Environmental Regulation and Technology Innovation

Juan-Pablo Montero*

Department of Industrial Engineering, Catholic University of Chile, and
Center for Energy and Environmental Policy Research,
Massachusetts Institute of Technology

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Abstract

Using two-period models, we compare innovation incentives at the industry level offered by five environmental policy instruments: emissions standards, grandfathered marketable permits, auctioned permits, taxes, and subsidies. Unlike previous literature, we show that a “command-and-control” instrument such as emissions standards may offer more incentive than do any of the other four “market-based” instruments. One reason is that permits markets are subject to a “negative spillover effect” in that aggregate private incentives are lower than total benefits of the innovation. On the other hand, since costs savings from innovations are convex, emission standards far off from the least-cost allocation can lead to higher aggregate cost savings. However, as the degree of heterogeneity in industry’s innovation opportunities increases market-based instruments are more likely to provide more incentives. Our results also indicate that all four market-based instruments provide the same incentives under a competitive setting and equal aggregate reductions across instruments.

Keywords: technology innovation, environmental regulation, market-based instruments

JEL Classification L50, O38, Q28

*Any correspondence should be sent to: Catholic University of Chile, Casilla 306, Correo 22, Santiago, Chile. Phone 56-2-686-5873, fax 56-2-686-5876, e-mail jpmonter@ing.puc.cl.
1. Introduction

In recent years, policymakers have given significantly more attention to the use of “market-based” environmental policy instruments, such as marketable permits and taxes, in place of more traditional “command-and-control” instruments such as emission and technology standards. At least two arguments have been advanced favoring their wider use. The first is the “static efficiency” argument that states that market-based instruments offer firms a more cost-effective way to achieve a given aggregate emission-reduction target (Montgomery, 1972). The second is the “dynamic efficiency” argument that claims that market-based approaches provide firms more incentive to develop and adopt efficient pollution-control technologies because it is always in firms’ best interests to find cheaper ways to control emissions (Tietenberg, 1985). This paper concerns the second claim, comparing relative innovation incentives, at the industry level provided by five instruments: emissions standards, grandfathered marketable permits, auctioned (marketable) permits, taxes, and subsidies.

The extent to which an environmental policy instrument forces firms to develop and adopt new, more efficient pollution-control technologies is an important policy

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2 For empirical support on this argument see Schmalensee et al (1998).

3 For purposes of this paper, the concept of “more efficient pollution-control technologies” is very broad, representing any technological changes that reduce pollution at lower cost. Such changes may include
evaluation criterion (Kneese and Schultze, 1978). In fact, Orr (1976) argues that technology adaptation (i.e., dynamic efficiency), rather than resource allocation (i.e., static efficiency), becomes key in effective solutions to long-term environmental challenges. Unfortunately, virtually no empirical study has addressed the dynamic efficiency attributes of market-based instruments,\(^4\) in large part, because few such programs have been implemented. As well stated by Hahn and Stavins (1992), in the absence of empirical research, the claim that market-based approaches would be more effective in forcing firms to innovate remains largely an untested hypothesis.\(^5\)

Nevertheless, a vast theoretical literature has evolved comparing various policy instruments’ effect on technological change, focusing mostly on analysis at the firm level.\(^6\) Wenders (1975) was one of the first to show that taxes and subsidies are superior to emissions standards in terms of innovation incentives. Several studies followed, with practically the same conclusion: market-based instruments provide more innovation incentives (e.g., Tietenberg, 1985; Downing and White, 1986; Milliman and Prince, 1989). Milliman and Prince (1989) offer perhaps the most comprehensive work at the firm level, concluding that auctioned permits and taxes are the most effective instruments to force technology innovation. Magat (1976) and Malueg (1989) provide less conclusive results, however, showing that incentives may depend on a firm’s specific technologies as well as more efficient and cheaper end-of-pipe pollution-control equipment, substitution of materials used as inputs, process redesign, and final product reformulation.


\(^5\) Empirical studies have been conducted, however, showing significant technological innovation forced by command-and-control instruments (Ashford, 1985 and 1993).

\(^6\) Note that more developed than the environmental economics literature on innovation is the industrial organization literature. See Reinganum (1989) for a survey.
such elements of instrument design as the firm’s position in the emissions market before and after its adoption of a new technology.\(^7\)

Although firm-level studies provide valuable insights, some limitations make extension of the results to the industry level difficult without further analysis. Because policy makers are usually more interested in evaluating possible impacts of policy alternatives on whole industries (or areas with large numbers of firms) rather than on any one firm, we believe these shortcomings have important implications from a public policy perspective. We have identified at least three important limitations of firm-level studies. First, to compare various instruments, firm-level studies must posit that all instruments impose the same emission limit or reduction for each individual firm or emitting source. For instance, a Pigouvian tax must be set such that a firm’s reduction response precisely equals the relevant emission standard. Market-based schemes, however, are designed specifically to focus on aggregate limits rather than individual limits. Industry-level studies allow individual emission limits to differ across instruments as long as the aggregate emissions level remains constant.

Second, private and social returns from innovation are not always the same. Private agents cannot always capture the full benefits of their innovations. A “negative (or positive) spillover effect” results if a firm’s profits from innovating depend negatively (or positively) on how many others innovate (Beath et al., 1995).\(^8\) If this were relevant in our environmental policy context, firm-level studies could not control for it because they concern only one agent. While the issue may not be important in the cases of taxes and

\(^7\) Note that when standards and tax levels are constant over time, Magat (1976) is totally consistent with all previous studies that used “separable” control and production cost functions (i.e., infinite labor substitutability between production and pollution control). When there is a low degree of labor substitutability, Magat (1976) argues that emission standards may force more innovation than equivalent taxes.
emissions standards because these instruments involve no market interaction among firms, it does matter in the cases of marketable and auctioned permits, as later sections will show.

Finally, firm-level studies may not be able to capture all market interactions. Specifically, incentive effects in marketable permits systems depend not only on permit prices and price changes after adoption, but also on whether firms are permit buyers or sellers (Malueg, 1989). As such a firm-level study simply cannot evaluate incentive effects in a system including both buyers and sellers. In a recent paper, Jung et al. (1996) address this shortcoming with an industry-level study. Expanding on Milliman and Prince (1989), they compare relative incentive effects of the same five instruments we are considering here. Jung et al.’s (1996) ranking of instruments, from those providing the most incentive to the least, is: auctioned permits, taxes (subsidies), marketable permits, and emissions standards. Surprisingly, their ranking is independent of the size of the industry, the industry abatement cost structure, and innovation opportunities—because their assumptions overlook the first two shortcomings identified above.9

In a comparison of marketable permits and emission standards, the market price of permits and the decision to adopt new technology ideally would be endogenous. In addition, the emission standards and initial distribution of permits ideally would not only be the same, but also would not necessarily equal the first-period, least-cost reduction allocation. Similarly, for a comparison between emission standards and taxes, the specific standards of each firm ideally would differ from the least-cost allocation. These extensions

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9 Montero (1997) discusses in more detail Jung et al’s (1996) restrictive assumptions, along with a simpler proof to their proposition 1 and a correction.
are important, since insufficient information and political constraints prevent regulators from setting standards in a cost-minimizing way.

