MARKETS FOR ENVIRONMENTAL PROTECTION: DESIGN AND PERFORMANCE

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Abstract

Policy makers in different parts of the world are paying more attention to environmental markets (i.e., tradeable permits markets) as an alternative to the traditional command-and-command control approach of setting uniform emission and technology standards. I extend the basic (perfect information) model of a permits market to accommodate for practical considerations including regulator's asymmetric information on firms' costs, uncertainty on benefits from pollution control, incomplete enforcement, incomplete monitoring of emissions and the possibility of voluntary participation of non-affected sources. Implications for instrument design and implementation are provided.

Resumen

Las personas encargadas de diseñar y/o implementar políticas públicas en diferentes partes del mundo están prestando cada vez más atención al tema de los "mercados ambientales" (i.e., mercados de permisos de contaminación negociables) como una alternativa al enfoque tradicional de fijar cuotas uniformes de emisión y estándares tecnológicos. Este artículo extiende el modelo básico (información completa) de un mercado de permisos para adecuarlo a varias consideraciones prácticas, incluyendo asimetrías de información del regulador sobre los costos de las firmas, incertidumbre sobre los beneficios del control de la contaminación, implementación incompleta, monitoreo incompleto de las emisiones y la posibilidad de participación voluntaria de fuentes no afectadas. Se muestran además las implicaciones del diseño e implementación de los instrumentos.

Keywords: Environmental regulation, permits markets, asymmetric information, incomplete enforcement.

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1. Introduction

Policy makers in different parts of the world are paying more attention to environmental markets (i.e., tradeable emission permits markets) as an alternative to the traditional command-and-command control approach of setting uniform emission and technology standards. A notable example is the 1990 U.S. Acid Rain Program that implemented a nationwide market for electric utilities' sulfur dioxide (SO_2) emissions (Schmalensee *et al*., 1998; Ellerman *et al*., 2000). The U.S. Environmental Protection Agency's (EPA) emissions trading policy represents another and older attempt to implement environmental markets to mitigate air pollution problems in urban areas across the country (Hahn, 1989; Foster and Hahn, 1995; Tietenberg, 1985). In addition, a few less developed countries are also beginning to experiment in different forms with emissions trading (World Bank, 1997; Montero *et al*., 2003; Stavins, 2003a).

These experiences should not leave the impression that environmental markets have come anywhere close to replacing the traditional command-and-control approach. More reason to believe that permit markets are expected to play an increasing role in the solution of environmental problems in the future. In this sense, experience with existing permit markets help understand the importance of practical considerations for the design and implementation of these markets and for establishing the conditions under which they are likely to perform better than alternative instruments. My intention in this paper is not to provide an exhaustive treatment of all practical considerations that may prove relevant, but only some of those that have caught my attention as I review the performance of existing permits programs (particularly the Acid Rain Program in the U.S. and the total suspended particulate program of Santiago), and proposals for implementation of new ones (particularly carbon trading for dealing with global warming and a comprehensive permits program for curbing air pollution in Santiago).

The rest of the paper is organized as follows. In Section 2 I develop a basic model of pollution control where I illustrate the advantage of permits over alternative instruments such as standards. In Section 3 I extend the basic model to accommodate for some practical considerations that have proved relevant in the design of permit markets. They include regulator's uncertainty on costs and benefits from pollution control, incomplete enforcement, incomplete monitoring of emissions and the possibility of voluntary participation from sources not originally regulated. Section 4 discusses topics for further research.

2. The Basic Model

Consider a continuum of firms of mass 1. In the absence of environmental regulation, each firm emits one unit of pollution which can be abated at a cost c. The value of c, which is private information, differs across firms according to the (continuous) density function $g(c)$ and cumulative density function $G(c)$

defined over the interval $[\underline{c}, \bar{c}]$. These functions are known by the welfare-maximizing regulator. Although the regulator does not know the control cost of any particular firm, he can derive the aggregate abatement cost curve for the industry, $C(q)$, where $0 \leq q \leq 1$ is the aggregate quantity of emissions reduction.[1] The regulator also knows that the benefit curve from emissions reduction in any given period is $B(q)$. As usual, I assume that $B'(q) > 0$, $B''(q) \leq 0$, $C'(q) > 0$, $C''(q) \geq 0$, $B'(0) > C'(0)$, and $B'(q) < C'(q)$ for q sufficiently large.

Letting the regulator's welfare function be $W(q) = B(q) - C(q)$, the first-best reduction level q^* solves $B'(q^*) = C'(q^*) = c^*$, where $G(c^*) = q^*$. It is first-best optimal that firms with costs equal or below c^* be the only ones reducing emissions. To implement the first-best solution the regulator can either set a Pigouvian tax on emissions equal to $\tau = c^*$ or allocate a total of $x = 1 - q^*$ tradeable emission permits (recall that aggregate counterfactual emissions are equal to 1). If the regulator introduces a tax τ, firms with $c < \tau$ will reduce emissions while firms with $c > \tau$ will prefer to pay the tax. Thus, when τ is set at the first-best level c^*, firms will have incentives to reduce exactly up to the first-best level q^*.

If, on the other hand, the regulator distributes x permits either for free or through an auction, the market clearing price will be $p = C'(1 - x) = G^{-1}(1 - x)$. In particular, if the regulator allocates to each firm x permits for free, firms with $c > p$ will be making no reductions and buying extra permits to cover their emissions while firms with $c < p$ will be reducing their emissions and selling all their permits. Thus, when x is set at the first best level $1 - q^*$, the resulting clearing price will be exactly at the first-best level c^*.

In this particular setting in which the regulator knows both the aggregate abatement cost curve and the benefit curve, he is clearly indifferent as to whether use a price instrument (taxes) or a quantity instrument (permits) to reach the first-best solution. More generally, he can use either taxes or permits to achieve any emission goal (other than $1 - q^*$) at the lowest cost.

In practice, however, we rarely see regulators using taxes or permits. With a few exceptions, they almost exclusively rely on the traditional command-and-control approach of setting (uniform) emission and technology standards. Under this approach, a regulator with an aggregate emission goal of x would require each firm to emit no more than x. Clearly, this approach will result in an inefficient allocation of abatement across firms unless they have identical abatement costs (i.e., $\underline{c} = \bar{c}$), which is unlikely. As typically occurs under standards, high cost firms are reducing too much while low cost firms are reducing too little. Because of this efficiency loss, economists have been long arguing for the wider use of market-based instruments such as permits (Dales, 1968; Montgomery, 1972).

