily extended to that case in which the output market is perfectly competitive but the permits market is still imperfectly competitive. Think, for example, of a few copper refineries closely located that are subject to the same sulfur dioxide regulation and that sell their copper productions in the international market. Since strategic effects no longer matter in the output market, we need only concentrate on direct effects and strategic effects in the permits market. The output market is modeled in two ways. First, as has been typically done in the literature [3, 7, 10, 11], I abstract entirely from the output market, keeping individual output and output price fixed. Then, I consider a competitive output market with a large number of firms competing á la Cournot.

In extending the model, I maintain the assumptions that instrument design is invariant to R&D, all instruments achieve the same emissions target $\overline{E}$ initially (i.e., before R&D), and firms are symmetric whenever necessary. The latter assumption is partially relaxed at the end of this section by considering a non-uniform allocation of standards and permits.

5.1. *Fixed Output*

If individual output $\bar{q}_i$ and output prices $\overline{P}$ are fixed, then under standards regulation, for any given level of k_i, firm i obtains profits

$$\pi_i = \overline{P}\bar{q}_i - k_i C(\bar{q}_i - \bar{e}_i), \tag{23}$$

where $\bar{e}_i$ is $\bar{h}_i q_i$ under performance standard regulation. Direct effects are immediate and equal to

$$\left|\frac{d\pi_i}{dk_i}\right| = C(\bar{q}_i - \bar{e}_i). \tag{24}$$

Under permits regulation, for any given level of k_i, firm i maximizes profits

$$\pi_i = \overline{P}\bar{q}_i - k_i C(\bar{q}_i - e_i) - \sigma \cdot (e_i - \epsilon_i) \tag{25}$$

with respect to e_i in a Nash bargaining game. Note that $\epsilon_i = 0$ under auctioned permits regulation. As in (16), the Nash bargaining solution is

$$k_i C_i'(\bar{q}_i - e_i) = k_j C_j'(\bar{q}_j - e_j) = \sigma. \tag{26}$$

Using the envelope theorem, R&D incentives under permits are

$$\left|\frac{d\pi_i}{dk_i}\right| = C_i(\bar{q}_i - e_i) + (e_i - \epsilon_i)\frac{d\sigma}{dk_i}. \tag{27}$$

Since $d\sigma/dk_i > 0$ (see Appendix E), Eq. (27) indicates, as before, that a buyer of permits ($e_i > \epsilon_i$) has more incentives than does a seller. A buyer of permits benefits relatively more from the innovation by reducing not only his or her own abatement costs but also the cost of the remaining permits he or she needs to buy. A seller, on the other hand, is adversely affected by the innovation because of the drop in permits price and therefore has fewer R&D incentives.

For symmetric firms, (27) becomes (see Appendix E for the derivation of $d\sigma/dk_i$)

$$\left|\frac{d\pi}{dk}\right| = C(\bar{q} - e) + (e - \epsilon)\frac{C'}{2}, \tag{28}$$

and since $e = \bar{e}$ (which equal to ϵ under tradeable permits) by symmetry, we can establish the following.

PROPOSITION 6. *Under perfect competition in the output market (such that output and output price are fixed) and imperfect competition in the permits market, emission standards, performance standards, and tradeable permits provide equal R&D incentives, but fewer incentives than provided by auctioned permits.*

Auctioned permits provide the most incentive because of the strong strategic effects that do not exist under standards regulation. Provided that output price is not affected by any individual firm, a firm that invests in R&D benefits directly not only from lower abatement costs, but also from a lower clearing price of permits and higher output.

5.2. *Cournot Output*

If, instead, a very large number of firms compete á la Cournot in the output market, the results of Section 5.1 vary in some important ways. Eliminating strategic effects from (6) and (10), R&D incentives under emission and performance standards become, respectively,

$$\left|\frac{d\pi_i}{dk_i}\right| = C(q_i - \bar{e}_i) \tag{29}$$

and

$$\left|\frac{d\pi_i}{dk_i}\right| = C(q_i - \bar{h}_i q_i). \tag{30}$$

Since FOCs are again given by (5) and (9),[15] respectively, output would be higher under performance standards while abatement would be higher under emission standards. The latter result implies that incentives are greater under emission standards.