This paper addresses all the above shortcomings using two-period models. Unlike previous literature, we present possible cases in which emission standards provide more innovation incentives than do any of the other four market-based instruments. One reason is that grandfathered and auctioned permits are subject to a “negative spillover effect”; another reason is that, because cost savings from innovations are convex, emissions standards far from the least-cost allocation can lead to higher aggregate cost savings than would be realized with a tax (subsidy) or permits approach, which are independent of the initial permits/standards allocation for an industry with large number of firms. We find that instruments’ comparative advantage depend on factors such as the initial allocation of permits and standards, heterogeneity of an industry’s innovation opportunities, and industry size.

The next section of the paper develops a two-period model, also explaining firm- and industry-level approaches for estimating innovation incentives. Since no invariant ranking of instruments can be made to simplify organization of the remainder of this paper, we have arranged the material as follows. Section 3 compares marketable permits with emission standards. Section 4 adds auctioned permits. Section 5 compares emission standards with taxes (subsidies). Section 6 compares taxes (subsidies) with auctioned and marketable permits. Finally, section 7 offers concluding remarks and thoughts for future research.
2. The model

Consider two periods, $t = 1, 2$, and an industry with $n \geq 2$ profit-maximizing firms subject to an environmental regulation. The industry must reduce $Q$ units of emissions of a certain (uniformly mixed) pollutant during each period. Assume that firm’s unrestricted emissions $u_i$ (i.e., emissions in the absence of regulation) remain unchanged over time, that demand for the industry’s output likewise remains constant, and that no firm enter or exit the market. For notational simplicity, assume no discounting. Finally, assume that agents have complete information and perfect foresight.

To achieve the emissions reduction target, $Q$, the environmental regulator may use any one of five policy instruments: emission standards, (Pigouvian) taxes, subsidies, grandfathered marketable permits (hereafter, marketable permits), or auctioned permits. Assume the authority knows today’s aggregate marginal control cost of the industry, so s/he can levy a Pigouvian tax on emissions such that “total” emissions during the first period would be equal regardless the instrument. Also assume perfect monitoring and enforcement and no transaction costs in the permits market.\(^\text{10}\)

In the first period, the regulator also commits to second-period emission limits or taxes (subsidies). Assume that the regulation (i.e., tax level and aggregate emissions target) remains the same during the second period, regardless of whether or not firms adopt more efficient technologies. Thus, we rule out non-commitment (Laffont and Tirole, 1996) and ratcheting (Milliman and Prince, 1989). Note that, because firms adopt new technologies during the second period, aggregate emissions would be lower under the tax
instrument. For completeness, we also study the case when the regulator lowers the tax level in the second period so aggregate emissions remain the same.

Firm’s $i$ control costs given a state of technology “$s$” is given by

$$C_{is} = C_{is}(q_{is})$$

where $q$ is the amount of emissions reduction, $C(q)$ is the abatement cost function with the usual convexity properties, that is $C'(q), C''(q) \geq 0$; and sub-index “$s$” is the state of the abatement technology that takes the value of 1 and 2 before and after innovation respectively. In the first period $s = 1$, and in the second period $s$ can be 2 or 1 depending on whether the firm innovates or not. Thus, we say that $q_{is}$ and $C_{is}$ are, respectively, the level of reduction and control cost of firm $i$ when using technology $s$.$^{11}$ Following the literature in industrial organization (Tirole, 1988) and environmental economics (Tietenberg, 1985; Downing and White, 1986; Malueg, 1989; Milliman and Price, 1989; Jung et al., 1996), we assume that innovation leads to lower marginal control-cost at any level of reduction, so $C'_{i1}(q) \geq C'_{i2}(q)$ and $C''_{i1}(q) \geq C''_{i2}(q)$ $\forall q \geq 0$.\textsuperscript{12}

While a more complex model would allow the policy instruments to affect the nature of the innovation, here we focus on the more tractable problem of the decision of whether to pursue an innovation (e.g. adopt a new technology or adapt a production process) that the firm knows (with some certainty) will reduce abatement costs in the next period. Thus,

\textsuperscript{10} In the limit, when transaction costs are very high, the marketable permit and the emission standard approach yield the same reductions pattern. See Montero (1998) for more on how transaction costs and uncertainty affect pollution permits markets.

\textsuperscript{11} To illustrate our results with more clarity, in some cases we will rely on linear marginal costs curves of the form $C_{is}' = k_{is}q_{is}$. 

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the economic incentives, \( \pi \), that an individual firm face to innovate are given by savings in compliance costs due to the innovation, which do not necessarily equal the difference in compliance costs between periods, \( \Delta C \). Compliance costs include control costs along with payments (transfers) associated with permits, taxes, or subsidies.\(^{13}\)

To construct a benchmark for evaluating incentives offered by the different regulatory instruments at the industry level, we compute the industry-level incentive (\( ILI \)) as the sum of firms’ incentives (Jung et al., 1996). If we assume a positive correlation between cost savings from the innovation and the probability that the firm will pursue the innovation, the number of innovations in a particular industry will generally increase with \( ILI \).\(^ {14}\) Hence our relative rankings across regulatory instruments are based on these aggregate innovation incentives, with the highest ranked instrument inducing the greatest \( ILI \). We now proceed to comparing \( ILI^{ES} \), \( ILI^{MP} \), \( ILI^{AP} \), \( ILI^{TX} \), and \( ILI^{SB} \)—the industry-level incentives associated with the policy instruments of emissions standards, marketable permits, auctioned permits, taxes, and subsidies, respectively.

3. Emission standards vs. marketable permits

This section compares industry-level incentives under emission standards and marketable permits—\( ILI^{ES} \) and \( ILI^{MP} \), respectively. We model the permits market as a

\(^{12}\) The second condition assures that marginal cost curves cross only once; at \( q \leq 0 \). We also assume that individual unrestricted emissions, \( u_i \), are large enough so an interior solution always exists.

\(^{13}\) Note that although the higher \( \pi \) the more likely the innovation is, if R&D expenditures associated to the innovation are too high, a firm may not innovate even if \( \pi > 0 \).

\(^{14}\) As in Tirole and Laffont (1996), \( ILI \) can also be thought as proportional to the expected revenues of an inventor.
static game with complete information. If the market involves few players, say, two, the
players’ decisions about innovation affect the equilibrium price of permits, which in turn
affects their decisions about whether or not to innovate. This market-interaction effect,
however, vanishes as the number of market players increase. In this section, we first
present the case of a two-firm industry and then the case of an $n$-firm industry in which all
firms are price-takers.

3.1 A two-firm industry

Our analysis assumes the initial allocation of permits equals the allocation of firm-
specific standards. Here we rely on graphical expressions for $ILIE$ and $ILIM$.