Leaving aside political economy considerations that may help explain the limited use of market-based instruments,[2] in the remaining of the paper I will

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[1] The aggregate cost curve is $C(q) = \int_{\underline{c}}^{y} c\,dG$, where $y = G^{-1}(q)$. Note that $C'(q) = y$, $C'(0) = \underline{c}$, and $C''(q) = 1/g(y)$.

[2] See Stavins (2003) for political economy.

extend the basic model to incorporate additional elements that regulators are likely to face in the practical design and implementation of environmental markets.

3. EXTENDING THE BASIC MODEL

The world of perfect information depicted in the basic model is hard to find in practice. Typically, regulators must design and implement policies in the presence of significant uncertainty about costs and benefits, and sometimes, under imperfect monitoring and enforcement as well. In what follows I will extend the basic model to account for some of these practical considerations.

My intention is not to provide an exhaustive treatment of all practical considerations that may prove relevant for the design of permits programs, but only some of those that have caught my attention as I review the performance of existing permits programs, particularly the Acid Rain Program in the U.S. (Ellerman *et al*., 2000) and the TSP in Santiago (Montero *et al*., 2002), and proposals for implementation of new ones, particularly carbon trading for dealing with global warming and a comprehensive permits program for curbing air pollution in Santiago. In extending the basic model, it is important to keep in mind that the normative implications of these practical considerations may affect the policy design in various ways that can go from a simple tightening of the basic design, to a combination of permits with some other instrument (such as taxes or standards), or yet, to the replacement of permits by an alternative instrument.

3.1. Imperfect information on costs and benefits

The basic model indicates that when the regulator has a good idea about the (aggregate) costs and benefits of pollution control along with perfect monitoring of emissions and full compliance, he can implement the first-best by either using a tax of c^* or allocating $1 - q^*$ permits. Several authors have extended the basic model to the case in which the regulator knows little about firms' costs but can costlessly monitor each firm's actual emissions and enforce compliance. To capture the regulator's imperfect information on costs in our model, let his prior belief be $c(\theta) = c + \theta$, where θ is some stochastic term such that $E[\theta] = 0$ and $E[\theta^2] > 0$, where $E[\cdot]$ is the expected value operator. I assume that θ is common to all individual costs $c \in [\underline{c}, \overline{c}]$, which produces the desired "parallel" shift of the aggregate marginal cost curve, $C'(q)$, by the amount θ. In other words, $C'(q, \theta) = C'(q) + \theta$. Recall that $c(\theta)$ continues to be firm's private information, so the realization of θ is known by all firms before they make and implement their compliance (and production) plans.[3]

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[3] While it is true that the regulator may (imperfectly) deduce uncertainty with a lag from the aggregate behavior of firms, I am assuming that he adheres to the original regulatory design from the beginning of time. Alternatively, we can say that new sources of cost uncertainty arise continually, so the issue of uncertainty is never resolved.

Because the introduction of θ leaves the regulator uncertain about the true aggregate marginal cost curve, he can no longer implement the first-best solution by simply allocating a certain number of permits. Making use of the revelation principle, Kwerel (1977) and Dasgupta *et al*. (1980) show that this information asymmetry does not prevent the regulator from achieving the first-best if he can use non-linear instruments (i.e., transfer to or from firms contingent on their cost revelations and emissions).[4] Alternatively, the regulator can achieve the first-best by announcing a non-linear tax schedule $\tau(q)$ equal to $B'(q)$, where q is the aggregate amount of reduction observed ex-post.[5]

Despite the welfare superiority of these non-linear instruments, experience shows that regulators always favor simple regulatory designs that can be implemented in practice.[6] For this particular reason it remains relevant to understand the implications of imperfect information on the design of relatively simple instruments such as permits, (linear) taxes and standards.

While cost uncertainty does not change the welfare advantage of permits over standards, in a seminal paper Weitzman (1974) showed that it does break the welfare equivalence between permits and taxes. To expand the basic model in a tractable way let follow Weitzman (1974) and Baumol and Oates (1988) and consider linear approximations for the marginal benefit and cost curves and additive uncertainty. I will also allow here the regulator be uncertain about benefits. Thus, let the expected marginal benefit and cost curves be, respectively

$$B'(q) = \underline{b} + B''q \tag{1}$$

$$C'(q) = \underline{c} + C''q \tag{2}$$

where $\underline{b} \equiv B'(0) > \underline{c} \geq 0, B'' < 0,$ and $C'' \equiv \bar{c} - \underline{c} > 0$ are all fixed coefficients.[7] To capture the regulator's uncertainty about the true shape of these curves at the time of regulatory design and implementation, let his prior belief for the marginal-benefit curve be $B'(q, \eta) = B'(q) + \eta$, where η is a stochastic term such that $E[\eta] = 0$ and $E[\eta^2] > 0$. For the marginal-cost curve, let the regulator's prior belief be as above, i.e., $c(\theta) = c + \theta$.

It is not difficult to show that the optimal tax and permits design are as in the certainty case, that is $\tau = c^*$ and $x = 1 - q^*$. Because of uncertainty, however, neither design will be optimal ex-post (unless $\theta = \eta = 0$). The relevant policy question then is which instrument is expected to come closer to the ex-post

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[4] In a later paper Spulber (1988) argues that the first-best may not be feasible under budget constraints.

[5] Note that with this tax scheme the regulator is making firms face the demand curve for emission reductions.

[6] This comment applies to the regulation public utilities as well (Rogerson, 2003).

[7] Note first that the linear marginal cost curve results simply from a uniform distribution for $g(c)$. Further, the notation is meant to be consistent with in the cost curve.

optimum. To explore this question we estimate the difference between the expected social welfare under the price instrument (taxes) and that under the quantity instrument (permits), which is given by

$$\Delta_{pq} \equiv \mathrm{E}[W(\tau, \theta, \eta) - W(x, \theta, \eta)] \tag{3}$$

where $\tau = c^*$ and $x = 1 - q^*$ are, respectively, the optimal price and quantity designs. The normative implication of (3) is that if $\Delta_{pq} > 0$, prices (i.e., taxes) provide higher expected welfare than quantities, and accordingly, ought to be preferred. If $\Delta_{pq} < 0$, quantities (i.e., tradeable permits) ought to be preferred.