Using the envelope theorem, incentives under permits regulation are now given by (FOCs are those specified in Section 3.3 with $P' \equiv \partial P(Q)/\partial q_i = 0$)

$$\left|\frac{d\pi_i}{dk_i}\right| = C_i(q_i - e_i) + (e_i - \epsilon_i)\frac{d\sigma}{dk_i}. \tag{31}$$

Note the absence of interaction in the output market. The term $d\sigma/dk_i$ is equal to zero (see Appendix F for a formal derivation) because the downward effect of R&D on σ from the lower marginal abatement cost curves is totally offset by higher output.[16] Thus, (31) becomes

$$\left|\frac{d\pi}{dk}\right| = C(q - e). \tag{32}$$

Therefore, we can establish the following.

PROPOSITION 7. *Under perfect (Cournot) competition in the output market and imperfect competition in the permits market, emission standards, tradeable permits, and auctioned provide equal R&D incentives and more incentives than provided by performance standards.*

One difference with respect to the previous case is that performance standards provide fewer R&D incentives. The explanation is that, now, firms can simultaneously accommodate output and emissions to reduce the overall cost of the environmental regulation. The other difference is that the price of permits remains unchanged to R&D because of output increases.

So far, we have assumed symmetry in all respects, including the allocation of standards and (tradeable) permits. In the following subsection, I relax the assumption regarding the uniform allocation of standards and permits.

5.3. *Non-uniform Allocation*

Consider the "Cournot competitive output" case to study the effect of a non-uniform allocation of emission standards and tradeable permits on total R&D, which is equal to $\sum_{i=1}^{n} K_i$.[17] Recalling that K_i^* satisfies $d\pi_i/dK_i = v_i$, optimal R&D under standards and permits, respectively, solves

$$C(q - \bar{e}) = \frac{-v}{f'(K^*)} \tag{33}$$

$$C(q - e) = \frac{-v}{f'(K^*)}. \tag{34}$$

[15] Note that $P'(Q)q_i$ approaches zero as the number of firms increases.

[16] As the number of firms n goes to infinity, $P'(Q)q_i$ becomes irrelevant relative to $P(Q)$. Therefore, the permits price $\sigma = k_i C_i'(q_i - e_i)$ approaches $P(Q)$ and, consequently, remains unaffected by changes in k_i.

[17] The analysis for performance standards follows directly from the analysis for emission standards.

The effect on individual R&D of a marginal deviation from the initial allocation $\bar{e} = \epsilon$ (taking into account only the direct effect of changes on $\bar{e}$ and ϵ, and not the indirect effect stemming from adjustments in the variables e and q) is equal to

$$\frac{\partial K^*}{\partial \bar{e}} = \frac{-vC'}{f''C^2} \tag{35}$$

$$\frac{\partial K^*}{\partial \epsilon} = 0. \tag{36}$$

As expected, (35) is negative, indicating that a less strict standard (higher $\bar{e}$) reduces incentives to invest in R&D. On the other hand, permits reallocation does not have any effect on incentives.

The effect on total R&D of a reallocation of emission standards $\bar{e}$ and permits ϵ among any two firms i and j to, for example, $\{\bar{e} + \Delta\bar{e}, \bar{e} - \Delta\bar{e}\}$ and $\{\epsilon + \Delta\epsilon, \epsilon - \Delta\epsilon\}$, respectively (where $\bar{e} = \epsilon$ and $\Delta\bar{e} = \Delta\epsilon$), can be estimated from the second-order derivatives as

$$\frac{\partial^2 K^*}{\partial \bar{e}^2} = \frac{2vC[C']^2 - vC^2C''}{f''C^4} + \frac{vf'''C'}{[f'']^2C^2}. \tag{37}$$

Provided that $\partial K^*/\partial\bar{e} < 0$, if (37) turns out to be positive, K^* would be convex in $\bar{e}$ and a reallocation of standards and permits would increase total R&D under standards and would have no effect under permits.