Figure 1 illustrates changes in compliance cost for each firm and for the industry,
while allowing the market price and the decision to adopt new technology to be
endogenous. Figure 1 assumes two polluting firms that must reduce emissions by $Q$
units, total, during each period. The pollution-control technologies for each firm ($i = 1,2$) in each
state ($s = 1,2$) are represented by the marginal control-cost curves, $C_{is}'$. Thus, $C_{i1}'$ depicts
the $i$th firm’s marginal cost of controlling emissions using current technology, and $C_{i2}'$
depicts the $i$th firm’s marginal cost of controlling emissions using a new, more efficient
pollution-control technology. The origin for the curve illustrating marginal cost of control
for the first firm is the left-hand axis; that for the second firm is the right-hand axis. This
diagram includes all possible allocations of the $Q$-units reduction between the two firms.

Letting $q_i^0$ be the initial reduction allocation, in order to reduce $Q$ units of emissions,
the regulator either sets emission standards equal to the pair $(u_1 - q_1^0, u_2 - q_2^0)$ or
distributes emissions permits equal to $(u_1 - q_1^0, u_2 - q_2^0)$ to firm 1 and 2 respectively.
distributes emissions permits equal to \((u_1 - q_1^0, u_2 - q_2^0)\) to firm 1 and 2 respectively. Under the marketable permits policy, firms trade permits until the market clears in each period. \(C\) is the market equilibrium for Period 1, and, assuming for a moment that both sources adopt new technology, \(E\) is the market equilibrium for the second period. The least-cost reduction allocations are \((q_{11}^*, q_{21}^*)\) and \((q_{12}^*, q_{22}^*)\) for Periods 1 and 2, respectively. In each period, marginal control costs across sources are the same and equal to equilibrium prices \(p_1\) and \(p_2\), respectively. Note that for the initial allocation \((u_1 - q_1^0, u_2 - q_2^0)\), firm 1 is the seller of permits and firm 2 is the buyer. We can now compute the change in compliance cost (including permits costs) and innovation incentives for each firm under emissions standards and marketable permits schemes.

Let us first calculate the industry-level incentives associated with emissions standards, \(ILI^{ES}\). In Figure 1, changes in compliance costs for firms 1 and 2 are given by:

\[
\Delta C_1^{ES} = A(OGF) = \pi_1^{ES} \tag{2}
\]

\[
\Delta C_2^{ES} = A(PHI) = \pi_2^{ES} \tag{3}
\]

where \(\Delta C_i^{ES}\) is the \(i^{th}\) firm’s change in compliance costs between periods under emissions standards, \(A(\cdot)\) is area, and \(\pi_i^{ES}\) is the \(i^{th}\) firm’s incentive to innovate. If we neglect fixed costs of innovation, both firms have positive incentives to innovate, regardless of how standards are set. In addition, because firms fully appropriate the innovation benefits, firms’ incentives equal changes in compliance costs. Therefore, \(ILI^{ES}\) is the sum of (2) and (3).
Let us now calculate industry-level incentives associated with marketable permits, \( IL_i^{MP} \). When both firms adopt new technologies, the changes in compliance cost (including control costs and transfers) for firms 1 and 2, respectively, in Figure 1 are given by

\[ \Delta C_{i1}^{MP} = A(ODE) - A(ABCD) \]

\[ \Delta C_{i2}^{MP} = A(PCE) + A(ABCE) \]

where \( \Delta C_{i}^{MP} \) is the \( i \)th firm’s change in compliance cost between periods under marketable permits. The sum of (4) and (5) is \( A(OEC) + A(PEC) \); unlike the case with emission standards, however, this value does not necessarily reflect the actual incentives firms face before innovation. Because this market includes only two players, the players’ decisions about innovation affect the equilibrium price, which in turn affects their decision about whether to innovate or not. The Nash equilibrium of this game is obtained as follows.\(^{15}\) The buyer’s dominant strategy is to innovate regardless of what the seller does. The seller knows the buyer’s strategy, and innovates as long as control cost savings from innovation exceed the loss in revenue from lower-priced permits. In Figure 1, the seller must decide between equilibrium price points L and E.

Unlike Jung et al. (1996), Milliman and Prince (1989), and others, in order to compute \( IL_i^{MP} \), we use firms’ changes in compliance costs from innovation, given other players’ best responses, rather than the change in compliance costs between periods. In Figure 1—provided point E is the Nash equilibrium—the seller’s incentives are
represented by changes in compliance costs from point E to point L, while the buyer’s incentives are represented by changes in compliance costs from E to M. Thus, when E is the Nash equilibrium, incentives for firms 1 and 2 are given by:

\[ \pi_1^{MP} = A(ODE) - A(AKLD) \]  
\[ \pi_2^{MP} = A(PEM) + A(ANME) \]

Note that \( \pi_1^{MP} > \Delta C_1^{MP} \) and \( \Pi_2^{MP} < \Delta C_2^{MP} \), so there is a “positive (negative) spillover” affecting the seller (buyer). Seller’s incentives are greater than compliance cost changes because the drop in price due to its innovation is only the distance \( KA \), rather than \( BA = p_1 - p_2 \). The buyer’s incentives, on the other hand, are lower than compliance cost changes because the seller’s innovation lowers the second-period equilibrium price. Finally, \( ILI_{MP} \), which equals \( \pi_1^{MP} + \pi_2^{MP} \), is not necessarily equal to \( \Delta C_1^{MP} + \Delta C_2^{MP} \). This leads to the following:

**Lemma 1:** For an industry comprising few firms, because firms in a permits market do not exactly appropriate the benefits of their innovations, the industry-level incentives index, \( ILI_{MP} \), does not necessarily equal the total benefits from innovation, which are savings in compliance costs. We say there is can be either a negative or positive spillover effect.

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15 For a given the state of the abatement technology, the seller and buyer Nash bargain over \( p \) and \( q \).
Graphical proof. Consider Figure 1 for two extreme cases. First, consider that firm 1’s innovation possibilities are minimal. At the limit, $C_{i1}(\cdot) = C_{i2}(\cdot)$ and $\pi_1^{MP} = 0$, $\Delta C_1^{MP} = -A(KBCL)$, and $\pi_2^{MP} = \Delta C_2^{MP} = A(PLC) + A(KBCL)$. Therefore, $IL_1^{MP} = [A(PLC) + A(KBCL)] > A(PLC) = \Delta C_1^{MP} + \Delta C_2^{MP}$. Let us now consider that firm 2’s innovation possibilities are minimal. By similar arguments it is not difficult to show that $IL_2^{MP} = [A(OJM) - A(NBCJ)] < A(OCM) = \Delta C_1^{MP} + \Delta C_2^{MP}$.