Expression (3) can be conveniently rewritten as

$$\Delta_{pq} = \mathrm{E}[\{B(q(\tau, \theta), \eta) - B(q(x, \theta), \eta)\} - \{C(q(\tau, \theta)) - C(q(x, \theta))\}] \tag{4}$$

The first curly bracket of the right hand side of (4) is the difference in benefits provided by the two instruments, whereas the second curly bracket is the difference in abatement costs. Using the linear approximations above, replacing $\tau = c^*$ and $x = 1 - q^*$, taking expectations and assuming that $\mathrm{E}[\theta\eta] = 0$, eq. (4) reduces to

$$\Delta_{pq} = \frac{\mathrm{E}[\theta^2]B''}{2(C'')^2} + \frac{\mathrm{E}[\theta^2]C''}{2(C'')^2} \tag{5}$$

where the first term of the right hand side is the difference in expected benefits (negative) and the second term is the difference in expected costs (positive). While taxes lead to lower expected costs permits lead to higher expected benefits (i.e., lower expected emissions). Finally, rearranging (5) reduces to

$$\Delta_{pq} = \frac{\mathrm{E}[\theta^2]}{2(C'')^2}(B'' + C'') \tag{6}$$

which is Weitzman's well known result.

The normative implications of (6) are quite clear: prices (i.e., taxes) ought to be preferred if the marginal cost curve is steeper than the marginal benefit curve; that is, if $C'' > |B''|$; otherwise quantities (i.e., permits) ought to be preferred. The rationale for using prices over quantities is the following. As long as miscalculating the ex-post optimum amount of control has lower welfare consequences than miscalculating the ex-post optimum (marginal) cost of control, which happens when the marginal cost curve is steeper than the marginal benefit curve, prices are preferred. In a quantity regime, the amount of control remains fixed while the cost of control is subject to large swings because of uncertainty. If the marginal cost curve is very steep, the (marginal) cost of control can deviate significantly from the ex-post optimum; situation in which a price instrument that fixes the marginal cost of control turns more appropriate. Note that benefit uncertainty is absent unless there is some correlation between θ and η.[8]

Because neither permits nor taxes are ex-post optimum, there seems to be room for a hybrid policy to improve upon either single-instrument policy. Roberts and Spence (1980) formally showed that a hybrid policy that combines $x = 1 - q^*$ permits with a tax $\tau > c^*$ and subsidy $s < c^*$ is always superior to either single-instrument policy.[9] If, for example costs happen to be higher than expected, i.e., $\theta > 0$, the allocation of $1 - q^*$ permits appear too tight ex-post resulting in too high prices. The introduction of the tax puts a ceiling on the permits price, which is equivalent as to having the regulator issuing additional permits. If, on the other hand, costs happen to be lower than expected, i.e., $\theta < 0$, the allocation of $1 - q^*$ permits appear too lenient ex-post resulting in too low prices. The introduction of the subsidy puts a floor on permits prices, which is equivalent as to having the regulator buying-back some permits.[10]

The idea of combining permits with taxes (but less with subsidies) is at the center of the debate on instrument design for reducing carbon dioxide emissions believed to be responsible for global warming. Early proposals had permits as the only single instrument to reduce these emissions (see, e.g., Kyoto Protocol), but because several studies have shown compliance costs to be quite uncertain, more recent proposals argue for the inclusion of a tax as a safety valve in case the price of permits climbs inefficiently high (Pizer, 2002).

3.2. Incomplete enforcement

It is well known that regulations are not always fully enforced; the TSP program in Santiago is a good example of that. To understand the implications of incomplete enforcement on policy design, in Montero (2002) I extend Weitzman (1974) analysis.[11] The regulator is responsible for ensuring individual firms' compliance with either the price or the quantity instrument. Firms are required to monitor their own emissions and submit a compliance status report to the regulator. Emissions are not observed by the regulator except during costly inspection visits, when they can be measured accurately. Thus, some firms may have an incentive to report themselves as being in compliance when, in reality, they are not.

The cost of each inspection is v, which I assume to be large enough that full compliance is not socially optimal (Becker, 1968).[12] Therefore, in order to verify

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[8] In fact, if θ and η are positively correlated, i.e., $E[\theta\eta] > 0$, an additional negative terms enters into (5) increasing the advantage of permits over taxes.

[9] In a subsidy scheme, the government pays firms for reductions.

[10] Note that if there are only two possible realizations of cost (high and low), the introduction of a tax and subsidy implement the first best.

[11] Stralund and Chavez (2000) also study the effects of incomplete enforcement on permits programs.

[12] Alternatively, we can simply say that the regulator lacks sufficient resources to induce full compliance.

reports' truthfulness, the regulator randomly inspects those firms reporting compliance through pollution reduction to monitor their emissions (or check their abatement equipment). Each firm reporting compliance faces a probability ϕ of being inspected. Firms found to be in disagreement with their reports are levied a fine $F(\leq \overline{F}$, where $\overline{F}$ is the maximum feasible fine, which value is beyond the control of the regulator) and brought under compliance in the next period.[13] To come under compliance, firms can reduce pollution or, depending on the regulatory regime, either pay taxes or buy permits. Firms reporting noncompliance face the same treatment, so it is always in a firm's best economic interests to report compliance, even if that is not the case.[14] Finally, I assume that the regulator does not alter its policy of random inspections in response to information acquired about firms' type, so each firm submitting a compliance report faces a constant probability ϕ of being inspected.[15]

After deriving the optimal price and quantity design under uncertainty and incomplete enforcement,[16] the Weitzman comparison between prices (i.e., taxes) and quantities (i.e., permits) shown in (5) changes to

$$\Delta_{pq} = \gamma(2-\gamma)\frac{\mathrm{E}[\theta^2]B''}{2(C'')^2} + \gamma\frac{\mathrm{E}[\theta^2]C''}{2(C'')^2} \tag{7}$$

where the first term of the right hand side is the difference in expected benefits and the second term is the difference in expected costs. Rearranging (7) leads to

$$\Delta_{pq} = \frac{\gamma \mathrm{E}[\theta^2]}{2(C'')^2}((2-\gamma)B'' + C'') \tag{8}$$

where $\gamma = \phi/(1+\phi) < 1$ is the fraction of the non-compliant firms (i.e., all those firms that have incentives to submit false reports) that are in compliance in any given period. Since $2 - \gamma > 1$, eq. (8) shows that incomplete enforcement improves the relative advantage of permits over taxes.