It is not possible to compute the sign of (37) without putting more structure to the model. Let us first consider the case where $f(K) = (1-\gamma)e^{-K} + \gamma$, for which we obtain the following: $\partial K^*/\partial\bar{e} = -C'/C$ and $\partial^2K^*/\partial\bar{e}^2 = (CC'' - [C']^2)/C^2$. The latter indicates that K^* is concave in $\bar{e}$ ($\partial^2K^*/\partial\bar{e}^2 < 0$).[18] Hence, if we reallocate standards and permits among any two firms i and j, total R&D would decrease under standards. However, if we let $f(K) = (1-\gamma)/(1+K) + \gamma$, K^* becomes convex in $\bar{e}(\partial^2K^*/\partial\bar{e}^2 < 0)$, so a reallocation of standards (and permits) will yield higher total R&D under standards.

Based on these general forms for $f(K)$, it is possible to establish the following result.

PROPOSITION 8. *In a market structure with a competitive output market, an imperfect permits market, and a non-uniform allocation of standards and permits, standards can lead to more, less, or the same total R&D than permits.*

The result that a reallocation of standards may lead to higher total R&D than does the same reallocation of permits is because the cost function C and hence incentives $|d\pi/dk|$ are convex in $\bar{e}$.[19] If $f(K)$ is not too convex, K^* will be convex in $\bar{e}$, indicating that a reallocation of standards will lead to higher total R&D. However, if $f(K)$ is sufficiently convex, such as $f(K) = (1-\gamma)e^{-K} + \gamma$, a reallocation of standards will lead to lower total R&D because R&D costs become relatively higher in an aggregate sense than abatement cost savings from R&D.

[18]This is the case for $C(z) = \alpha z^{\beta}$, where $z = q - e$, $\alpha > 0$, and $\beta > 2$.
[19]Note that incentives under performance standards would also be convex in $\bar{h}$.

6. COMPETITIVE PERMITS MARKET

The analysis of Section 3 is now extended to the case in which the permits market is perfectly competitive but the output market is not. Think, for example, of few power generating firms that are the only suppliers of energy in a deregulated power market and are subject to a nationwide (or worldwide) carbon dioxide control regulation. Since strategic effects no longer matter in the permits market, we concentrate on direct effects and strategic effects in the output market. We maintain both assumptions made in Section 3 that instrument design is invariant to R&D and that all instruments achieve the same emissions target $\overline{E}$ initially, i.e., before R&D.

Since there is only interaction in the output market, R&D incentives under emission and performance standards equal those obtained in Sections 3.1 and 3.2, respectively. Incentives under permits differ slightly.

As described in Section 3.3, under tradeable permits regulation, for any given level of k_i, firm i maximizes profits $\pi_i = P(Q)q_i - k_i C_i(q_i - e_i) - \sigma \cdot (e_i - \epsilon_i)$, where $\epsilon_i = 0$ in the case of auctioned permits. The third- and second-period FOCs are represented by (15) and (16), the only caveat being that now the price of permits σ is given instead of endogenously determined in a Nash bargaining game. Equation (15) can then be re-written as

$$P(Q) + P' q_i - \sigma = 0, \tag{38}$$

where $\sigma = k_i C_i'(q_i - e_i)$. Since output q is independent of k, from the envelope theorem, we have that incentives under permits are

$$\left| \frac{d\pi_i}{dk_i} \right| = C_i(q_i - e_i) + P'(Q) q_i \frac{dq_j}{dk_i}, \tag{39}$$

where $dq_j/dk_i = 0$. Equation (39) shows that R&D incentives are independent of the initial allocation of permits ϵ, which leads to the following result.

PROPOSITION 9. *In a competitive permits market, the initial allocation of permits does not affect R&D; therefore, incentives to invest in R&D under tradeable permits and under auctioned permits are the same.*

This finding contrasts with the results obtained by Jung *et al.* [7] and Milliman and Prince [11], who showed that in a perfectly competitive permits market auctioned permits provide greater incentives than tradeable permits. The reason is that these earlier studies failed to distinguish between R&D incentives and compliance cost differences (including payment transfers) between the situation before R&D and the situation after R&D. For example, these authors added to (39) a term that is positive for permit buyers, capturing costs savings from the lower permits price σ that results from aggregate R&D investments. While it is true that σ drops, say, to σ', as firms invest in R&D, from the perspective of any individual firm, the price σ' is unaffected by the firm's investment decision and therefore should be taken as given at the moment to invest in R&D. In such a case the initial allocation of permits does not affect R&D incentives, regardless of the presence of the output market.[20]

[20] In fact, if we abstract from the output market and consider only an abatement cost curve such as $C(z) = z^2$, the incentives to invest in R&D to reduce $C(z)$ to $(1 - \Delta k)C(z)$ when the price of permits is assumed constant at σ' are $\Delta\pi = (\sigma')^2 \Delta k / [4(1 - \Delta k)]$, independent of the initial allocation.