As we decrease the initial permit allocation, $A(AKLD)$ increases while $A(ODE)$ remains constant, so expression (6) could become negative—in which case, the seller of permits (firm 1) would have no incentive to innovate. Setting aside R&D costs, the seller would always have incentive to innovate when $A(AKLD)$ is smaller than $A(ODE)$, even for $q_1^0 = 0$, but would be indifferent for an initial allocation such that $\pi_1^{MP} = 0$. At this latter permit allocation, the benefits of selling permits at a lower price resulting from innovation exactly offset the cost of producing them. Note that because $A(ABCD) > A(AKLD)$, the seller may still exert effort to innovate if eq. (4) is negative. Here, sellers’ savings in control costs and permits revenues are sufficiently large to offset any loss from a further price drop. Thus, we conclude:

Lemma 2: In an industry comprising so few firms that their decisions affect the equilibrium price of permits, a seller of permits may have no incentive to innovate.
We can now graphically compare $ILI^ES$ with $ILI^MP$. It is not difficult to show in Figure 1 that as the initial distribution of emissions standards or permits $(u_1 - q_1^0, u_2 - q_2^0)$ moves toward the first-period, least-cost equilibrium $(q_{11^*}, q_{21^*})$, $A(NKLJ)$ becomes smaller, so $ILI^ES$ decreases while $ILI^MP$ increases. Conversely, as we move the initial allocation to the left of the least-cost equilibrium, $ILI^ES$ increases while $ILI^MP$ decreases. If $(u_1 - q_1^0, u_2 - q_2^0)$ is far enough to the least-cost equilibrium, we can establish:

Lemma 3: In a two-firm market, if the initial allocation is such that the seller does not innovate, $ILI^ES$ is always greater than $ILI^MP$.

Graphical proof. Based on Figure 1, let $\pi_1^{MP} = 0$, so $ILI^{MP} = \pi_2^{MP} = A(PCL) + A(KBCL)$. For convexity of the marginal cost curves we have that $A(HILC) > A(KBLC)$, so $ILI^{MP} < ILI^{ES} = A(PCL) + A(HILC)$.

We have established that $ILI^{MP}$ may be lower than $ILI^{ES}$. There are two reasons for this. First, as we move the initial permit allocation to the left of the least-cost equilibrium, the “negative spillover effect” dominates, and the net negative effect becomes more significant ($BN > BK$). Second, because $C_i''(q) \geq C_i''(q)$, cost savings are convex, so $ILI^{ES}$ increases with distance from the least-cost equilibrium.
3.2 An n-firm industry

Extending the previous analysis to an n-firm industry in which firms are price-takers in the permits market, we obtain analytical expressions for both ILI indices. Since no market interaction takes place among agents $ILI_{ES}$ is immediate

$$ILI_{ES} = \sum_{i=1}^{n} (C_i(q_i^0) - C_{i2}(q_i^0))$$ (8)

In estimating $ILI^{MP}$, recall that we are modeling firms’ marketplace interaction as a static game of complete information. Let $p_2$ be the second-period equilibrium price when all firms innovate and $p_2^{-i}$ the second-period equilibrium price when all firms except Firm $i$ innovate. We then express firm $i$’s incentives to innovate as follows:

$$\pi_i^{MP} = (q_i^0 - q_{i1}(p_2^{-i})) p_2^{-i} + C_{i1}(q(p_2^{-i})) - (q_i^0 - q_{i2}(p_2)) p_2 - C_{i2}(q(p_2))$$ (9)

where $q_{i2}(p_2)$ and $q_{i1}(p_2^{-i})$ are the firm’s $i$th reductions in the second period when all firms innovate and when all firms but $i$ innovate, respectively. Since $p_2 < p_2^{-i}$, as $q_i^0$ decreases and the firm becomes a seller of permits, eq. (9) may turn negative (see Lemma 2). This is easier illustrated for linear marginal costs curves ($C_i' = k_i q_i$). In this case, $\pi_i^{MP}$ is given by

$$\pi_i^{MP} = q_i^0 (p_2^{-i} - p_2) + \frac{(p_2)^2}{2k_{i2}} - \frac{(p_2^{-i})^2}{2k_{i1}}$$ (10)

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Because $p_2 < p_2^-$ and $k_{i2} < k_{i1}$, the sum of the second and third terms can be positive, negative, or zero. However, the higher the $q_i^0$, the more likely the whole expression can be positive. On the other hand, if we compare either eq. (9) or (10) with an expression for $\Delta C_{i}^{MP}$, the following lemma can be established:

**Lemma 4.** Regardless the size of the industry, an always-buyer (seller) of permits face negative (positive) spillover effects; where an always-buyer (seller) refers to the firm that buys (sells) permits in both periods.

**Proof.** Subtracting $\Delta C_{i}^{MP}$ from $\pi_{i}^{MP}$ we obtain

$$
\Delta C_{i}^{MP} - \pi_{i}^{MP} = q_i^0 \cdot (p_i - p_2^-) + p_2^- q_i (p_2^-) - C_{i1} (p_2^-) - p_i q_i (p_i) + C_{i1} (p_i)
$$

(11)

Since $p_1 > p_2^-$, the first term of the right hand side is positive, and the sum of the last four terms is negative. Depending on the value of $q_i^0$, eq. (11) can be either positive or negative—negative and positive spillover, respectively. First, if $q_i^0 \geq q_{i1}(p_1)$, which corresponds to an always-buyer, eq. (11) is positive. Conversely and provided that $p_2^- \geq p_2$, if $q_i^0 \leq q_{i1}(p_2)$, which correspond to an always-seller, eq. (11) is negative. Note that (11) is still negative if $q_i^0 \leq q_{i1}(p_2^-)$. Finally, if $q_{i1}(p_2^-) < q_i^0 < q_{i1}(p_1)$, the result is ambiguous.
As can be seen from eq. (9), as the number of firms grows, $p_2^i$ converges to $p_2$ and firms become price-takers. At the limit, $p_2^i = p_2$ and $\pi_i^{MP} > 0$, so every firm innovates. We can summarize these observations as follows:

**Lemma 5.** In an $n$-firm industry whose firms are price-takers in the permits market, every firm—even a potential seller of permits—has positive incentives to innovate.

**Proof.** When $p_2 = p_2^i$, eq. (9) reduces to $C_{i1}(p_2) + p_2(q_{i1}(p_2) - q_{i2}(p_2)) - C_{i2}(p_2)$, which is positive since $C_{i2}'(q) < p_2 \forall q < q_{i2}(p_2)$.

**Lemma 6.** In an $n$-firm industry whose firms are price-takers in the permits market, individual innovation incentives are independent of permit allocation, depending instead only on the characteristic of the old and new control technologies and the equilibrium price $p_2$.

Lemma 6 is an interesting result that, to some extent, parallels Montgomery’s (1972) finding that the initial permits allocation does not matter in terms of static efficiency.

$ILI^{MP}$ can now be estimated as

$$ILI_{MP} = \sum_{i=1}^{n} \pi_i^{MP}, \quad (12)$$

that for linear marginal costs reduces to
Figure 2 illustrates this result. \( C'_1 \) and \( C'_2 \) are marginal cost curves of the industry (I) before and after everyone has innovated, respectively. \( ILI^{MP} \) is given by \( A(OAB) \) and total cost savings from innovation, \( \Sigma \Delta C^{MP} \), are given by \( A(OCB) \), which is equal to \( (p_1 - p_2)Q/2 \) when marginal costs are linear. Since \( p_1 > p_2 \), we can extend Lemma 1 to the \( n \)-firms case, to establish the following:

Proposition 1. In a system of marketable permits involving \( n \) price-taker firms, total private benefits from innovations (\( ILI^{MP} \)) are always lower than total benefits (\( \Sigma \Delta C^{MP} \)). It is the result of a negative spillover effect, in that private agents cannot retain benefits equal to \( \Sigma \Delta C^{MP} - ILI^{MP} \).