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[13] To make sure that a non-compliant firm found submitting a false report is in compliance during the next period (but not necessarily the period after), we can assume that the regulator always inspects the firm during that next period, and in the case the firm is found to be out of compliance again, the regulator raises the penalty to something much more severe.

[14] Noncompliance and truth-telling could be a feasible strategy if firms reporting noncompliance were subject to a fine lower than F. See Kaplow and Shavell (1994) and Livernois and McKenna (1999) for details.

[15] As game theoretic models of incomplete enforcement have shown (for example, Harrington, 1988), the regulator clearly can improve upon a uniform inspection probability after learning (maybe imperfectly) about firms' type. But because the amount of control would still be depending on the actual control costs, the main result of the present paper would not change.

[16] Optimal designs include also values for ϕ and F. On this latter, it is optimal for the regulator to impose the largest feasible fine, that is $\overline{F}$. See Montero (2002) for more.

To explain this result requires first to understand that the presence of incomplete enforcement makes the effective (or observed) amount of control under a quantity instrument no longer fixed, as in a permits program with full compliance. Instead, it adapts to the actual cost of control. Indeed, if the marginal cost curve proves to be higher than expected by the regulator, more firms would choose not to comply, and consequently, both the effective amount of control and the cost of control would be lower than expected.

The fact that the effective reduction now becomes uncertain has two effects on the welfare comparison between prices and quantities that can be explained using (7). The first effect is captured in the first-term of the right hand side, which shows that the advantage of quantities over prices on the benefit side is reduced to $\gamma(2-\gamma) < 1$ relative to the case of full compliance (i.e., $\gamma = 1$).[17] The second effect is captured in the second-term of the right hand side of (7) that shows that the advantage of prices over quantities on the cost side is also reduced to $\gamma < 1$. Because $\gamma(2 - \gamma) > \gamma$, the second effect dominates and the overall advantage of prices over quantities is reduced. From (7) one also observes that incomplete enforcement makes both the marginal benefit curve and the marginal cost curve to look flatter, but because $\gamma(2 - \gamma) > \gamma$, it makes the marginal cost curve even more so. In addition, note that as γ falls, the welfare difference between the two instrument shrinks and disappears when there is no compliance at all (i.e., $\gamma = 0$).

Another way to interpret this result is that incomplete enforcement “softens” the quantity regime, making it resemble a non-linear instrument, as in Roberts and Spence (1976). Indeed, when costs prove to be higher than expected, some firms choose not to comply, increasing the effective amount of pollution.

3.3. Multipollutant markets

In dealing with Santiago air pollution, or more generally, in any urban pollution control effort, the design and implementation of good environmental policy necessarily involves more than one pollutant. Hence, the study of permit programs to simultaneously regulate various pollutants becomes very relevant. If the regulator has perfect information about costs and benefits of pollution control for each of the pollutants involved, it is evident that the regulator can implement the first-best through the allocation of permits to the different markets without the need for interpollutant trading. Under imperfect information on costs and benefits and possibly partial compliance, in Montero (2001) I show that the optimal permits design is more involved. It may be (second-best) optimal, under some conditions, to have the different pollutant markets integrated through some optimal exchange rates. In practical terms, it may be optimal allowing firms to cover their emissions of particulate matter (PM10) with permits of nitrogen oxides (NOx). Obviously some exchange rate must be defined.

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[17] From the concavity of the benefit curve, uncertainty in the reduction level reduces expected benefits.

To study under what conditions market integration is beneficial, I use the Weitzman framework and compare welfare under market integration vs. welfare under market separation. I consider two pollutants 1 and 2 (e.g., PM10 and NOx). If I impose some symmetry to the problem, that is $B_1'' = B_2'' = B''$, $C_1'' = C_2'' = C''$, $\phi_1 = \phi_2$, and θ_1 and θ_2 are i.i.d. and not correlated with η (the intercepts $\underline{c}$ and $\underline{b}$ and penalty fee F can vary across markets), the optimal amount of permits to be distributed under integration is the same that under separation. In addition, it is possible to establish that the welfare advantage of having markets working together (t) over separately (s) is given by the (familiar) expression

$$\Delta_{ts} = \frac{\gamma \mathrm{E}[\theta^2]}{2(C'')^2}((2-\gamma)B'' + C'') \tag{9}$$

where $\gamma = \phi/(1+\phi) < 1$ is again the fraction of non-compliant firms that are in compliance in any given period, $\mathrm{E}[\theta^2]$ captures regulator's uncertainty, $B'' < 0$ is the slope of the marginal benefit curves and $C'' > 0$ is the slope of the marginal cost curves.

The first in eq. (9) is that under full enforcement ($\gamma = 1$) the regulator should allow interpollutant trading (i.e., market integration) as long as the marginal cost curves are steeper than the marginal benefit curves. This result is analogous to the result obtained by Weitzman (1974), a similar rationale applies to our multipollutant markets story. Interpollutant trading provides more flexibility to firms in case costs are higher than expected, but at the same time, it makes the amount of control in each market more uncertain. Then, if the marginal cost curves are steeper than the marginal benefit curves, the regulator should pay more attention to cost of control rather than the amount of control, and therefore, have markets integrated. On the other hand, if the marginal benefit curves are steeper than the marginal cost curves, the regulator should pay more attention to the amount of control in each market, and therefore, have markets separated.

The presence of incomplete enforcement ($\gamma < 1$) has important effects on the multipollutant markets design as well. Since $2 - \gamma > 1$, (9) indicates that incomplete enforcement reduces the advantage of market integration: the regulator should allow interpollutant trading only if the marginal cost curves are $2 - \gamma$ times steeper than the marginal benefit curves.