The comparison between permits and standards is rather straightforward from the analysis in Section 3. Under the assumptions that firms are symmetric, $\bar{e} = e$ (and equal to ϵ under tradeable permits), and $\sigma = k_i C_i'(q_i - e_i)$, it is immediate from FOCs (5) and (38) that output levels under permits and emission standards are the same. Output and abatement levels under performance standards are lower and higher, respectively, than they are under either permits or emission standards. This implies that direct effects under emission standards and permits are equal to and higher than, respectively, what they are under performance standards. However, under both emission and performance standards, there is an additional positive strategic effect that does not exist under permits. I summarize in the following.

PROPOSITION 10. *In a market structure characterized by an imperfect* (*Cournot*) *output market and a competitive permits market*, *emission standards provide more R&D incentives than permits*. (*Unless the demand curve is too elastic*, *performance standards also provide more incentives than permits*.)

Proposition 10 can be illustrated using the numerical exercise presented in Tables I and II. The only requirement is that the strategic effects from tradeable and auctioned permits be deleted. As before, under the elastic demand curve of Table II, it is possible to make a case in which permits offer more R&D incentives than do performance standards. Such a case is feasible because firms' interactions in the output market are substantially reduced as demand becomes more responsive (elastic).

7. COMPETITIVE MARKETS

The analysis of Section 3 can finally extended to that case in which permits and output markets are perfectly competitive. Since strategic effects no longer matter, we need only concentrate on direct effects, or, more precisely, on abatement levels $q_i - e_i$. We maintain the two assumptions that instrument design does not change with R&D and all instruments achieve the same emissions target $\overline{E}$ initially, i.e., before any R&D.

By symmetry (i.e., $\bar{e} = e = \epsilon$), direct effects $C(q_i - e_i)$ under emission standards and permits are equal. Direct effects under performance standards $C(q_i - \bar{h}_i q_i)$, however, are lower; therefore we establish the following.

PROPOSITION 11. *Under perfectly competitive markets in which all instruments achieve the same emissions target initially*, *emission standards*, *tradeable permits*, *and auctioned permits provide equal R&D incentives that exceed those under performance standards*.

This finding contrasts again with the results obtained by Jung *et al.* [7] and Milliman and Prince [11], who showed that auctioned permits provide greater incentives than permits and emission standards. As discussed below Proposition 9, the reason is that these authors failed to distinguish between R&D incentives and compliance cost differences between the situation before R&D and the situation after R&D.

Finally, from the analysis in Section 6, it is not difficult to infer that in a competitive setting, the initial allocation of permits does not affect R&D incentives; whether permits are auctioned off or distributed gratis is therefore irrelevant. The allocation of standards, however, can have an effect on total R&D (i.e., $\sum_{i=1}^{n} K_i$). Provided that output FOCs for standards have not changed from those specified in Section 5 (competitive output market), total R&D could increase or decrease with a reallocation of standards, depending on $f(K)$ and C (in other words, depending on whether K_i^* is convex or concave in $\bar{e}$). Then, we have the following.

PROPOSITION 12. *In a market structure characterized by competitive permits and output markets and a non-uniform allocation of standards and permits, emission standards may lead to more, less, or the same total R&D than permits.*

8. CONCLUSIONS

In this paper, I compared the incentives to invest in environmental R&D offered by four policy instruments—emission standards, performance standards, tradeable permits, and auctioned permits—when firms' interactions in the permits and output markets are important. The results indicate that environmental R&D rankings differ from those found by earlier studies because R&D incentives depend on both direct (or cost-minimizing) effects and strategic effects. In fact, I have found that standards may offer greater R&D incentives than do permits. The explanation is that the strategic effect under standards is always positive, in that a firm's R&D investment reduces its own costs but not those of its rivals, allowing the firm to increase output and profits. Under tradeable (auctioned) permits, however, the strategic effect may be negative because a firm's R&D investment spills over through the permits market (or permits auction), reducing its rivals' costs and thereby helping its rivals to increase output.