Proof. Provided that all firms innovate according to Lemma 5, the difference between \( \Sigma \Delta C^{MP} \) and \( ILI^{MP} \) can be written as:

\[
\Sigma \Delta C^{MP} - ILI^{MP} = \sum_{i=1}^{n} \left\{ (q_i^0 - q_i(p_i))p_i + C_i(q(p_i)) - (q_i^0 - q_i(p_2))p_2 - C_i(q(p_2)) \right\} - \sum_{i=1}^{n} \left\{ (q_i^0 - q_i(p_2^i))p_2^i + C_i(q(p_2^i)) - (q_i - q_i(p_2))p_2 - C_i(q(p_2)) \right\}
\]

Given that for \( n \) large \( p_2^i = p_2 \), and \( \sum q_i^0 = \sum q_i(p_i) \), eq. (14) reduces to
\[ \sum_{i=1}^{n} \left\{ C_{ii}(q(p_i)) - C_{ii}(q(p_2)) - (q_0^i - q_1^i(p_2))p_2 \right\} = \sum_{i=1}^{n} \int_{q_{ii}(p_2)}^{q_0^i(p_1)} (C_{ii}(q) - p_2) dq \]

Since \( C_{ii}'(q) > p_2 \) for all \( i \) and \( q \in [q_{ii}(p_2), q_1^i(p_1)] \), it follows that \( \Sigma \Delta C^{MP} > ILI^{MP} \).

**Proposition 1** indicates that while market interaction allows minimization of total compliance costs in each period, which would be most unlikely under an emission standards approach, it has the adverse net effect of lowering innovation incentives. Note that the negative spillover effects on buyers more than offset the positive spillover effects on sellers.

We now turn to comparing \( ILI^{MP} \) vs. \( ILI^{ES} \). While \( ILI^{MP} \) remains constant (Lemma 6), \( ILI^{ES} \) changes with the initial allocation of emission permits/standards, \( u_i - q_0^i \). Furthermore, since eq. (8) is convex in \( q_0^i \), there is an initial allocation vector \( q^0 = (q_1^0, ..., q_n^0) \) that solves

\[ q^{0*} = (q_1^{0*}, ..., q_n^{0*}) = \arg\min \left\{ \sum \pi^{ES}_i (q_0^i) \right\}. \tag{15} \]

Let denote \( ILI^{ES^*}(q^{0*}) \) the resulting minimand. Straight optimization for linear marginal costs curves leads to

\[ ILI^{ES^*} = \left( \sum_{i=1}^{n} \frac{1}{\Delta k_i} \right)^{-1} \frac{O^2}{2} \]
and

\[ q_i^{0*} = \left( \sum_{j=1}^{n} \frac{1}{\Delta k_j} \right)^{-1} \frac{Q}{\Delta k_j} \]  

where \( \Delta k_i = k_{i1} - k_{i2} \). It is possible to show that, in general, \( q^{0*} \) is not far from the cost-effective pattern of reduction.

In comparing \( ILI^{ES} \) and \( ILI^{MP} \), we first consider the case in which innovation opportunities are similar across firms—that is, \( C'_{i2}(\cdot) = \gamma C'_{i1}(\cdot) \) or \( k_{i2} = \gamma k_{i1},^{16} \) with \( \gamma < 1 \) and constant. In this case, \( q^{0*} \) coincides with the cost-effective allocation in either period and \( ILI^{ES*} = A(OCB) \), as shown in Figure 2. For linear marginal costs, \( ILI^{ES*} = (p_1 - p_2)Q/2 \). Furthermore, since \( ILI^{MP} = A(OAB) \) is fixed while \( ILI^{ES} \) increases as the allocation of permits/standards departs from \( q^{0*} \), we can establish that when \( C'_{i2}(\cdot) = \gamma C'_{i1}(\cdot) \) for all \( i \), \( ILI^{MP} < ILI^{ES} \) for any initial allocation \( q^0 \) of permits/standards. The question that remains is what if innovation opportunities differ across firms. We are interested in the effect of having different values of \( \gamma \) on \( ILI^{ES} \) while keeping \( ILI^{MP} \) unchanged. Because of convexity, simple experimentation with eq. (16) shows \( ILI^{ES*} \) decreases as we increase some \( \Delta k \)'s at the expense of others, while maintaining \( p_2 \) and hence leaving \( ILI^{MP} \) unchanged (which is obtained by maintaining \( \Sigma(1/k_{i2}) \) constant).

Consider the following simple example. There are 100 small firms \( (i=1,2,\ldots,100) \) that have to reduce in total \( Q = 100 \). They are symmetric in linear marginal costs, \( k_{i1} = 1 \) for all \( i \), and in the initial reduction allocation of permits/standards, \( q_{i0} = 1 \) for all \( i \). Also let
unrestricted emissions to be large enough to have always an interior solution. The first period (or before the innovation) equilibrium price is \( p_1 = 1 \). If we let innovation opportunities to be symmetric across firms such that \( k_{i2} = 0.5 \) for all \( i \), we have that \( p_2 = 0.5 \), \( ILI^{ES} = 25 \), and \( ILI^{MP} = 12.5 \). Let us now make innovation opportunities heterogeneous across the industry such that 50% of the firms face no innovation opportunities (\( k_{i2} = k_{i1} = 1 \)), 33.4% face little opportunities (\( k_{i2} = 0.85 \)), and the remaining 16.6% face large opportunities (\( k_{i2} = 0.15 \)). Under these circumstance, \( p_2 \) remains unchanged and so does \( ILI^{MP} \), but \( ILI^{ES} \) reduces to 9.6. Furthermore, \( ILI^{ES} \) can drop even further if we re-allocate the initial allocation \( q^0 \) in such a way that all reduction requirements are imposed over the firms that face little or no innovation opportunities. To summarize we establish:

Proposition 2. An emission standards approach may (and always does, when innovation opportunities are similar across firms) provide more innovation incentives than would a marketable permit approach in an industry with \( n \) permits price-taker firms, due to the "negative spillover" and convexity of cost savings effects. However, when innovation opportunities differ across firms and the initial allocation of standards is not too far from \( q^0^* \), a marketable permits approach is likely to provide more incentives.

Proposition 2 contains two important results that merit further explanation. First, it suggests that as standards get worse—in that they prescribe a pattern of emissions reductions far from the efficient or least-cost pattern—they are more likely to promote

\[\text{That } \gamma \text{ is constant does not mean that } \Delta k_i = \Delta k_j \forall i \neq j. \text{ In fact, holding } p_2 \text{ constant, } ILI^{ES*} \text{ may be higher if } k_{i1}'s \text{ differ across firms.}\]
innovation than are cost-effective policies. This is because cost savings are convex in the level of reduction, so allocations far from \( q^{**} \) yield higher aggregate savings from the innovations. On the other hand, it says that the more heterogeneous the innovation opportunities across firms are, the more likely a marketable permit system will provide more innovation incentives. This is because in a command-and-control system, the chances of placing good innovation opportunities in firms with little incentives (cost savings) increases with heterogeneity, while in a market permits system, a good innovation opportunity traduces into high innovation incentives regardless the number of permits the firm initially received.