3.4. Voluntary participation

For either practical or political reasons, phase-in or less than fully comprehensive tradeable permit programs with voluntary opt-in possibilities are attracting considerable attention among policy makers. The Acid Rain Program provides a good example. Under the Substitution provision of this program, electric utility units not originally affected by the program could voluntarily become subject to all compliance requirements of affected units and receive SO_2 tradeable permits approximately equal to their 1988 emissions level (7 years before compliance). Another salient example is provided by current emissions trading proposals in dealing with global warming that call for early carbon dioxide restrictions on OECD countries with (voluntary) substitution possibilities with the rest of the world. Yet another example is provided by trading proposals in dealing with air pollution in Santiago that would allow voluntary participation of non-affected sources (e.g., expansion or creation of parks to sequester PM10).

Although the Substitution provision was primarily designed to allow those non-affected electric units with low abatement cost to (voluntarily) opt-in, Montero (1999) explains that a large number of non-affected units opted in because their unrestricted or counterfactual emissions (i.e., emissions that would have been observed in the absence of regulation) were below their permit allocations. In other words, they had received *excess* permits. While shifting reduction from high-cost affected units to low-cost non-affected units reduces aggregate compliance costs, excess permits may lead to social losses from higher emissions than had the voluntary provision not been implemented.

As with any other regulatory practice, the optimal design of a phase-in permits program with opt-in possibilities for non-affected firms is subject to an asymmetric information problem in that the regulator has imperfect information on individual unrestricted emissions and control costs. In world of perfect information (as in the basic model), a regulator would issue permits to opt-in firms equal to their counterfactual emissions. In practice, however, the regulator cannot anticipate the level of counterfactual emissions. Yet, he must establish a permit allocation rule in advance that cannot be changed easily even if new information would suggest so.[18]

As explained by Montero (2000), in deciding how to set the permits allocation rules for affected and opt-in firms, the regulator faces the classical trade-off in regulatory economics[19] between production efficiency (minimization of aggregate control costs) and information rent extraction (reduction of excess permits). In fact, a too restrictive allocation rule for opt-in sources may be effective in controlling the issuance of too many excess permits but at the same time may prove ineffective in attracting low-cost sources. A more generous allocation rule, on the other hand, may be effective in attracting most low-cost possibilities but ineffective in preventing the issuance of excess permits to opt-in sources (with both high and low costs).

To study this regulatory problem, in Montero (2000) I extend the basic model in different directions. First, I consider two group of firms: affected and non-affected firms. Second, I let firm's unrestricted emissions or counterfactual emissions be u, which are expected to be equal to historic emissions, that is $E[u] = 1$. The actual value of u, however, is firm's private information which differs across firms according to some density function $g_u(u)$ and cumulative

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[18] Instead of using an allocation rule, one can work on a case-by-case basis, which most certainly would make the opt-in process more costly for both the regulator and firms.

[19] See Laffont and Tirole (1993).

density function $G_u(u)$ defined over the interval $[\underline{u}, \bar{u}]$. Third, since abatement cost may differ, on average, across the two groups of firms,[20] I let $c \in [\underline{c}, \bar{c}]$ for affected firms and $c \in [\underline{c}, \tilde{c}]$ for non-affected firms, where $\tilde{c}$ may be equal to, higher or lower than $\bar{c}$. The regulator's problem is that of finding permit allocations for affected and opt-in firms that maximizes social welfare subject to imperfect information, cost and benefit uncertainty and design constraints (for example, the definition of the group of firms is assumed beyond the control of the regulator).

One of the results of Montero (2000) is that if the regulator has two instruments –the permit allocation to originally affected firms and to opt-in firms (those non-affected firms that have decided to opt-in)– in the absence of income effects and distributional concerns, the regulator can achieve the first-best outcome. To do so, the regulator sets the permit allocation of opt-in firms high enough (i.e., $\bar{u}$) such that all non-affected firms opt-in. The total excess permits that are expected to be allocated to opt-in sources (i.e., $\bar{u} - 1$) are deducted from the allocations to affected sources. If the regulator, however, cannot make "permit transfers" from affected to opt-in sources, so that he has only one instrument –the permit allocation to opt-in firms– he achieves a second-best outcome in which the opt-in allocation is lower than the first-best allocation to the point where the gains from information rent extraction are just offset by the productive efficiency losses of leaving some low-cost non-affected firms outside the program.[21]

3.5. Incomplete monitoring

Most market experiences implemented so far suggest that conventional permits programs are likely to be used in cases where emissions can be closely monitored, which almost exclusively occurs in large stationary sources like electric power plants and refineries (e.g., Acid Rain Program in the U.S., RECLAIM Program in Southern California). It should not be surprising then, that environmental authorities continue relying on command-and-control instruments (i.e., standards) to regulate emissions from smaller sources because compliance with such instruments only requires the authority to ensure that the regulated source has installed the required abatement technology or that its emissions per unit of output are equal or lower than a certain emissions rate standard.

In addition, some regulators view that a permits program where emissions cannot be closely observed is likely to result in higher emissions than under an

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[20] In the global warming, it is likely that carbon abatement costs of sources affected by the Kyoto Protocol are, on average, significantly higher than the costs of non-affected sources (i.e., less developed countries).

[21] Montero (2000) also find that the second-best result is sensitive to uncertainty in benefits and aggregate control cost. In fact, if benefit and cost uncertainties are correlated negatively or not at all, the regulator benefits from setting the opt-in rule slightly above the "certain" second-best allocation.

alternative standards regulation because the former provides firms with more flexibility to choose output and emissions. As we shall see, this latter concern is entirely valid because there may be cases in which permits may lead to higher emissions than standards.

Thus, it appears that environmental markets are not suitable for effectively reducing air pollution in cities such as Santiago-Chile or Mexico City where emissions come from many small (stationary and mobile) sources rather than a few large stationary sources. Rather than disregard environmental markets as a policy tool, I think the challenge faced by policy makers in cities suffering similar air quality problems is when and how to implement these markets using monitoring procedures that are similar to those under CAC regulation.

While the literature provides little guidance on how to approach this challenge,[22] it is interesting to observe that despite its incomplete information on each source's actual emissions, Santiago-Chile's environmental agency has already implemented a market to control total suspended particulate (TSP) emissions from a group of about 600 stationary sources (Montero *et al*., 2002). Based on estimates from annual inspection for technology parameters such as source's size and fuel type, Santiago's environmental regulator approximates each source's actual emissions by the maximum amount of emissions that the source could potentially emit in a given year.[23]

I believe that a close (theoretical and empirical) examination of this "quasi-emissions" permit program represents a unique case study of issues of instrument choice and design that can arise in the practical implementation of environmental markets in which regulators face important information asymmetries and have a limited number of policy instruments.