The paper also presents results for different market conditions. If permits and output markets are perfectly competitive, tradeable permits and auctioned permits provide equal R&D incentives because incentives are independent of the number of grandfathered permits received. Further, if firms are symmetric and standards uniformly allocated, total R&D under emission standards also equals total R&D under permits. If the allocation of is non-uniform, total R&D under emission standards can be greater or lower than total R&D under permits, depending on abatement costs and the R&D production function. As a follow-up to these latter results, it would be interesting to consider other types of ex ante asymmetries among firms, under either perfect or imperfect competition. Firms often have different production and R&D costs because of size (economies of scale) or past experience. They may also have different costs to adopt new technologies because of previous investments or commitments such as long-term contracts.

APPENDIX A

Under emission standards regulation, the FOCs for firms i and j are

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - \bar{e}_i) = 0 \tag{A1}$$

$$P(Q) + P'(Q)q_j - k_j C_j'(q_j - \bar{e}_j) = 0. \tag{A2}$$

Totally differentiating both expressions with respect to k_i yields

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_i}{dk_i} + P''q_i \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - C_i' - k_i C_i'' \frac{dq_i}{dk_i} = 0 \quad \text{(A3)}$$

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_j}{dk_i} + P''q_j \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - k_j C_j'' \frac{dq_j}{dk_i} = 0. \quad \text{(A4)}$$

Assuming that firms are symmetric, subtracting (A4) from (A3) and rearranging (A4), we obtain the following system of equations,

$$(P' - kC'')\frac{dq_i}{dk_i} + (-P' + kC'')\frac{dq_j}{dk_i} - C' = 0 \quad \text{(A5)}$$

$$(P' + P''q)\frac{dq_i}{dk_i} + (2P' + P''q - kC'')\frac{dq_j}{dk_i} = 0, \quad \text{(A6)}$$

which leads to

$$\frac{dq_j}{dk_i} = \frac{C' \cdot (P' + P''q)}{(P' - kC'')(-3P' - 2P''q + kC'')}. \quad \text{(A7)}$$

This is the fraction of the last term in (7) in the text.

APPENDIX B

Under performance standards regulation, the FOCs for firms i and j are

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - \bar{h}_i q_i) = 0 \quad \text{(B1)}$$

$$P(Q) + P'(Q)q_j - k_j C_j'(q_j - \bar{h}_j q_j) = 0. \quad \text{(B2)}$$

Totally differentiating both expressions with respect to k_i yields

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_i}{dk_i} + P''q_i \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - C_i' - (1-\bar{h}_i)k_i C_i'' \frac{dq_i}{dk_i} = 0 \quad \text{(B3)}$$

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_j}{dk_i} + P''q_j \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - (1-\bar{h}_j)k_j C_j'' \frac{dq_j}{dk_i} = 0 \quad \text{(B4)}$$

Assuming that firms are symmetric, subtracting (B4) from (B3) and rearranging (B4), we obtain the following system of equations,

$$(P' - kC'')\frac{dq_i}{dk_i} + (-P' + (1-\bar{h})kC'')\frac{dq_j}{dk_i} - C' = 0 \quad \text{(B5)}$$

$$(P' + P''q)\frac{dq_i}{dk_i} + (2P' + P''q - (1-\bar{h})kC'')\frac{dq_j}{dk_i} = 0, \quad \text{(B6)}$$

which leads to

$$\frac{dq_j}{dk_i} = \frac{C' \cdot (P' + P''q)}{(P' - (1-\bar{h})kC'')(-3P' - 2P''q + (1-\bar{h})kC'')}. \quad \text{(B7)}$$

This is the fraction of the last term in (11) in the text.