4. Auctioned permits, marketable permits, and emission standards

This section extends the previous analysis to include the effect of auctioned permits on firms’ incentives for innovation. We model the auction process as a static game with complete information and consider the two previous cases as well—an industry with two (or few) firms and industry with \( n \) price takers firms.

4.1 A two-firm industry

Under the auction permits approach, firm \( i \)'s innovation incentives are given by

\[
\pi^a_i = (u_i - q_{i1}(\bar{p}_2^-))\bar{p}_2^- + C_{i1}(q(\bar{p}_2^-)) - (u_i - q_{i2}(\bar{p}_2))\bar{p}_2 - C_{i2}(q(\bar{p}_2))
\]  

(18)
where $u_i$ are unrestricted emissions and $i = 1, 2$. If few players or firms, say two, are involved, players’ decisions regarding innovation affect the equilibrium price of permits, that is $p_{2-i} > p_2$. But contrarily to grandfathered marketable permits, this market interaction does not affect their decision about whether or not to innovate because $\pi_i^{AP} > 0$. In other words the Nash equilibrium is that both firms innovate. We can establish the following:

Lemma 7. Because all firms are buyers of permits under an auction permits scheme, all firms have positive incentives to innovate, regardless of the industry size and other firms’ incentives. Furthermore, auction permits are always subject to a negative spillover effect in that innovation incentives are lower than compliance cost savings.

Proof. Figure 3 illustrates innovation incentives under different policy instruments for a firm $i$ that is subject to a “market-interaction effect,” in that $p_{2-i} > p_2$. For simplicity we assume that the industry has two identical firms, so $q_i^0$ coincides with the reductions in either period under the auction scheme. Note that to have an interior solution $q_i(p_{2-i}) < u_i$ and that because of symmetry distance $BH = HF$. It is straightforward then to show that

$$\Delta C_i^{AP} = A(ODIKE) > A(OBJKE) = \pi_i^{AP} > 0.$$  

The above result is consistent with Lemma 2 in that buyers are always subject to a negative spillover effect. If we compare $ILI^{AP}$ and $ILI^{MP}$, we have the following:

Lemma 8. In an auction scheme with so few players that each player’s action affects the auction equilibrium price, $ILI^{AP} > ILI^{MP}$. 

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Proof. Subtracting eq. (18) from (9) and assuming for the moment that the Nash equilibrium for the grandfathered marketable permit system (MP) is that both firms innovate, we obtain that $\pi_i^{AP} - \pi_i^{MP} = (u_i - q_i^0)(p_2^{-i} - p_2)$. Since $u_i > q_i^0$ (by construction) and $p_2^{-i} > p_2$, we have that $ILI^{AP} > ILI^{MP}$. If the Nash equilibrium of MP compromises a firm that does not innovate (see Lemma 2), $ILI^{MP}$ is even lower, so we still have that $ILI^{AP} > ILI^{MP}$.

The rationale behind this result is simple. Firm $i$ has more incentives under the auction scheme because it always has to buy more permits than under any allocation of grandfathered permits. In case it receives none, it would have equal incentives.

According to the analysis in 3.1 and Lemma 7 it is reasonable to think that, in the case of a small industry, $ILI^{AP}$ is more likely to be greater than $ILI^{ES}$. It is possible to establish:

Lemma 10. For $u_i$ sufficiently large we will always have that $ILI^{AP} > ILI^{ES}$.

Proof. Let us take Figure 3 again. It is not difficult to show that $\pi_i^{AP} - \pi_i^{ES} = A(EHJK) - A(BDH)$, which can be positive or negative. For low values of $u_i$ ($u_i'$) and large $C_i''(\cdot)$ (point $D'$) it may be that $A(BD'H) > A(EHJ'K')$. However, as $u_i$ increases, $A(BD'H)$ remains fixed while $A(EHJ'K')$ increases.
4.2 An n-firm industry

The market-interaction effect present in an auction scheme vanishes as the number of market players grows. At the limit, when there are \( n \) price-taker firms, \( p_{2-i} = p_2 \), so eqs. (9) and (18) converge, and \( \pi_i^{\text{ap}} = \pi_i^{\text{mp}} \). We can then establish the following:

**Proposition 3.** In an industry with \( n \) permits price-taker firms, an auctioned permits approach provides the same innovation incentives as a marketable permits approach, due to a stronger "negative spillover effect" impacting the auctioned permits approach.

**Figure 2** shows that the negative spillover effect becomes more significant under an auctioned permits approach than under a marketable permits approach. The total benefits not retained by private agents are equal to areas \( A(ABC) \) and \( A(BCDE) \). Thus, we can also establish that:

**Proposition 4.** An emission standards approach may (and always does, when innovation possibilities across firms are similar) provide more incentives to innovate than an auctioned permits approach in an industry with \( n \) permits price-taker firms, due to a more pronounced "negative spillover effect" and the convexity of cost savings effect. When firms’ innovation possibilities differ and the initial allocation of standards is not far from the cost-effective allocation, on the other hand, an auctioned permits approach is more likely to provide greater innovation incentives.
Propositions 3 and 4 contrast sharply with previous studies such as Milliman and Prince (1989) and Jung et al. (1996), which found auctioned permits to provide more innovation incentives than any of the other four instruments. Although this may be true in a system of very few firms, it is certainly not the case in an industry comprising many firms.

5. Emission standards vs. taxes and subsidies

We now explore those circumstances under which a tax or subsidy approach would provide greater incentives to innovate than would an equivalent emissions standards approach—that is to say that aggregate emission reduction during the first period would be the same under either policy alternative. Since a constant tax and/or subsidy levels would yield higher emissions reductions after innovations than any of the other four instruments, we also study the case when the regulator lowers the tax and subsidy levels such that emissions reductions in the second period are equal across instruments.\(^{17}\)

5.1 Constant tax and subsidy levels

When taxes and subsidies are unchanged (no ratcheting), there is no market interaction and one player’s action does not affect other players’ actions or incentives. Thus, whether we proceed with a two- or \(n\)-firm industry approach is irrelevant. On the

\(^{17}\) This is different than the ratcheting the government would do to stay in the social optimum. In the case of a tax instrument, for instance, if the marginal benefit curve is invariant overtime, the government
other hand, since taxes and subsidies remain unchanged, they are symmetric in terms of innovation incentives, as we shall explain.