To explore the implications of imperfect monitoring on the design of a permits program and on whether permits program should still be preferred to the conventional standards regulation, in a recent paper I extend the basic model in different directions. Maintaining the notation in Montero (2004), I consider a competitive market for an homogeneous good supplied by a continuum of firms of mass 1.

Each firm produces output q and emissions e of a (uniform flow) pollutant. When the firm does not utilize any pollution abatement device $e = q$. Market inverse demand is given by $P = P(Q)$, where Q is total output and $P'(Q) \leq 0$. Total damage from pollution is given by $D(E)$, where E are total emissions and $D'(E) > 0$. Functions $P(Q)$ and $D(E)$ are known to the regulator.

A firm can abate pollution at a positive cost by installing technology x, which reduces emissions from q to $e = (1 - x)q$. Hence, the firm's emission rate

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[22] In his survey, Lewis (1996) only briefly mentions the implications of imperfect monitoring on instrument design.

[23] As it turns out, using the source's maximum emissions as a proxy does not prevent any adverse effects that the use of permits (instead of CAC regulation) could eventually have on aggregate emissions. The choice of proxy is an arbitrary matter because the number of permits being allocated can always be adjusted accordingly with no efficiency effects.

is $e/q = 1 - x$. Each firm is represented by a pair of cost parameters (β, γ). A firm of type (β, γ) has a cost function $C(q, x, \beta, \gamma)$ where β and γ are firm's private information. To keep the model mathematically tractable, I assume that the cost function has the following quadratic form in the relevant output-abatement range[24]

$$C(q, x, \beta, \gamma) = \frac{c}{2}q^2 + \beta q + \frac{k}{2}x^2 + \gamma x + vxq \tag{10}$$

where c, k and v are known parameters common to all firms and $c > 0$, $k > 0$, $\Lambda \equiv ck - v^2 > 0$ and $v \gtreqless 0$.[25]

Function (10) incorporates two key cost parameters that are essential to model firms' behavior under permits and standards regulation. One of these cost parameters is the correlation between β and γ (denoted by ρ), which captures whether firms with higher output ex-ante (i.e., before the regulation) are more or less likely to install more abatement x. The other cost parameter is v, which captures the effect of abatement on output ex-post (note that we have constrained v to be the same for all firms, thus, a negative value of v would indicate that, on average, the larger the x the larger the increase in q ex-post).[26] As we shall see, the values of the cost parameters v and ρ play a fundamental role in the design and choice of policy instruments when emissions are not closely monitored.

Although the regulator does not observe firms' individual values for β and γ, we assume that he knows that they are distributed according to the cumulative joint distribution $F(\beta, \gamma)$ on $\beta \in [\underline{\beta}, \overline{\beta}]$ and $\gamma \in [\underline{\gamma}, \overline{\gamma}]$.[27] To simplify notation further and without any loss of generality I let $E[\beta] = E[\gamma] = 0$. I also use the following notation: $\mathrm{Var}[\beta] \equiv \sigma_\beta^2$, $\mathrm{Var}[\gamma] \equiv \sigma_\gamma^2$, $\mathrm{Cov}[\beta, \gamma] \equiv \rho\sigma_\beta\sigma_\gamma$ and $F_{\beta\gamma} \equiv \partial^2 F(\beta, \gamma)/\partial\beta\partial\gamma$.

Firms behave competitively, taking the output clearing price P as given. Hence, in the absence of any environmental regulation, each firm will produce to the point where its marginal production cost equals the product price (i.e., $C_q(q, x, \beta, \gamma) = P$), and install no abatement technology (i.e., $x = 0$). Because production involves some pollution, this market equilibrium is not socially

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[24] This is the quadratic approach introduced first by Weitzman (1974).

[25] The parameter v can be negative, for example, if switching to a cleaner fuel saves on fuel costs but involves such a large retrofitting cost (i.e., high k) that no firm switches to the cleaner and cheaper fuel unless regulated.

[26] Ideally, one would like a richer model in which $v = \delta$ can vary across firms, where $\delta > 0$ is the firm's private information drawn over some known interval $[\overline{\delta}, \underline{\delta}]$ and according to some known cumulative distribution. Then, a positive correlation between γ and δ would produce that a higher x leads to an ex-post higher q. Solving that model, however, requires numerical techniques.

[27] Note that we can easily add aggregate uncertainty to this formulation by simply letting $\beta^i = \beta^i + \theta$ and $\gamma^i = \gamma^i + \eta$, where θ and η are random variables common to all firms.

optimal. The regulator’s problem is then to design a regulation that maximizes social welfare.

I let the regulator’s social welfare function be now

$$W = \int_0^Q P(z)dz - \int_{\underline{\beta}}^{\overline{\beta}}\int_{\underline{\gamma}}^{\overline{\gamma}} C(q, x, \beta, \gamma)F_{\gamma\beta}d\beta d\gamma - D(E) \tag{11}$$

where $Q = \int_\beta \int_\gamma q(\beta, \gamma)F_{\gamma\beta}\,\mathrm{d}\gamma\mathrm{d}\beta$ is total output and $E = \int_\beta \int_\gamma (1 - x(\beta, \gamma))q(\beta, \gamma)F_{\gamma\beta}\,\mathrm{d}\gamma\mathrm{d}\beta$ is total emissions. In this welfare function, the regulator does not differentiate between consumer and producer surplus and transfers from or to firms are lump-sum transfers between consumers and firms with no welfare effects.

We have explained that information asymmetries regarding costs may not prevent the regulator from attaining the first-best resource allocation if he can costlessly monitor each firm’s actual emissions e (Kwerel, 1977; Dasgupta *et al*., 1980; Spulber, 1988; Lewis, 1996). We are also interested in the problem in which the regulator cannot perfectly observe firms’ actual emissions $e = (1 - x)q$; although he can costlessly monitor firms’ abatement technologies or emission rates x. As in Santiago’s quasi-emissions trading program, this information asymmetry will be present when both continuous monitoring equipment is prohibitively costly and individual output q is not observable. Thus, if the regulator asks for an output report from the firm, we anticipate that the firm would misreport its output whenever this was to its advantage. In this case, the regulator cannot implement the social optimum regardless of the information he or she has about firm’s costs.[28]

Even if the regulator has perfect knowledge of firm’s costs and, therefore, can ex-post deduce firm’s output based on this information and the observation of x, the fact that he cannot make the policy contingent on either emissions or output prevents him from implementing the first-best. In other words, the regulator cannot induce the optimal amounts of output and emissions with only one instrument (i.e., x).[29] Consequently, the regulator must necessarily content himself with “second-best” policies.