APPENDIX C

Under tradeable permits regulation, the FOCs in the permits and output markets for firms i and j are

$$P(Q) + P'(Q)q_i - k_i C_i'(q_i - e_i) = 0 \tag{C1}$$

$$P(Q) + P'(Q)q_j - k_j C_j'(q_j - e_j) = 0 \tag{C2}$$

$$k_i C_i'(q_i - e_i) - k_j C_j'(q_j - e_j) = 0 \tag{C3}$$

$$e_i + e_j - \overline{E} = 0. \tag{C4}$$

Totally differentiating all four expressions with respect to k_i yields

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_i}{dk_i} + P''q_i \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - C_i' - k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i}\right) = 0 \tag{C5}$$

$$P' \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) + P'\frac{dq_j}{dk_i} + P''q_j \cdot \left(\frac{dq_i}{dk_i} + \frac{dq_j}{dk_i}\right) - k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i}\right) = 0 \tag{C6}$$

$$C_i' + k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i}\right) - k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i}\right) = 0 \tag{C7}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0. \tag{C8}$$

From (D7) and (D8), assuming that firms are symmetric, we obtain

$$\frac{de_i}{dk_i} = \frac{1}{2}\frac{dq_i}{dk_i} - \frac{1}{2}\frac{dq_j}{dk_i} + \frac{C'}{2kC''} \tag{C9}$$

$$\frac{de_j}{dk_i} = \frac{1}{2}\frac{dq_j}{dk_i} - \frac{1}{2}\frac{dq_i}{dk_i} - \frac{C'}{2kC''}. \tag{C10}$$

Substituting (C9) into (C5) and (C10) into (C6) to become (C5′) and (C6′), respectively, and then subtracting (C6′) from (C5′), we obtain

$$\frac{dq_i}{dk_i} = \frac{dq_j}{dk_i}. \tag{C11}$$

Finally, substituting (C11) into either (C5′) or (C6′) leads to

$$\frac{dq_j}{dk_i} = \frac{C'}{2(3P' + 2P''q - kC'')}, \tag{C12}$$

which is (19) in the text.

APPENDIX D

The total effect of k_i on σ can be estimated from (C7) as

$$\frac{d\sigma}{dk_i} = C_i' + k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i}\right) = k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i}\right). \tag{D1}$$

Using the second equality, for example, and Eqs. (C10)–(C12), we obtain

$$\frac{d\sigma}{dk_i} = \frac{(3P' + 2P''q)C'}{2(3P' + 2P''q - kC'')}, \tag{D2}$$

which is positive since $P' + P''q < 0$ by assumption.

APPENDIX E

To estimate the effect of a small change of k_i in the equilibrium of the permits market σ, let us re-write the corresponding FOCs as

$$k_i C_i'(\bar{q}_i - e_i) = k_j C_j'(\bar{q}_j - e_j) = \sigma \tag{E1}$$

$$e_i + e_j = \overline{E}. \tag{E2}$$

Totally differentiating both expressions with respect to k_i yields

$$C_i' - k_i C_i'' \frac{de_i}{dk_i} = -k_j C_j'' \frac{de_j}{dk_i} = \frac{d\sigma}{dk_i} \tag{E3}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0, \tag{E4}$$

which, by solving for symmetric firms, leads to

$$\frac{de_i}{dk_i} = -\frac{de_j}{dk_i} = \frac{C'}{2kC''} \tag{E5}$$

$$\frac{d\sigma}{dk_i} = \frac{C'}{2}, \tag{E6}$$

which is part of the last term in (28) in the text.

APPENDIX F

Using the FOCs of Appendix D but recalling that the output market is now competitive, we totally differentiate all four expressions with respect to k_i to obtain

$$C_i' + k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i} \right) = 0 \tag{F1}$$

$$k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i} \right) = 0 \tag{F2}$$

$$C_i' + k_i C_i'' \cdot \left(\frac{dq_i}{dk_i} - \frac{de_i}{dk_i} \right) - k_j C_j'' \cdot \left(\frac{dq_j}{dk_i} - \frac{de_j}{dk_i} \right) = 0 \tag{F3}$$

$$\frac{de_i}{dk_i} + \frac{de_j}{dk_i} = 0. \tag{F4}$$

Since either (F1) or (F2) is equal to $d\sigma/dk_i$, we have that

$$\frac{d\sigma}{dk_i} = 0. \tag{F5}$$

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