**Figure 4** presents the particular case of a two-firm industry. Assume the two polluting firms are identical in Period 1 and that, in total, they must reduce at least $Q$ units of emissions during each period. As before, the pollution-control technologies ($s = 1,2$) for each firm ($i = 1,2$) are represented by the marginal control cost curves, $C'_s$. We allow the firms’ technology innovation possibilities to differ. The arbitrary emission reduction standards ($q_1^0$, $q_2^0$) are set such that total reductions $Q = q_1^0 + q_2^0$ is equal to $q_{11}(\tau) + q_{21}(\tau)$, where $\tau$ is the Pigouvian tax (or subsidy level) and equal to the equilibrium price $p_1$. $C_{11}^{-1}(\tau) = q_{11}^*$ and $C_{21}^{-1}(\tau) = q_{21}^*$ represent the least-cost allocations to the two firms during Period 1. In Period 2, the least-cost reduction allocation ($q_{12}^*$, $q_{22}^*$) would be higher for both firms.

We can now compute the change in compliance cost (including tax or subsidy payments) if a pollution tax (subsidy) is levied on the industry. Unlike the case with marketable permits, in this case it is always in firms’ interests to develop new technologies. Thus, changes in compliance costs for firms 1 and 2, respectively, are given by:

\[
\Delta C_{1T}^{TX} = A(OAHI) - A(OGHI) = A(OAG) - A(OJA) = \Delta C_{1S}^{SB} \tag{19}
\]

\[
\Delta C_{2T}^{TX} = A(OAHI) - A(OBHI) = A(OAB) - A(OJA) = \Delta C_{2S}^{SB} \tag{20}
\]

would also lower the tax level but not as much, unless the marginal benefit curve is totally inelastic (i.e.
where $\Delta C_i^{TX}$ and $\Delta C_i^{SB}$ are the $i$th firm’s changes in compliance costs under taxes and subsidies, respectively. Firms retain all benefits of innovation, so $\pi_i^{TX} = \pi_i^{SB} = \Delta C_i^{TX} = \Delta C_i^{SB}$, and $ILI^{TX} (= ILI^{SB})$ is the sum of (19) and (20).

For emission reduction standards ($q_1^0$, $q_2^0$), we find that the change in compliance costs for firms 1 and 2, respectively, are given by:

\[
\Delta C_1^{ES} = A(OEF) = \pi_1^{ES} \tag{21}
\]

\[
\Delta C_2^{ES} = A(ODC) = \pi_2^{ES} \tag{22}
\]

and, as before, $ILI^{ES}$ is the sum of (21) and (22).

A graphic comparison of $ILI^{TX}$ with $ILI^{ES}$ offers no definite answer as to which $ILI$ index is larger. For instance, the fact that in Figure 4, $A(ADCB)$ is greater than $A(FEAG)$ suggests that $ILI^{TX} < ILI^{ES}$. However, as firm 1’s innovation opportunities increase and the standards are set closer to the first-period, least-cost allocation, $ILI^{TX}$ can easily exceed $ILI^{ES}$.

We can explore this further by developing an analytical expression for $ILI^{TX}$. Let us consider $n$ small firms. Innovation incentives for firm $i$ are given by

\[
\pi_i^{TX} = (u_i - q_{i1}(\tau))\tau + C_{i1}(q(\tau)) - (u_i - q_{i2}(\tau))\tau - C_{i2}(q(\tau)) = \pi_i^{SB} \tag{23}
\]
Integrating, we obtain that $ILI^T = ILI^{SB} = A(OCF)$ in Figure 2, that for linear marginal costs reduces to the more simple expression

$$ILI^T = ILI^{SB} = \frac{\tau^2}{2p_1p_2}(p_1 - p_2)Q = \frac{p_1}{2p_2}(p_1 - p_2)Q$$

(24)

In comparing $ILI^T$ with $ILI^{ES}$, let us follow the analysis in section 3.2. Assuming first that innovation possibilities are the same across firms, we have that $ILI^{ES*} = A(OCB)$, which is equal to $(p_1 - p_2)Q/2$ when marginal costs are linear. Because $p_1 > p_2$, we have that $ILI^T > ILI^{ES*}$. While $ILI^T$ remains fixed, $ILI^{ES}$ increases as the allocation of standards departs from the cost-effective allocation $q^{*}$.

If we take the previous example of the 100 small firms and let the aggregate reduction target of 100 to be equally imposed upon only 40 of the 100 firms, we have that $ILI^{ES}$ goes from 25 ($ILI^{ES*}$) to 62.5, while $ILI^T$ remains at 50. Thus, due to the “convexity of cost savings effect,” worsening standards—those prescribing increasingly inefficient patterns of emissions reductions—are more likely to promote innovation than are cost-effective policies such as taxes or subsidies. In contrast, if we let innovation possibilities to differ across firms, $ILI^{ES*}$ will decrease relative to $ILI^T$. Recall that we must keep $ILI^T$ unchanged as we increase some $\Delta k$’s at the expense of others. This requires maintaining $p_2$ constant (i.e., $\Sigma(1/k_i) = \text{constant}$). Summarizing:

**Proposition 5.** An emission standards approach may provide more innovation incentives than a tax (subsidy) approach in an industry with $n \geq 2$ firms, due to the convexity of cost savings effect. When firms innovation opportunities differ and the initial
allocation of standards is not far from the cost-effective allocation, on the other hand, a tax (subsidy) approach is more likely to provide greater innovation incentives.

5.2 Lower tax and subsidy levels

As suggested by Wenders (1975), taxes and subsidies may not be symmetric in terms of innovation incentives if the regulator reacts after innovation has taken place (in period 2) by adjusting the tax and subsidy levels. This “ratcheting” effect on incentives is studied only for the case of a large number (n) of small firms. To keep total emissions reductions unchanged, we let the regulator lower the tax and subsidy level to \( \tau < \tau \). Innovation incentives for the \( i \)th price-taker firm under a tax and subsidy regimes are given, respectively, by

\[
\pi_{i}^{TX} = (u_i - q_{i1}(\tau'))\tau' + C_{i1}(q(\tau')) - (u_i - q_{i2}(\tau'))\tau' - C_{i2}(q(\tau'))
\]

\[
\pi_{i}^{SB} = C_{i1}(q(\tau')) - \tau'q_{i1}(\tau') - C_{i2}(q(\tau')) + \tau'q_{i2}(\tau')
\]

Since all firms innovate (see Lemma 6) we will have that \( \tau = p_2 \). We establish that

Lemma 10. If ratcheting is considered, innovation incentives under the tax and subsidy regime are still the same. However, costs savings between periods are higher under the tax regime.
Proof. For the first part simply rewrite eq. (25). To obtain cost savings between periods replace \( \tau \) for \( \tau \) in the first two term of the right hand side of (25) and (26), then subtract (25) from (26) to obtain \( u_i \cdot (\tau - \tau') > 0 \).

Note that the latter part of Lemma 9 is Wenders’ (1975) result, who had suggested that subsides offer less incentives. Finally to obtain ILI indexes, we integrate eq. (24) and get that \( ILI^{TX} = ILI^{SB} = A(OAB) \) in Figure 2.

6. Taxes and subsidies vs. auctioned permits and marketable permits

It remains for us to compare taxes (or subsidies) with both marketable permits and auctioned permits. Because of the “market power effect,” our results will depend on whether firms are price-takers or not in the marketable-permits and auctioned-permits policy alternatives. Let us first study an industry with few firms and the case of \( n \) price takers firms. Our results incorporate the ratcheting effect only in the latter case.