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[28] Consider the extreme situation in which regulator knows both β and γ. His optimal policy will be some function $T(x; \beta, \gamma)$ in the form of either a transfer from the firm or to the firm. Then, firm (β, γ) takes $P(Q)$ and $T(x; \beta, \gamma)$ as given and maximizes $\pi(q, x, \beta, \gamma) = P(Q)q - C(q, x, \beta, \gamma) - T(x; \beta, \gamma)$ with respect to q and x.

[29] See Proposition 2 of Lewis and Sappington (1992) for the same conclusion in a related problem. On the other hand, since the regulator can have a good idea of total emissions E from air quality measures, one might argue that Holmström’s (1982) approach to solving moral hazard problems in teams may apply here as well. However, in our context this approach is unfeasible because the large number of agents would require too big transfers; either from firms as penalties or to firms as subsidies.

Rather than considering a full range of policies, in what follows I will concentrate on the effect of imperfect monitoring on the design of simpler policies such as standards and permits (taxes are equivalent to permits unless we introduce aggregate uncertainty; see footnote above). Under standards regulation, the regulator's problem is to find the emission rate standard x_s to be required to all firms that maximizes social welfare $W(\cdot)$ (subscript "*s*" denotes standards policy and subscript "*p*" denotes permits policy).

On the other hand, under the permits policy, the regulator's problem is to find the total number of (quasi-emission) permits $\tilde{e}_0$ to be distributed among firms that maximizes social welfare. If we denote by R the equilibrium price of permits,[30] the regulator knows that firm (β, γ) will take R as given and solve

$$\max_{q,x} \pi(q, x, \beta, \gamma) = Pq - C(q, x, \beta, \gamma) - R \cdot (\tilde{e} - \tilde{e}_0)$$

where $\tilde{e} = (1-x)\tilde{q}$ are firm's quasi-emissions and $\tilde{q}$ is some arbitrarily output or capacity level that is common to all firms (the exact value of $\tilde{q}$ turns out to be irrelevant because it simply works as a scaling factor).

Assuming that $P(Q) = P$ and $D(E) = hE$, the welfare advantage of the optimal permits policy over the optimal standards policy reduces to

$$(12)\quad \Delta_{ps} = \int_{\underline{\beta}}^{\overline{\beta}}\int_{\underline{\gamma}}^{\overline{\gamma}} [\{C(q_s,\ x_s) - C(q_p,\ x_p)\} + \{(1-x_s)q_s - (1-x_p)q_p\}h]\, F_{\beta\gamma}\, d\gamma d\beta$$

Recalling that $e = (1-x)q$, the first curly bracket of the right hand side of (12) is the difference in costs between the two policies, whereas the second curly bracket is the difference in emissions that multiplied by h gives the difference in pollution damages. After some algebra (12) becomes

$$(13)\quad \Delta_{ps} = \frac{v^2\sigma_\beta^2 - 2cv\rho\sigma_\beta\sigma_\gamma + c^2\sigma_\gamma^2}{2c\Lambda} - \frac{h\cdot(kv\sigma_\beta^2 - (kc+v^2)\rho\sigma_\beta\sigma_\gamma + cv\sigma_\gamma^2)}{\Lambda^2}$$

and after collecting terms, it reduces to

$$(14)\qquad \Delta_{ps} = A_1\sigma_\beta^2 + A_2\sigma_\gamma^2 + A_3\rho\sigma_\beta\sigma_\gamma$$

where $A_1 = (v^2\Lambda - 2ckhv) / 2c\Lambda^2$, $A_2 = (c\Lambda - 2chv) / 2\Lambda^2$ and $A_3 = (ckh + hv^2 - v\Lambda) / \Lambda^2 > 0$. Note that A_1, A_2 and ρ can be either positive, negative or zero,[31] so

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[30] Note that under a tax policy, the optimal price R will be the quasi-emissions tax. If we add aggregate uncertainty to the model, both policies will not be equivalent from an efficiency standpoint.

[31] Recall that for interior solutions in all cases we must have $ck > (h-v)^2$, $ck > v^2$, and $h > v$.

the magnitude of Δ_{ps} depends on the value of the different parameters of the model.

The ambiguous sign of (14) is due to an inevitable trade-off between flexibility and potential higher emissions that a regulator will face when implementing a permits program under imperfect monitoring. Expression (13) illustrates this trade-off more clearly. The first term is the difference in costs between the two policies. Since $-1 \leq \rho \leq 1$, this term is always positive which indicates that the optimal permits policy is always less costly than the optimal standards policy. The second term is the difference in damages, which can either be positive, negative or zero depending on the value of the different parameters of the cost function. Hence, a quasi-emissions permits policy will always lead to cost savings but it can also lead to higher emissions.

While the actual magnitude of Δ_{ps} will depend on the value of the different parameters of the model, its sign is governed by the key cost parameters v and ρ. For example, the permits policy will be unambiguously superior when $v < 0$ and $\rho > 0$. This is so because when $v < 0$, firms doing more abatement are at the same time increasing output relative to other firms. Similarly, when there is a positive correlation between abatement and production costs (i.e., $\rho > 0$), larger firms are more likely to do more abatement.

Contrary to what occur when emissions are perfectly monitored, these results indicate that neither permits nor standards is the appropriate policy choice in all cases. Because of this ambiguity, there seems to be room for a hybrid policy to improve upon either single-instrument policy. Since permits are always superior in terms of costs but standards are not always superior in terms of emissions, it remains to be seen whether and when a hybrid policy would provide a net welfare gain.

As it turns out, the combination of instruments does not necessarily leads to higher welfare in this model. The exact shape of the region in which the hybrid policy dominates either single-instrument policy depends on the parameter values. A simple numerical exercise may be useful. In Figure 1, line $\ell_{h=p}$ indicates the combinations of v and ρ for which the hybrid policy just converges to the permits policy for the following parameters values: $P = k = c = 4$, $h = 2$, $\overline{\beta} = 2$, = $\underline{\beta} = -2$, $\overline{\gamma} = 1$, $\underline{\gamma} = -1$.[32] The figure also includes the line $\ell_{\Delta=0}$ (i.e., combinations of v and ρ that yield $\Delta_{ps} = 0$) and the line $\ell_{\Delta E=0}$ (i.e., combinations of v and ρ for which the permits policy and the standards policy yield the exact same level of emissions). One can distinguish three regions in the figure. To the left of $\ell_{h=p}$, there are those combinations for which the hybrid policy coincides with the permits policy. As the first row of Table 1 shows, if $v = -0.5$ and $\rho = 0.6$, for example, social net benefits (W) are 33% higher under the permits policy than under the standards policy. Note also that in some places of this region the hybrid policy does not improve upon the permits-alone policy despite the fact

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[32] The simulation is carried out with only four type of firms: $(\overline{\beta}, \overline{\gamma})$, $(\overline{\beta}, \underline{\gamma})$, $(\underline{\beta}, \overline{\gamma})$ and $(\underline{\beta}, \underline{\gamma})$. Also, the value of the different parameters limit the range of v to [–0.5, 0.7].

FIGURE 1
HYBRID AND SINGLE-INSTRUMENT POLICIES

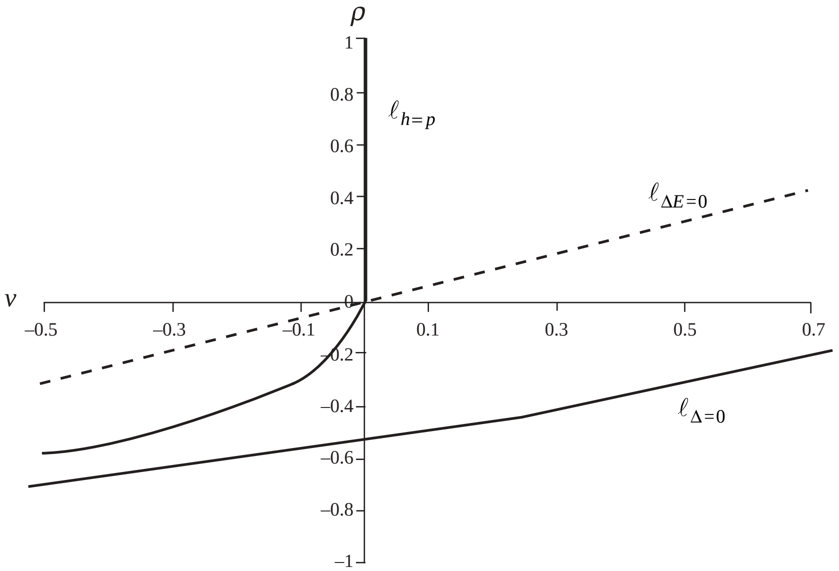

TABLE 1
HYBRID AND SINGLE-INSTRUMENT POLICIES: DESIGN AND WELFARE

v	ρ	x_s	$R\tilde{q}$	x_s^h	$R^h\tilde{q}^h$	W_s	Δ_{ps}	Δ_h
–0.5	0.6	0.65	2.08	0	2.08	123.64	41.08	0
0.6	0.5	0.38	2.07	0.18	1.99	82.04	13.66	1.72
0.7	–0.5	0.36	2.10	0.21	1.49	79.74	–6.37	2.07

that emissions are higher than under a standards-alone policy. The logic behind this result is that the introduction of some binding standard (in combination with permits) would not only reduce emissions but also increase production and abatement costs. And in this particular region, the latter effect dominates.

The second region –between the lines $\ell_{h=p}$ and $\ell_{\Delta=0}$– includes all those combinations for which the hybrid policy is superior to the permits-alone policy, which in turn, is superior to the standards-alone policy. For example, if $v = 0.6$ and $\rho = 0.6$, the welfare gain from implementing the hybrid policy (Δ_h) is 12.6% of Δ_{ps}, as shown in the second row of the table. It is interesting to observe that despite welfare may not increase by much, policy designs are quite different (the hybrid policy includes a standard that is almost half the one in the standards-alone policy; though the equilibrium permit price do not vary much). Finally, the third region –to the right of $\ell_{\Delta=0}$– includes those combinations of v and ρ for which the hybrid policy is welfare superior to the standards-alone policy, which in turn, is superior to the permits-alone policy. Here, the gain from implementing the hybrid policy as opposed to the standards-alone policy is substantial, 32.5% of $|\Delta_{ps}|$.[33]

4. FINAL REMARKS

I have extended the basic model of pollution control under perfect information to accommodate topics that seem relevant for the design and implementation of environmental markets in practice. Either for space constraints or limited literature, several topics have been left out. Let me mention a few. The first is whether the initial allocation of permits makes much difference on the performance of the market and on overall welfare. A free allocation of permits may induced too much entry from long-run perspective which does not happen when they are auctioned off (Spulber, 1985). In the presence of pre-existing tax distortion (e.g., labor and capital taxes), a free allocation of permits may also be welfare inferior to auctioning them off (Goulder *et al*., 1997).

A second important topic that has attracted considerable attention in the global warming discussion is the effect of regulation on technological change. Market-based instruments such as permits are taxes are generally believed to provide firms with more incentives to innovate and adopt newer technologies than traditional standards regulation (e.g., Jung *et al.*, 1996). However, such view has been somehow challenged recently (e.g., Montero, 2002). More empirical analysis is needed here.

Other topics not covered include the design of permits markets for non-uniformly mixed pollutants (O’Ryan, 1996), the welfare implications of allowing firms to trade permits intertemporally (Ellerman and Montero, 2002), the effect of market power on instrument design and performance (Hahn, 1984; Liski and Montero, 2003), the welfare comparison between permits and standards when the regulator cannot set emission targets optimally (Oates *et al.*, 1989), and the design of permit markets in a few players context and where emissions (effort) are imperfectly monitored at the individual level but not at the aggregate level. Further research on this latter topic is particularly relevant if we want to introduce permit markets for water pollution control. The literature on moral hazards in teams pioneered by Holmström (1982) should be the starting point.

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[33] Note that despite that $\sigma_\gamma = 0.5\sigma_\beta$, there is no region in Figure 1 where the hybrid policy converges to the standards-alone policy.

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