6.1 A few-firm industry

We first establish the following:

Lemma 11. In a few-firm industry, a tax (subsidy) approach is likely to provide more incentive than a marketable-permits approach, but it may provide the same, or less.
Graphical proof. Figure 3 illustrates the innovation incentives under different policy instruments for a representative firm $i$ subject to a “market power effect,” in that $p_2^i > p_2$. The proof is as follows. If only firm $i$ has innovation possibilities, so that $p_2^i = p_1$, and the initial allocation of permits to firm $i$ is very small ($u_i - q_i \approx 0$ and positive), $ILI^{MP} \approx A(ODIKE)$ and $ILI^{TX} = A(ODG)$. Therefore $ILI^{MP} > ILI^{TX}$. However, if the initial reduction allocation is instead $q_i^0$, $ILI^{MP}$ reduces to $A(ODE)$ while $ILI^{TX}$ remains the same. In this case, $ILI^{MP} < ILI^{TX}$. Furthermore, if both firms have identical innovation opportunities and the initial allocation is $q_i^0$, we have that $ILI^{MP} = 2A(OBHE) < 2A(ODG) = ILI^{TX}$.

Lemma 12. In a few-firm industry, a tax (subsidy) approach can provide more, the same, or less incentive to innovate than an auctioned-permits approach.

Graphical proof. As Figure 3 shows, $\pi_i^{AP} = A(OBJKE)$ and $\pi_i^{TX} = A(ODG)$. Therefore, $\pi_i^{AP} <(=)(>) \pi_i^{TX} \iff A(EFJK) <(=)(>) A(BDGF)$.

6.2 An $n$-firm industry

Let us now study the more general case of an industry with $n$ price-taker firms. When the market-power effect disappears in both the marketable-permits and auctioned-permits markets, $ILI^{MP}$ and $ILI^{TX}$ are given by Eqs. (13) and (25), respectively, and $ILI^{MP} = ILI^{MP}$, based on Proposition 3. Since $\tau = p_1 > p_2$, what immediately follows is:
Proposition 6. *In an industry with n price-taker firms, a tax (subsidy) approach provides more innovation incentives than either a marketable- or an auctioned-permits approach, since the "negative spillover effect" affects only the marketable- and auctioned-permits policy alternatives.*

The reason is that the tax level does not adjust after the adoption of new technologies, unlike the permits market, in which permit prices tend to fall during the second period. Firms anticipate the lower second-period permits price, so have less incentive to innovate than they would have under a tax (subsidy) approach, where they would face the cost of higher taxes—or the benefit of higher subsidies—relative to second-period permits.

However if we consider ratcheting we have that $ILI^{TX}$ and $ILI^{SB}$ reduce exactly to the level of $ILI^{MP}$ and $ILI^{AP}$. Therefore:

Proposition 7. *In an industry with n price-taker firms and where the regulator adjust the tax and subsidy levels so emissions reduction are equal across instruments, the innovation incentives provided by any of the four market-based instruments are the same.*

This is the result of a “negative spillover effect” upon tax and subsidy regimes as well. Proposition 7 is a remarkably result. It is saying that under a competitive setting and equal reduction requirements, market-based instruments are not only cost-effective (or static efficient) equivalent but also dynamic-efficient equivalent.
7. Conclusions

This paper has provided a comprehensive analysis of the impact of various environmental policy instruments on industry incentives to innovate in more efficient pollution-control technologies. Using two-period models, we have shown that, unlike what has been previously reported, a command and control instrument such as emission standards may provide more innovation incentives than any of the market-based instruments studied here—grandfathered marketable permits, auctioned permits, taxes and subsidies. One reason is that grandfathered and auctioned permits are subject to a “negative spillover effect,” in that aggregate private incentives fall short of “total benefits” of an innovation. The other reason is that because costs savings from innovations are convex at the emission-reduction level, emissions standards far from the least-cost allocation can lead to higher aggregate cost savings than would be realized with a tax, subsidy, or permits approach.

However, as innovation opportunities differ across firms, market-based instruments are more likely to provide higher incentives. We also showed that incentives are sensitive to industry size and whether the government adjusts the tax and subsidy level after the innovation (ratcheting). In fact, for an industry with a large number of price taker firms and provided that the government lowers the tax and subsidy level such that emissions after the innovation are the same across instruments, innovation incentives are the same for all four market-based instruments.

We have left unexplored several issues that may affect the calculation of the industry level incentives indexes, \( ILI \), that formed the base of our instrument ranking. In fact, we have ignored costs of fixed innovation costs in the form of R&D expenditures, the fact
that abatement technology and emissions reduction choices may be discrete rather than continuous, the nature of the innovation process, the impact of various policy instruments on firm entry/exit conditions and on the output market, the ease in the dissemination of new information, and market and regulatory uncertainty.

Market uncertainty in the form of permits price uncertainty may lead to underinvestment in innovation expenditures in the permits markets (see Pindyck, 1991). On the other hand, regulatory uncertainty in the form of noncommitment or ratcheting is also possible, though unlikely in the short run, due to either political and informational constraints. Nevertheless, theoretical exercises have shown that, given noncommitment or ratcheting, instrument rankings can change—sometimes significantly. Magat (1978) found that taxes would provide the same incentive as continuously changing emission standards, so the same reduction level is achieved with either instrument. Recently, Laffont and Tirole (1996) found that “plain” permits markets may provide little or no incentive to innovate in cases where a regulator shows little commitment to upholding permit prices.

In addition, it is important to note that in some instances, U.S. environmental policy is written in such a way that what appear to be emission standards are instead technology-based standards (Portney, 1990). This is because emission standards were set on the basis of what can be done with available technology, rather than what should be done to achieve ambient quality standards. Magat (1979) conjectures that unless benefits from innovation can be appropriated by their owners, and unless regulatory agencies can quickly revise regulations based on new abatement technologies, requiring other firms to pay to adopt them, technology-based standards offer less incentive to innovate than do equivalent emission standards. If that is the case, the $ILI$ index corresponding to technology-based standards should be lower than that for emission standards.
While many of the aforementioned issues deserve further theoretical research, the hypothesis that marketable permit schemes provide significantly different incentives to innovate than firm-specific standards constitutes an important area for empirical research, as well. The sulfur-dioxide trading program of the 1990 Clean Air Act Amendments—the largest and perhaps most successful experiment in the use of tradeable permits ever implemented—could provide valuable data for such empirical tests.

Finally, the conclusions of this paper, even if supported by eventual empirical evidence, do not imply that society must be inclined to use those instruments providing the most innovation incentives. A broader welfare analysis would consider other criteria in addition to technology promotion, such as static efficiency or cost-effectiveness, enforceability, administrative ease, and public acceptability, in the selection of the appropriate environmental policy instrument. An especially interesting area for future research might be to combine static and dynamic efficiency criteria.

References


Figure 1. Firm and industry incentives under marketable permits and standards
Figure 2. Innovation incentives for an \( n \)-firm industry
Figure 3. Innovation incentives for an individual firm
Figure 4. Firm and industry incentives under taxes and standards